NASA/CR–2019-220267 Volume II

Structural Framework for Flight II: NASA's Role in Development of Advanced Composite Materials for Aircraft and Space Structures

Final Report

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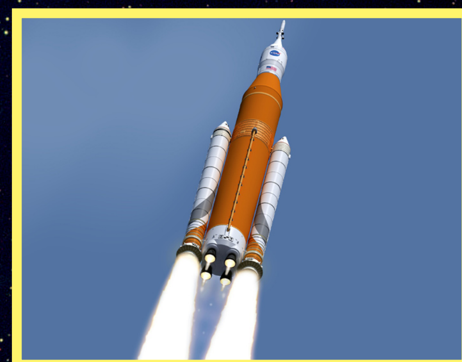
STRUCTURAL FRAMEWORK FOR FLIGHT II

Research at NASA Langley Research Center on Metallic Materials



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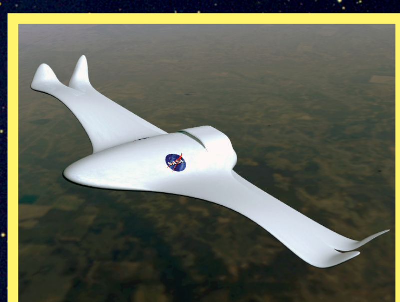

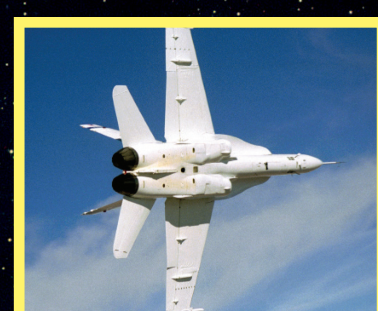

Structural Framework for Flight II: NASA Langley's Role in Development and Application of Metallic Materials and Structures for Aircraft and Space Launch Vehicles

By

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A special thanks also to Dr. Joseph Heyman for drafting the NDE section and to Dr. William H. Prosser for his support of the effort to draft the NDE Section. Also, we acknowledge and thank Dr. James C. Newman, Jr. for his outstanding contributions to the fatigue and fracture parts of this monograph and to Dr. Ivatury S. Raju for his support of this work. Appreciation is also expressed to Dr. Rajagopalan Sivakumar for his technical contributions to this Monograph.

I also want to acknowledge the dedicated support and hard work of the AS&M technical team that labored many hours to research and draft the different sections of this monograph. Team members included Dr. Darrel R. Tenney, Mr. Thomas T. Bales, Dr. James C. Newman Jr., Dr. Joseph Heyman, and Dr. Edgar A. Starke, Jr. I want to especially express thanks to Dr. James C. Newman for his many hours of work to document the excellent contributions made by the outstanding NASA engineers that pioneered the fatigue and fracture work at NASA that significantly contributed to damage tolerance of modern methodologies used to enhance safety of flight for modern aircraft and launch vehicles. Also, a special thanks to Dr. Robert S. Piascik for his excellent contributions to the durability and damage tolerance sections. Much of the information on the influence of environmental factors on small crack growth is drawn from Dr. Piascik's research.

Finally, a tribute is given to all the NASA Langley Materials and Structures scientists and engineers, aerospace industry contractors, and university faculty and students who contributed to the development of lightweight metals and structures in support of National Aeronautics and Space Administration Programs. Recognition also goes to the technicians who performed much of the experimental work, and to the shop personnel at Langley that fabricated metallic test specimens and fixtures over the past eight decades of metallic materials and structures development at NASA Langley Research Center.

Dr. Darrel R. Tenney
Hampton, Virginia
February 1, 2017

PREFACE

This document is intended to serve several purposes. First, as a source of collated information on Metals Research conducted at Langley from 1917 to 1958 as a National Advisory Committee for Aeronautics (NACA) field Research Center and from 1958 to today (2014) as a National Aeronautics and Space Administration (NASA) Research Center. Although several excellent books have been written to document the historical work and outstanding contribution NACA/NASA made to aerodynamics, flight systems, and other key flight vehicle disciplines the pioneering work and contributions made in structures and materials has only been partially recorded in achievable documents. The first such document entitled "Structural Framework for Flight I: NASA'S Role in Development of Advanced Composite Materials for Aircraft and Space Structures" was published in 2010. This monograph is a companion document to the Composites Monograph and serves as a key reference for readers wishing to grasp the underlying principles and challenges associated with developing and applying advanced metallic materials and structures to new aerospace vehicle concepts. Second, it identifies the major obstacles encountered in developing and applying light alloys on advanced flight vehicles, as well as lessons learned in overcoming these obstacles. Third, it points out current barriers and challenges to "light-weighting" future vehicles. This is extremely valuable for steering research in the future when breakthroughs in new materials or processing science may eliminate/minimize some of the critical barriers that have traditionally been impediments to further reduction in the structural weight of flight vehicles. Finally, a review of past work and identification of future challenges will hopefully inspire new research opportunities and development of revolutionary materials and structural concepts for future flight vehicles. The specific objectives of this *Structural Framework for Flight: NASA's Role in Development of Light Weight Metallic Materials and Structures for Aircraft and Space Launch Vehicles* monograph are:

1. **Knowledge Capture:** The intent is to capture and distill into one document, selected examples of the major advancements made to the metallic materials knowledge base, generated in over nine decades of research performed at the Langley Research Center or under Langley-sponsored grants and contracts. From 1920 through 2013, NASA's structures and materials research on lightweight metallic structures was aimed at developing the foundational technologies required to mature lightweight metallic materials and structural concepts to the point where they could be certified for primary load-carrying aircraft and spacecraft structures. The goal was to improve performance and reduce weight and cost of aerospace vehicles and spacecraft. Thousands of technical reports on the results of NASA's research were published in the open literature, and many thousands of technical talks were presented at national and international meetings. These reports and talks were authored by NASA researchers, academic researchers working on NASA-sponsored grants and cooperative agreements, research partners in other government research laboratories, and industry researchers working on NASA-sponsored contracts. Although several books have been published on NASA's contributions to aerodynamics and flight systems, this is only the second report focused

on documenting a comprehensive knowledge capture of the structures and materials research performed and/or sponsored by Langley.

2. **Lessons Learned:** During the course of these ninety years of research on lightweight metallic structures, many lessons were learned on both the methods and approaches used in the conduct of the research, and the principal findings coming from this research. In this study, emphasis was placed on both identification of the lessons learned and on identifying the primary factors which either contributed to successful completion of research objectives or failure to meet planned milestones.
3. **Assessment of Emerging Technology:** The study assessed the technology readiness of emerging new materials and structural concepts for application to innovative new air vehicle concepts and new space transportation concepts. This information is valuable for the selection of highest payoff projects for funding.
4. **Identification of Grand Challenges for the Future:** This study identified the major technical challenges remaining to be solved for reducing the weight and improving the performance of future advanced concept air vehicles, advanced space launch vehicles, and high-performance space hardware for space science and space exploration missions.

This monograph is organized to highlight the successful application of light alloys on aircraft and space launch vehicles, the role of NASA in enabling these applications for each different class of flight vehicles, and a discussion of the major advancements made in discipline areas of research. In each section, key personnel and selected references are included. These references are intended to provide additional information for technical specialists and others who desire a more in-depth discussion of the contributions. Also in each section, lessons learned and future challenges are highlighted to help guide technical personnel either in the conduct or management of current and future research projects related to light-weighting advanced air and space vehicles.

The metallic materials and structures work at Langley support NASA Space Technology Roadmaps and Priorities as reported in the recent National Research Council (NRC) study performed for NASA entitled “NASA Space Technology Roadmaps and Priorities: Restoring NASA’s Technological Edge and Paving the Way for a New Era in Space.” For example, The Top Technical Challenges for Technology Objective C: Expand our understanding of Earth and the universe in which we live (remote measurements). The top technical challenges C1 and C3 (ranked from C1 to C10) are:

C1) Improved Access to Space: Dramatically reduce the total cost and increase reliability and safety of access to space.

C3) Lightweight Space Structures: Develop innovative lightweight materials and structures to reduce the mass and improve the performance of space systems such as (1) launch vehicle and payload systems; (2) space and surface habitats that protect the crew, including multifunctional structures that enable lightweight radiation shielding, implement self-monitoring capability, and require minimum crew maintenance time; and (3) lightweight, deployable synthetic aperture radar antennas, including reliable mechanisms and structures for large-aperture space systems that can be stowed compactly for launch and yet achieve high-precision final shapes.

Other technology objectives identified in this report are also supported, but these are included here to indicate that the cutting edge work being performed in metallic materials and structures is relevant to future NASA missions.

EXECUTIVE SUMMARY OF METALLIC MATERIALS RESEARCH AT NASA LANGLEY

Many of the significant advances in aircraft and launch vehicles have been enabled by improved materials and materials manufacturing processes. Improving the efficiency and performance of aircraft and space launch rockets and vehicles has been a research focus for NASA and its predecessor agency NACA since the early 1920s. This period was characterized by multiple military and commercial aircraft development programs, a robust group of aerospace companies and second-tier suppliers, and significant government investment in technology development, flight test vehicles, and supporting infrastructure. Together these factors resulted in significant improvements in flight vehicle characteristics and established the United States on the leading edge of aerospace technology.

There is a need to find heroic stories about engineering in general and, for the purposes of this report, heroic stories about metallic materials and structures. Selected heroic stories about metallic materials and structures have been documented. By all accounts, the metallic materials research conducted at Langley Research Center since NACA and then NASA was formed has made outstanding contributions to the development of high-performance lightweight structures for aircraft and launch vehicles and to the fundamental understanding that has enhanced application of aerospace alloys to non-aerospace applications. In this document, the authors have attempted to identify the major contributions and lessons learned in the conduct of both focused and basic research on metallic materials and structures at Langley Research Center. Although this has been a daunting task, they have captured and distilled valuable information on the metallic materials research programs implemented and the impact of this research. Some of this information comes from the collective experience of the authors, who spent much of their professional career either directly conducting research on aerospace materials and structures or managing materials and structures research projects and/or programs. Much additional insight was gained from an exhaustive study of the literature and contract reports generated on Langley-funded research projects. Also, valuable information and crucial insight was provided by retired and current researchers engaged in projects where high-performance lightweight vehicle structure was a key technology area.

The lessons learned in this section are presented in more detail in the different sections of the document. In most cases, the authors have attempted to synthesize the multiple lessons learned from all the different sections of this monograph into a higher-level look at the key knowledge gained from this study. However, these top-level comments are not intended to supplant the more detailed comments presented at the end of each section.

Based on the results of this examination of metallic materials and structures research, the challenges for enhancing the performance and safety of future vehicles and the longer-term application of new materials and manufacturing technologies to revolutionary new aircraft and launch vehicle concepts, have been identified. These challenges are based upon lessons learned, and are intended to provide guidance to technical personnel and management in the planning and execution of current and future research projects related to lightweight/high-performance aerospace structures. An epilogue section has also been added which addresses future research on materials and structures in a "Third-Generation NASA" and draws from proven success models to propose a path way forward in a dynamic and ever changing Research and Development (R&D) environment.

Major Contributions

1. **Flight Safety:** Langley provided leadership and stimulus to the commercial aircraft industry, airline operators, and the Federal Aviation Administration (FAA) for the development of "Failsafe" technologies to insure the safety of aircraft flight and launch vehicle structures. Particularly noteworthy was the advancement of the understanding of the role of crack closure in fatigue crack growth and prediction of fracture toughness and failure. Many contributions to the development of progressive failure analyses were made in fatigue and fracture studies conducted at Langley and the application of these analyses in important National Programs such as the NASA/FAA/DoD Aging Aircraft Program.
2. **Development of Al-Li Alloys:** Langley research on Al-Li alloys both in-house and on contract was instrumental in the successful development of the 2195 Al-Li alloy used for the super lightweight tank (SLWT) for the space shuttle. A total weight savings of 7500 lbs. was achieved versus the standard LH2 tank used for prior shuttle flights. This weight savings was achieved using a new alloy combined with a new design for the LH2 Tank-Orthogrid. The first SLWT flew June 2, 1998 on STS 91– six months ahead of the International Space Station (ISS) need date.
3. **Foundational Technology Base:** Langley Research and Development Base and Focused programs were the primary source of the foundational technology base required to commit to the use of lightweight alloys in aircraft and space launch vehicle primary structures. This included a fundamental understanding of materials behavior, fabrication technologies, test methods, inspection methodologies, structural analyses, and environmental effects. Testing articles ranged from coupons to built-up structural components.
4. **Support for Development of Airworthiness:** Solutions to technical problems that posed an issue for flight safety were developed by Langley in close cooperation with the FAA. This included development of test standards, inspection criteria, analyses codes and other methodologies to insure airworthiness of metallic structures. FAA durability and damage tolerance specialists were included on NASA's advisory committees and in working groups.
5. **Environmental Degradation of Aerospace Alloys:** Langley made major contributions to understanding the corrosion behavior of Al alloys, Ti alloys, and high-strength steels used for aircraft landing gears. This included the development of ASTM Corrosion standards and extensive exposure testing to measure and characterize the corrosion behavior of alloys heat treated to temper conditions expected for service. Langley also tested a wide range of candidate superalloys for use as metallic heat shields for the Shuttle Program. This work focused on determining the performance on leading

candidate high-temperature alloys in hypersonic flowing air environments designed to simulate reentry conditions for the shuttle.

6. **Structural Efficiency of Aerospace Structures:** Langley designed, fabricated, and tested a broad range of structural panel concepts in an effort to establish relations between structural efficiency and panel weight. Static load tests and cyclic load testing were performed to establish failure envelopes and failure mechanisms. Structural analyses codes were developed and refined to accurately predict failure lifetimes for typical stress levels expected for flight vehicles.

7. **Manufacturing Technology:** Langley also made significant contributions to manufacturing technologies of lightweight metallic structures for flight vehicles. Notable among these are superplastic forming (SPF) and weld brazing of titanium panels, superplastic forming and diffusion bonding (SPF/DB) titanium 4 sheet sandwich panels, weld-bonded SPF beaded web truss core sandwich, shear forming, spin forming, spin forming of domes, roll forging, integrally stiffened Al-Li extrusions, and counter roll forming. In the areas of near-net-shape forming and additive manufacturing. NASA Langley Research Center (LaRC) is the originator and world leader in electron beam freeform fabrication (EBF^3) technology development. EBF^3 is a NASA-patented additive manufacturing process designed to build complex, near-net-shape parts requiring substantially less raw material and finish machining than traditional manufacturing methods. EBF^3 is a process by which NASA plans to build metal parts in zero gravity environments.

8. **Crashworthiness:** Langley, in conjunction with the U.S. Army-Aerostructures Directorate, led the research on energy absorption of airframe structures in aircraft and rotorcraft. Fundamental failure and energy absorbing buckling modes for subfloor structure were identified and different energy absorption concepts were tested in crash test of helicopter cabins in the Landing Loads Test Facility.

9. **Fabrication Technology:** NASA Langley provided leadership and support in the development and/or utilization of processes that lowered the costs and improved quality of metallic structures. Langley pioneered development of superplastic forming of titanium and aluminum alloys for flight weight structural panels including several different types of bonding.

10. **Quantitative Nondestructive Evaluation (NDE):** Langley has been a leader in this technical area and worked with industry and the FAA to identify the appropriate NDE techniques to establish airworthiness of aircraft structures. Langley pioneered the development of physics-based modeling to enable predictive capability of NDE technologies in the fields of radiography, ultrasonics, thermography, electromagnetics, and optics. The development of the Simpson Meter which greatly improved the accuracy of eddy current inspection for crack detection around rivets in aircraft structures was particularly noteworthy. The eddy current probe, developed at NASA Langley Research Center, provided a null-signal in the presence of unflawed material without the need for any balancing circuitry.

11. **Hot Structures:** Langley has developed hot structure technology for several hypersonic vehicles. Significant reductions in vehicle weight can be achieved with the application of hot structures which do not require parasitic thermal protection systems (TPS). Hot

structures have been developed for vehicles including the X-43A, X-37, and the Space shuttle. These trans-atmospheric and atmospheric entry flight systems that incorporate hot-structures technology are lighter weight and require less maintenance than those that incorporate parasitic, thermal-protection materials that attach to warm or cool substructure. The development of hot structures requires a thorough understanding of material performance in an extreme environment, boundary conditions and load interactions, structural joint performance, and thermal and mechanical performance of integrated structural systems that operate at temperatures ranging from 1500°C to 3000°C, depending on the application.

12. **Durability and Damage Tolerance:** Several codes for the prediction of stress intensity factors, crack propagation and fatigue crack growth were funded entirely or in part by the Durability and Damage Tolerance and Reliability Branch (DDTRB) at NASA Langley during the Aircraft Structural Integrity Program (ASIP). Among these are ZIP3D, FRANC3D, STAGS, and FASTRAN II. The ZIP3D computer code was developed to model three-dimensional crack configurations and to calculate the corresponding stress-intensity factors. The FRANC3D code also has solid modeling capabilities for three dimensional configurations and can adaptively remesh the configuration as the crack grows. The STAGS finite element code was interfaced with FRANC3D to develop a flexible computational platform for predicting crack growth in cylindrical stiffened shells. Stress-intensity-factor solutions are used as input data for the FASTRAN II code to predict fatigue crack growth. The FASTRAN II code is based on the mechanics of plasticity induced crack closure. The effects of prior loading history on fatigue behavior, such as crack-growth retardation and acceleration, are computed on a cycle-by-cycle basis. The code will predict the growth of cracks exhibiting the small-crack effect, as well as of two- and three-dimensional cracks exhibiting the classical Paris law crack-growth behavior. Other codes, such as NASGRO, a general-purpose damage-tolerance analysis code developed at NASA Johnson Space Center (JSC), have been developed in collaboration with DDTRB.

13. **Structural Analyses Codes:** Code development has been a major strength of Langley for many years. Langley managed and contributed to the development of NASTRAN and other structural analysis codes.

Major Lessons Learned

Since its formation in 1917, Langley Research Center has conducted cutting edge R&D on advanced metallic materials and structures. The early years (1917–1958, NACA) were largely focused on materials and structures for civilian and military aircraft. With the formation of NASA in 1958 Langley continued to research materials and structures for aircraft, but also conducted extensive R&D for launch vehicles. Some of the key lessons learned during the rich history of NASA Langley are given below.

1. **Leadership:** The leaders of NACA recognized early on that advances in materials and structural concepts were critical to the advancement of aviation. Evidence of this recognition was the early (1939) design and construction of a dedicated structures and materials research and test laboratory at Langley Field. This facility was specifically designed for materials and structures testing ranging from small materials coupons to large built-up structural panels representative of fuselage structures of aircraft. The

foundation and floor structure of this facility was designed to accommodate very large test frames such as the million-pound test machine installed during construction and is still being used today. Many other facilities were designed and built at Langley (listed in a later section on Materials and Structures Center of Excellence) for materials and structures R&D related to the development of all types of flight vehicles. NASA and Langley leadership also made a strong commitment of a critical mass of personnel and resources to materials and structures research. Both of these actions were essential to making significant contributions in a timely manner.

2. **Sustained Commitment:** Langley has sustained a continuing commitment to R&D of metallic materials for over nine decades by doing the following:
   a) Maintaining an excellence in research and a long track record of positive accomplishments
   b) Engaging industry, universities and other government agencies as partners in planning and implementing the research
   c) Practicing excellent project management: meeting milestones and deliverables on time and within budget
   d) Working with NASA-level advisory committees to achieve agency budget priority and technical level advisory committees for guidance and technical critique of work

3. **Model for Success:** An implementation model for success was a sustaining Research and Technology (R&T) base program combined with focused technology projects. The combination of base and focused projects allowed the long-term problems to be addressed in the base program and the near-term higher technology readiness level (TRL) R&D to be implemented with industry in the focused programs. The combination promoted an efficient use of funding, facilities, and personnel. Langley has always been a willing participant in assisting in failure analyses of NASA wind tunnel facilities, aircraft accidents, shuttle accidents, crashes of military aircraft, and other accidents investigated by National Transportation Safety Board (NTSB). Lessons learned from these investigations has proved valuable in setting priorities for future R&D efforts to improve safety of NASA ground based facilities and flight vehicles.

4. **Proactive Education and Training:** A proactive education and training thrust was a critical ingredient in advancing advanced alloys and metallic structures for new vehicle concepts. Strong ties with universities have been a key part of NASA strategy to do cutting edge research in new materials. NASA-UVA Light Aerospace Alloy and Structures Technology Program (LA2ST); Research NASA Grant NAG1-745 was funded by NASA Langley from 1986 through 2004. The output of this grant includes 143 publications (103 archival journal or reviewed book publications), 31 PhD dissertations or MS theses, 147 external technical presentations, 34 NASA progress reports, and 5 NASA Contractor Reports. Since 1986, 42 graduate students, including 38 citizens of the United States, have been involved with LA2ST research; 34 have received the MS or PhD degree. Seven post-doctoral research associates have participated in LA2ST research. A total of 13 different university professors worked on the LA2ST Program since 1986. Langley personnel have actively participated in and provided leadership in national and international technical societies and technical subgroups to advance discipline-specific technologies.

5. **Multidisciplinary Research:** A multidisciplinary approach was used to solve tough technical issues typically beyond the scope of any single discipline. In particular, the interaction between NASA Langley, the metallic materials producers, the aerospace manufacturers, the regulatory agencies like the FAA, and the airline users has proved to be very successful in producing highly reliable and safe air vehicles for the flying public. Improvements in metallic materials and associated advancements in fabrication technologies have enabled the development of advanced structural concepts that meet the design requirements of the vehicle concept as defined by all the other vehicle disciplines including, aerodynamics, controls, propulsion, etc. Collaborative efforts with the Department of Defense (DoD) Laboratories, the Federal Aviation Administration (FAA), the National Institute of Standards and Technology (NIST), and other government organizations has been a central element of Langley's strategy to support national R&D efforts. Within NASA, Langley has partnered with MSFC on SLWT and Ares, JSC on Orion, and Glenn and Armstrong on Aero programs.

6. **Building Block Approach:** This approach was used to accurately predict failure of a complex built up structure. The combination of analytical modeling to predict failure and experimental validation tests was a critical ingredient in the success of the building block approach championed by Langley. This approach has included material coupon level testing, fabrication technology development to produce the required structural elements, testing at the sub element level combined with structural analyses to predict failure loads, process scale up and manufacture of components, and testing of representative structural elements. Extensive instrumentation and high-speed video was used to observe failure sequence. Failure analyses were performed on failed specimens to determine if material properties, fabrication processes, or structural design was the limiting factor.

7. **Structural Analyses:** Development of new analyses codes and capabilities were a critical ingredient in gaining new insights and fundamental understanding of new phenomena in a new technology area. The development of high-speed computing in recent years has enabled the development of local/global analyses with sufficient fidelity to accurately predict fatigue crack growth and buckling modes in complex structural elements. Projected future increases in computational power and speed will enable the coupling of computational materials including process modeling, computational structures, and prediction of service life residual strengths.

8. **Bridging Technologies:** Synergy between neighboring areas of expertise with the metallic materials discipline has proved to be a successful approach for integrating new ideas and solutions into materials research. Materials development has included mechanical property testing, aging and heat treating studies, fatigue and fracture studies, processing technology development, joining, environmental effects, and impact damage tolerance.

9. **Uncertainty Planning:** NASA has always had a dynamic budget driven by both national priorities and a yearly budget appropriation making it difficult to sustain continuity of funding for multi-year R&D Projects. The net result of this has been that almost none of the focused R&D projects were fully funded to the original plan. Major intermediate milestones need to be planned with this in mind so that major accomplishments can still be made if the projects gets re-planned or terminated. These accomplishments can provide a basis for future planning and advocating for additional funding.

10. **Archiving Data:** A plan and process to secure and archive key data needs to be an integral part of any project plan. The common practice of “handing off” key data, test procedures, or other critical information to the next researcher on the project was not effective for archiving data. Changes in personnel assignments, transfers, and periodic “building clean-up” lead to loss of data, test specimens, and in some cases, test fixtures.
11. **Personnel Mobility:** An environment that encourages movement of researchers to and from base and focused R&D programs without prejudice is needed.
12. **New Challenges:** Langley must reenergize the structures and materials research disciplines to meet future challenges and opportunities associated with the stringent performance and safety requirements of tomorrow’s revolutionary vehicle concepts. A “Grand Challenges” planning team needs to search out new technologies for the next “S Curve” opportunity and identify payoff necessary to advocate for new initiatives.

Grand Challenges

Aircraft structural design is evolutionary, not revolutionary. However, this does not mean that there have not been new technologies that have had significant impact in the past and others that are presently in an early stage of development that will have profound impact in the future. Of the technologies currently under development, there are several areas that offer the potential for revolutionary changes to aerospace structures. These areas include multifunctional structures, simulation-based prototyping, and computational design of materials compositions, processing parameters, and fabrication technologies to produce near-net-shape structural components. These technologies have the potential to revolutionize the development of future aerospace hardware for aviation, space launch vehicles, and space science instruments.

Section 16, “Metallic Materials R&D Technical Challenges,” of this monograph contains a discussion of major technical challenges and significant programmatic challenges for NASA researchers working in a Government laboratory. Some of the key technical challenges include the following:

1. Certification by analyses
2. Materials by design: multi-scale modeling and measurements
3. Manufacturing Technologies
4. High-fidelity failure prediction: micro and nanoscopic mechanisms
5. Realize benefits of multifunctional materials systems
6. Intelligent materials and structures: larger, more integrated structure
7. Hybrid structures enabled by advanced manufacturing techniques
8. Non equilibrium compositions, amorphous metals
9. Additive manufacturing with functionally graded alloy structure

Some of the key programmatic challenges for NASA researchers include the following:

1. Doing innovative research in a “third-generation NASA”
2. Conducting cutting edge research in a rapidly expanding global technology environment

3. Fundamental research in a high-profile project-oriented environment (foundational technologies vs. glitz and glamor) (desire for instant gratification)
4. Securing a project pull in a shifting mirage of potential future projects and missions (short half-life roadmaps)
5. Securing advocacy in a shrinking NASA technology budget

Additional study of these challenges is recommended to identify high-priority activities that have the potential to make game changing contributions to future hardware systems. R&D needs to have a customer that is willing to use the technology if successful. Customer pull is essential to acquiring funding to do the work. NASA is very much a project agency, and the mission directorates are only willing to fund R&D that has a payoff for future missions, generally on their long-range roadmaps. Systems analysis is essential for identifying potential benefits from new technologies.

Having stated that additional study is required on each of the above Grand Challenges; it is the belief of our team that advanced manufacturing technologies is the highest priority activity. Manufacturing technology is also a national R&D initiative because of the importance of reducing time and cost to produce ever more complex structures for advanced systems. Additive manufacturing or 3-D printing is a process of making a three-dimensional solid object of virtually any shape from a digital model. 3-D printing is achieved using an additive process, where successive layers of material are laid down in different shapes. 3-D printing is considered distinct from traditional machining techniques, which mostly rely on the removal of material by methods such as cutting or drilling (subtractive processes).

CONTENTS

1. INTRODUCTION

NASA has played a key role in the development of materials and structures technologies for the past several decades. NASA research and development has been critical to the successful development of aircraft, space launch vehicles, and space satellites. In this monograph we will highlight the major advancements made in materials and structures and show the application to commercial transports, general aviation aircraft, rotorcraft, space rockets, and to launch vehicles such as the now retired space shuttle.

To review and analyze the many contributions Langley Research Center has made to aerospace structures and materials it is necessary to start at the beginning of NACA and continue through the research programs currently being conducted by NASA today. A brief background of both NACA and NASA puts into perspective the breadth and depth of the aerospace metallic materials and structures work performed in support of the development of flight vehicles ranging from small general aviation aircraft to large modern transports and the development of early space rockets to the Space shuttle and beyond.

In examining the accomplishments of the last 90-plus years since the formation of NACA, it is often uncertain who first developed a technology, or even who developed a given technology. In many cases there are no clear answers because different groups of people and organizations were involved at different points along the way. Often the research of one group served as a springboard to another, which then expanded or adapted the research, leading eventually to a solution to the original problem. Many technologies described here were derived in this fluid, organic, yet still purposeful way. In many cases, even when NASA was not the first or the end developer of a technology, the Agency contributed significantly to a technology's advancement and operational use. NASA-developed technology or its derivatives can be found on every aircraft in the current United States commercial and military aircraft fleets. There are, however, specific cases where NASA Langley's contributions are clearly identified and these are highlighted in this monogram. It is by no means complete, but it is intended to give the reader a foundational understanding of the broad range and significance of these key technological accomplishments in metallic materials and structures and what they contributed to the advancement of flight.

1.1. The National Advisory Committee for Aeronautics (NACA)

Figure 1.1-1: The NACA Seal

From March 3, 1915 until October 1, 1958, the National Advisory Committee for Aeronautics (NACA) provided advice and carried out much of the cutting-edge research in aeronautics in the United States.[1] Modeled on the British Advisory Committee for Aeronautics, the advisory committee was created by President Woodrow Wilson in an effort to organize American aeronautical research and raise it to the level of European aviation. Its charter and $5,000 initial appropriation (low even for 1915) were appended to a naval appropriations bill and passed with little notice. The committee's mission was to "direct and conduct research and experimentation in aeronautics, with a view to their practical solution."

NACA was involved in virtually all areas of aeronautics.[2] Initially consisting of 12 unpaid members, in its first decade it counseled the federal government on several aviation-related issues. These included recommending the inauguration of airmail service and studying the feasibility of flying the mail at night. During World War I, NACA recommended creating the Manufacturers Aircraft Association to implement cross-licensing of aeronautics patents. NACA proposed establishing a Bureau of Aeronautics in the Commerce Department, granting funds to the Weather Bureau to promote safety in aerial navigation, licensing of pilots, aircraft inspection, and expanding airmail. It also made recommendations to President Calvin Coolidge's Morrow Board in 1925 that led to passage of the Air Commerce Act of 1926, the first federal legislation regulating civil aeronautics. It continued to provide policy recommendations on the Nation's aviation system until its incorporation in the National Aeronautics and Space Administration (NASA) in 1958.

NACA came into being, much like its successor organization, NASA, in response to the success of other international organizations.[3] Even though the Wright brothers had been the first to make a powered airplane flight in 1903, by the beginning of World War I in 1914, the United States lagged behind Europe in airplane technology. In order to catch up, Congress founded NACA on March 3, 1915 as an independent government agency reporting directly to the President. Unlike

NASA, NACA began almost without anyone noticing. Initially the task of the committee was to coordinate efforts already underway across the nation. However, its mission and workforce soon grew to cover a greater role in aeronautics research in the U.S.

While not originally intended to administer laboratories, NACA's expanding role led to the creation of its first research and testing facility in 1920, the Langley Memorial Aeronautical Laboratory (LMAL). The name was shorted to Langley Aeronautical Laboratory in 1948 and with the dissolution of NACA and foundation of NASA in 1958 the name was changed to Langley Research Center (LaRC).

During the late 1910s and the 1920s, NACA conducted many types of flight tests, involving both models and full-scale aircraft. Many of the test flights took place in a series of wind tunnels NACA developed. Advances, such as the NACA cowling, for which NACA won the Collier Trophy in 1929, and streamlining studies to improve the aerodynamics of aircraft resulted in greatly increased aircraft speed and range. Throughout the next three decades, NACA continued to expand its influence in the field of aviation by recruiting top notch engineers and scientists to work in ever larger and more advanced technological facilities.

Wind tunnels were not NACA's only research methodology; other important approaches included structural, avionics, and flight testing. But none matched the importance and utility of wind tunnels. Not until NACA created the Glenn Engine Laboratory in 1942, for example, did propulsion research begin to approach the priority accorded to traditional tunnel work (and this, perhaps, too late to answer postwar critics who decried NACA for not having matched the Germans and British in turbine research). Likewise, in the 1950s, aircraft manufacturer Douglas argued that NACA should do for structures and materials what the agency had done for propulsion: create a separate materials laboratory that was out of the shadow of the aerodynamics core. Although, this recommendation was not acted on it is true that during the1950s and later years, materials and structures did receive more funding resulting in a significant acceleration in materials and structures for aerospace applications. By the early 1950s a fatigue and fracture laboratory was built at Langley. Other facilities were also built in the years that followed including a new light alloy laboratory built in 1996. (A listing of the materials and structures facilities at Langley Research Center are listed in a report by Dr. Charlie Harris entitled "Structures & Materials Facilities at the NASA Langley Research Center." Throughout the 43-year history of NACA, significant technical contributions were made to the highly successful development of lightweight alloys of aluminum and titanium which played a critical role in the evolution of flight vehicles which have enabled safe and affordable air travel for the flying public. These same technology advancements were critical to the development of military aircraft essential to our national security.

NACA began to hit its stride in the 1930s and 1940s, when the threat and reality of a new world war forced rapid development and testing of new aircraft and the addition of two new laboratories, the Ames Aeronautical Laboratory in 1940 and the Aircraft Engine Research Laboratory, or the Cleveland laboratory, in 1941 (this laboratory was later renamed the Glenn Research Center and has since been renamed the Glenn Research Center). During this period, using wind tunnel testing, NACA developed airfoil shapes for wings and propellers, which simplified aircraft design. The shapes eventually found their way into the designs of many U.S. aircraft of the time, including a number of important World-War-II-era aircraft, such as the P-51 Mustang.

After World War II, NACA began to work on the goal of supersonic flight. To further this goal, an adjunct facility to Langley, NACA Muroc Unit, was established in California at the Air Force's Muroc Field (later renamed Edwards Air Force Base). NACA worked closely with the U.S. Air Force and Bell Aircraft to design the first supersonic aircraft. This collaboration marked a significant departure for NACA. It had never before dealt with the initial design and construction of a research plane. This change in policy was a successful one. NACA made a number of contributions to the design, including a changed tail.

The first supersonic flight took place in 1947 in an experimental airplane, the X-1, piloted by Captain Charles "Chuck" Yeager and monitored by NACA personnel. This supersonic flight paved the way for further research into supersonic aircraft, leading to the development of swept wings as well as a new shape for aircraft.

In 1951, Richard Whitcomb, a NACA engineer, invented the concept of the area rule, which required trimming or indenting the midsection of an airplane's fuselage in the area where the wing joined it. The resulting Coke bottle "look" decreased drag and made it easier for a plane to go supersonic. The appearance of most modern combat aircraft, especially fighters, is a result of this breakthrough.

During the 1950s, as the Cold War deepened, NACA devoted more and more time and research to missile technology. It was responsible for developing the tactics and designs for the reentry of space vehicles. Initially, the focus was on missile warheads but later was applied to the possibility of manned vehicles. NACA expanded once again, adding a site for launching rocket-propelled airplane models for high-speed tests at Wallops Island.

At the same time, NACA began to look ahead to the possibility of crewed spaceflight. In the late 1950s, NACA developed a plan that called for a blunt-body spacecraft that would reenter with a heat shield, a worldwide tracking network, and dual controls that would gradually give the pilot of the craft greater control. All of these would become part of the space program, but not under NACA.

On October 4, 1957, the Soviet Union launched Sputnik 1, the world's first artificial satellite. In 1958, responding to the nation's fear of falling behind the Soviets in the utilization and exploration of outer space, Congress passed the National Aeronautics and Space Act of 1958, which formed a new civilian space agency, NASA. NACA officially turned over operations to NASA on October 1, 1958. The new agency would be responsible for civilian human, satellite, and robotic space programs, as well as aeronautical research. NACA and its missions and projects were incorporated into the new agency. Other programs and facilities from existing agencies, most notably the Army's Jet Propulsion Laboratory (JPL) and Redstone Arsenal at Huntsville, Alabama (now the Marshall Space Flight Center) were also incorporated into NASA. Many of NACA's personnel took high-level positions in NASA and were responsible for the earliest decisions regarding the human space program. Many aeronautics researchers took the opportunity to move into space research.

Between its founding in 1915 and its incorporation into NASA in 1958, NACA accomplished many technological feats. It was a major force for technological change in aeronautics. NACA's efforts were in a large part responsible for turning the American airplane from slow cloth-and-wood biplanes of the World War I era into the jets of today. The foundations of NASA and the success of its many missions rest squarely on the cornerstone of NACA's organizational and technical expertise.

References

[1] http://www.centennialofflight.gov/essay/Evolution_of_Technology/NACA/Tech1.htm
[2] Orders of Magnitude: A History of the NACA and NASA, 1915-1990. NASA SP-4406. Washington, D.C.: U.S. Government Printing Office, 1989. Also at http://www.hq.nasa.gov/office/pao/History/SP-4406/cover.html
[3] http://history.nasa.gov/naca/overview.html

1.2. The National Aeronautics and Space Administration (NASA)

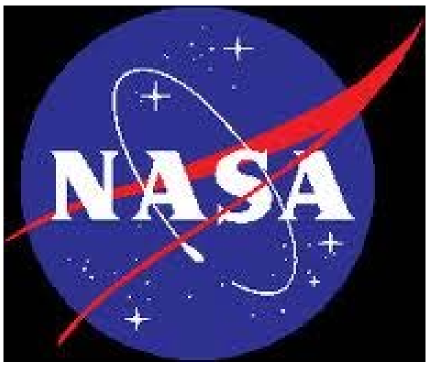


Figure 1.2-1: The NASA Insignia.

1.2.1. Formation of NASA

After the Second World War, the Defense Department launched serious research push into the fields of rocketry and upper atmosphere sciences to ensure American leadership in technology. As part of this push, President Dwight D. Eisenhower approved a plan to orbit a scientific satellite as part of the International Geophysical Year (IGY) for the period from July 1, 1957 to December 31, 1958, a cooperative effort to collect scientific data about the Earth. Quickly, the Soviet Union jumped in, announcing plans to orbit its own satellites. The Naval Research Laboratory's Vanguard project was selected on September 9, 1955 to support the IGY effort, but while it enjoyed exceptional publicity throughout the second half of 1955, and all of 1956, the technological requirements in the program were too big and funding levels too small to ensure success.[1]

The Soviet Union launched Sputnik 1, the first man-made earth satellite, on October 4, 1957. This was followed on November 3 with the second satellite, Sputnik 2. The United States attempted a satellite launch on December 6, using the NRL's Vanguard rocket, but it barely struggled off the ground, then fell back and exploded. On January 31, 1958, after finally receiving permission to proceed, von Braun and the Army Ballistic Missile Agency (ABMA) pace development team used a Jupiter C in a Juno I configuration (addition of a fourth stage) to successfully place Explorer 1, the first American satellite, into orbit around the Earth.

Effective at the end of March 1958, the U.S. Army Ordnance Missile Command (AOMC), was established at Redstone Arsenal. This encompassed the ABMA and its newly operational space programs. In August, AOMC and Advanced Research Projects Agency (a Department of Defense organization) jointly initiated a program managed by ABMA to develop a large space booster of approximately 1.5-million-pounds thrust using a cluster of available rocket engines. In early 1959, this vehicle was designated Saturn.

On April 2, President Dwight D. Eisenhower recommended to Congress that a civilian agency be established to direct nonmilitary space activities, and on July 29, the President signed the National Aeronautics and Space Act, creating the National Aeronautics and Space Administration (NASA) (**Figure 1.2-1**). The nucleus for forming NASA was the National Advisory Committee for Aeronautics (NACA), with its 7,500 employees. Although there was then an official space agency, the Army continued with certain far-reaching space programs. In June 1959, a secret study on Project Horizon was completed by ABMA, detailing plans for using the Saturn booster in establishing a manned Army outpost on the Moon. Project Horizon, however, was rejected, and the Saturn Program was transferred to NASA.

The U.S. manned satellite space program, using the Redstone as a booster, was officially named Project Mercury on November 26, 1958. On October 21, 1959, President Eisenhower approved the transfer of all Army space-related activities to NASA. This was accomplished effective July 1, 1960, when 4,670 civilian employees, about $100 million worth of buildings and equipment, and 1,840 acres of land transferred from AOMC/ABMA to NASA's George C. Marshall Space Flight Center. MSFC officially opened at Redstone Arsenal on this same date, and was dedicated on September 8 by President Eisenhower in person.

The law creating NASA defined aeronautical and space activities as

> (a) research into, and the solution of, problems of flight within and outside the Earth's atmosphere; (b) the development, construction, testing, and operation for research purposes of aeronautical and space vehicles;(c) the operation of a space transportation system including the Space shuttle, upper stages, space platforms, and related equipment; and (d) such other activities as may be required for the exploration of space.[2]

It also defined aeronautical and space vehicles as "aircraft, missiles, satellites, and other space vehicles, manned and unmanned, together with related equipment, devices, components, and parts."[3]

Early in its history, NASA was already seeking to put a human in space. Once again, the Soviet Union beat the U.S. to the punch when Yuri Gagarin became the first man in space on April 12, 1961. However, the gap was closing and on May 5, 1961, Alan B. Shepard, Jr. became the first American to fly into space when he rode his Mercury capsule on a 15-minute suborbital mission. Project Mercury was the first high-profile program of NASA, which had as its goal placing humans in space. The following year, on February 20, John H. Glenn, Jr. became the first U.S. astronaut to orbit the Earth.

Following in the footsteps of Project Mercury (**Figure 1.2-2)**, Gemini continued NASA's human spaceflight program to and expanded its capabilities with spacecraft built for two astronauts. Gemini's 10 flights also provided NASA scientists and engineers with more data on weightlessness, perfected reentry and splashdown procedures, and demonstrated rendezvous and docking in space. One of the highlights of the program took place during the Gemini 4 on June 3, 1965, when Edward H. White, Jr. became the first U.S. astronaut to perform a spacewalk.

The crowning achievement of NASA's early years was Project Apollo (**Figure 1.2-3**). When President John F. Kennedy announced, "I believe this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to Earth," NASA was committed to putting a man on the Moon. The Apollo Moon project was a massive effort that required significant expenditures, costing $25.4 billion, 11 years, and 3 lives to accomplish.

On July 20, 1969, Neil A. Armstrong made his now famous remarks, "That's one small step for (a) man, one giant leap for mankind" as he stepped onto the lunar surface during the Apollo 11 mission. After taking soil samples, photographs, and doing other tasks on the Moon, Armstrong and Aldrin rendezvoused with their colleague Michael Collins in lunar orbit for a safe journey back to Earth. There were five more successful lunar landings of Apollo missions, but only a failed one rivaled the first for excitement. All totaled, 12 astronauts walked on the Moon during the Apollo years.

The Luna, Ranger, Surveyor, and Lunar Orbiter spacecraft served as the prelude to the piloted Moon landings and gave us the first images of the Space Age. The 12 humans walking on the Moon were the pinnacle of man's space voyages to date. The stories of Neil Armstrong and Buzz Aldrin touching down on the Moon in July 1969, followed by 10 others by 1972; the experiences of the ill-fated Apollo 13; and the astronauts roving over the surface of another world will forever be remembered by those who lived through the period of the Apollo Program. **Figure 1.2-3** shows a picture of Buzz Aldrin on the Moon. In the right-hand background is the Lunar Module Eagle. On Aldrin's right is the deployed Solar Wind Composition experiment.

Figure 1.2-2: Project Mercury astronaut selection was announced on 9 April 1959, only six months after NASA was formally established on 1 October 1958. All were military test pilots.

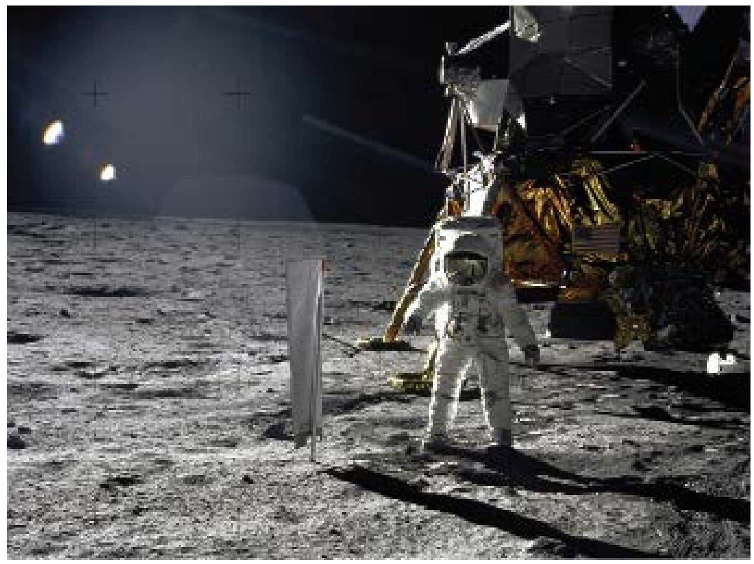


Figure 1.2-3: Astronaut Edwin E. "Buzz" Aldrin, Jr., Lunar Module pilot, is photographed during the Apollo 11 extravehicular activity on the lunar surface Sea of Tranquility (NASA Image AS11-40-5873).

Human spaceflight has required the design of capsules, rockets (**Figure 1.2-4**) and later the reusable shuttle (**Figure 1.2-5**) to carry humans into space. The engineering challenges inherent in the design of rockets and spacecraft were worked by teams of engineers from all the NASA centers and from industry and universities. Selected highlights of Langley's contributions to the materials and structures development required to enable the space launch vehicle development of the past 50 years will be presented in later sections of this Monograph.

Figure 1.2-4: The Apollo 11 Saturn V space vehicle lifts off with astronauts Neil A. Armstrong, Michael Collins, and Edwin E. "Buzz" Aldrin, Jr., at 9:32 a.m. EDT, 16 July 1969.

Figure 1.2-5: The first launch of the space shuttle was on 12 April 1981.

1.2.2. Current and Future Plans

On September 14, 2011, NASA Administrator Charles Bolden revealed the design for the new space launch system (SLS) that will give our nation an entirely new capability for human exploration beyond low-Earth orbit (LEO). An artist concept is shown in **Figure 1.2-6**. This advanced heavy-lift launcher will be America's[1] most powerful rocket since the Saturn V, and it will launch humans to places and destinations where no one has gone before. It will use a liquid hydrogen and liquid oxygen propulsion system, which will include the RS-25D/E from the Space Shuttle Program for the core stage and the J-2X engine for the upper stage. SLS will also use solid rocket boosters for the initial development flights, while follow-on boosters will be completed based on performance requirements and affordability considerations. The SLS will have an initial lift capacity of 70 metric tons. The first developmental flight, or mission, is targeted for the end of 2017.[4]

Langley Center Director Lesa Roe noted in an email message sent to all Langley employees (Sept. 15, 2011) that "The SLS selection is particularly exciting to us at Langley in light of our ongoing work in support of the Orion Multi-Purpose Crew Vehicle (MPCV) (**Figure 1.2-7**). The SLS will be designed to carry the Orion MPCV, as well as other important cargo, equipment and science experiments to Earth's orbit and destinations beyond LEO." She also noted that Langley expects to play a lead role in the aerodynamic characterization on the SLS vehicle, including both analysis and wind tunnel testing. In addition, we expect to provide support as needed for in-flight test development as well as structures design, analysis, and testing. The deep space launch system, in combination with the crew capsule already under development, opens the next chapter in America's[1] space exploration story. It is great news for NASA, for the nation, and for Langley.

The Space Launch System will be NASA's first exploration-class vehicle since the Saturn V took American astronauts to the Moon over 40 years ago. With its superior lift capability, the SLS will expand our reach in the solar system and allow us to explore cis-lunar space, near-Earth asteroids, Mars and its moons, and beyond. We will learn more about how the solar system formed, where Earth's water and organics originated, how life might be sustained in places far from our Earth's atmosphere and expand the boundaries of human exploration. These discoveries will change the way we understand ourselves, our planet, and its place in the universe.

Figure 1.2-6: Artist concept of SLS on launchpad.

Figure 1.2-7: Orion MPCV, or Multi-Purpose Crew Vehicle, and LAS, or Launch Abort System, test craft in the acoustic chamber at Lockheed Martin's facilities near Denver.

NASA is continuing to expand the envelope of flight vehicles. NASA moves to begin a historic new era of x-plane research (**Figure 1.2-8**). Exactly what these x-planes will look like, how they will operate, and their full capabilities have yet to be defined. These decisions will be made in conjunction with industry, the community, Congress, and the executive branch. However, metallic materials along with composites will play key roles in building advanced air structures with the enhanced capabilities required to achieve new horizons in flight.

Figure 1.2-8: NASA moves to begin historic new era of X-Plane Research.

1.2.3. Structures and Materials

Structures and materials has been an important research thrust for the development of flight vehicles during the past nine-plus decades of NACA and NASA. The research problems worked were driven by the problems of flight associated with the design of vehicles for different flight regimes. Structures and materials development has gone hand in hand with aeronautics to design and fabricate useful flight vehicles that were safe to fly, with performance characteristics acceptable for both civilian and military purposes. Highlights of some of the many accomplishments in materials and structures for aircraft and space launch vehicles will be presented in the following sections.

References

[1] History of National Aeronautics and Space Administration (NASA). http://space.about.com/cs/history/a/nasahistorya.htm
[2] "Aeronautics: The NASA Perspective," NASA Fact Sheet, February 10, 1981.
[3] U.S. Congress, *NASA Aeronautics and Space Act of 1958 (as Amended),* sec. 103 (Washington, D.C.: U.S. Government Printing Office, 1958).
[4] NASA Announces Design for New Deep Space Exploration System, 9/14/11. http://www.nasa.gov/exploration/systems/sls/sls1.html

2. Success Stories and NASA LaRC's Role

This section contains highlights of research performed at Langley Research Center or sponsored on grants or contracts by Langley that have made significant contributions to the successful development of modern aircraft and space launch systems. It is particularly worth noting that NASA Langley has made many contributions to aviation safety[1] over many years. A discussion of all those contributions is beyond the scope of this monograph, but selected highlights of those contributions that directly relate to structures and materials will be presented as part of this section on success stories. The organizational structure for this look is to select one or more particularly noteworthy highlights for different classes of air vehicles and space launch vehicles. A sampling of the highly successful R&D projects includes the following:

1. Stress-corrosion cracking of Apollo fuel tank—Barry Lisagor, Tom Bales, et al.
2. Aging Aircraft Program—Charlie Harris, et al.
3. Advanced Launch System lead role for structures and materials—Tom Bales, et al.
4. Al-Li alloy development for super lightweight tank—John Wagner, et al.
5. Near-net-shape manufacturing technology—Karen Taminger, Marcia Domack, John Wagner, et al.
6. Shell Buckling Knockdown Factor Project (SBKF)—Mark Hilburger, et al.

There are many more that are meritorious, but these have been highlighted to illustrate the scope and impact on both aeronautics and space missions. A key factor in the successful execution of materials and structures projects has been the technical expertise of the research staff and the world class facilities and laboratories at Langley.

2.1. Commercial Transports

Langley's research and testing of advanced materials and structures has played a critical role in establishing a technology foundation on which ever improving aircraft has been produced since the 1920s. There is not a commercial aircraft or military aircraft in this country or anywhere in the world that has not benefited from the materials and structures technologies developed by Langley. Particularly in the early days of aviation, Langley was a training ground for young engineers who went to the aerospace industry. NASA sponsored contracts with industry and with academic institutions, which also played a key role in advancing aviation both through research results and through helping to develop the technical skills required to design and build world class aircraft. Perhaps nowhere has these contributions been more important to our country than in the commercial transport aircraft sector.

Figure 2.1-1: Boeing 787 Commercial Transport Aircraft

http://www.tuvie.com/boeing's-groundbreaking-787-dreamliner-airplane/.

The newest Boeing aircraft, the 787-8 Dreamliner, shown in **Figure 2.1-1** has been described as the first production transport airplane made mainly of polymer composites. However, in reality it uses approximately 50% structural metals for critical load carrying structure. Light alloys have been and will continue to be used in future aircraft for selected applications where their combination of properties and cost make them competitive with composite materials. Advances in near-net-shape processing and additive manufacturing are expected to make advanced metallic components very cost competitive for future aircraft applications. The historical airframe component weights for commercial transport type aircraft is shown in **Figure 2.1-2**.

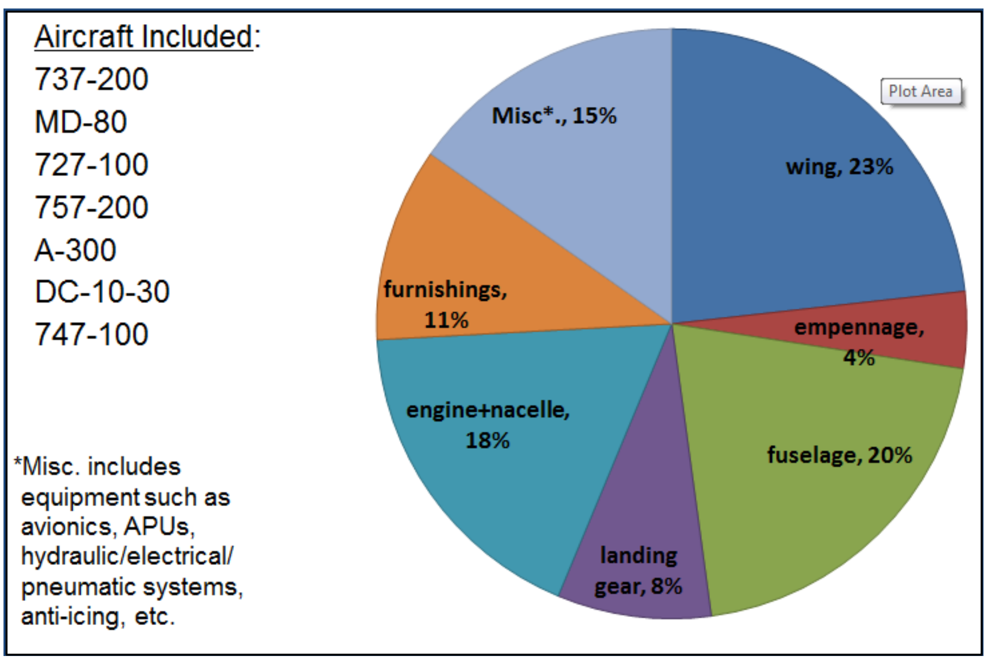


Figure 2.1-2: Historical Airframe Component Weights.

The approximate percentages of different metallic materials used in some of the commercial aircraft flying today are shown in **Table 2.1-1**. The material properties that are most important for different components of a typical transport aircraft are shown in **Figure 2.1-3.** A classical paper by J. L. Staley and D. J. Lege[2] published in 1993 contains an excellent discussion of advances in aluminum alloy properties for structural applications in transportation. A more recent but similar article was by E. A. Starke,[3] and J. T. Staley in 1996.

Table 2.1-1: Material Composition in Commercial Aircraft.[2]

Aircraft	Aluminum	Steel	Titanium	PMCs	Other
Boeing 747	81 wt.%	13 wt.%	4 wt.%	1 wt.%	1 wt.%
Boeing 757	78 wt.%	12 wt.%	6 wt.%	3 wt.%	1 wt.%
Boeing 767	80 wt.%	14 wt.%	2 wt.%	3 wt.%	1 wt.%
Boeing 777	70 wt.%	11 wt.%	7 wt.%	11 wt.%	1 wt.%
Boeing 787	20 wt.%	10 wt.%	15 wt.%	50 wt.%	5 wt.%
DC-10	78 wt.%	14 wt.%	5 wt.%	1 wt.%	2 wt.%
MD-11	76 wt.%	9 wt.%	5 wt.%	8 wt.%	2 wt.%
MD-12	70 wt.%	8 wt.%	4 wt.%	16 wt.%	2 wt.%

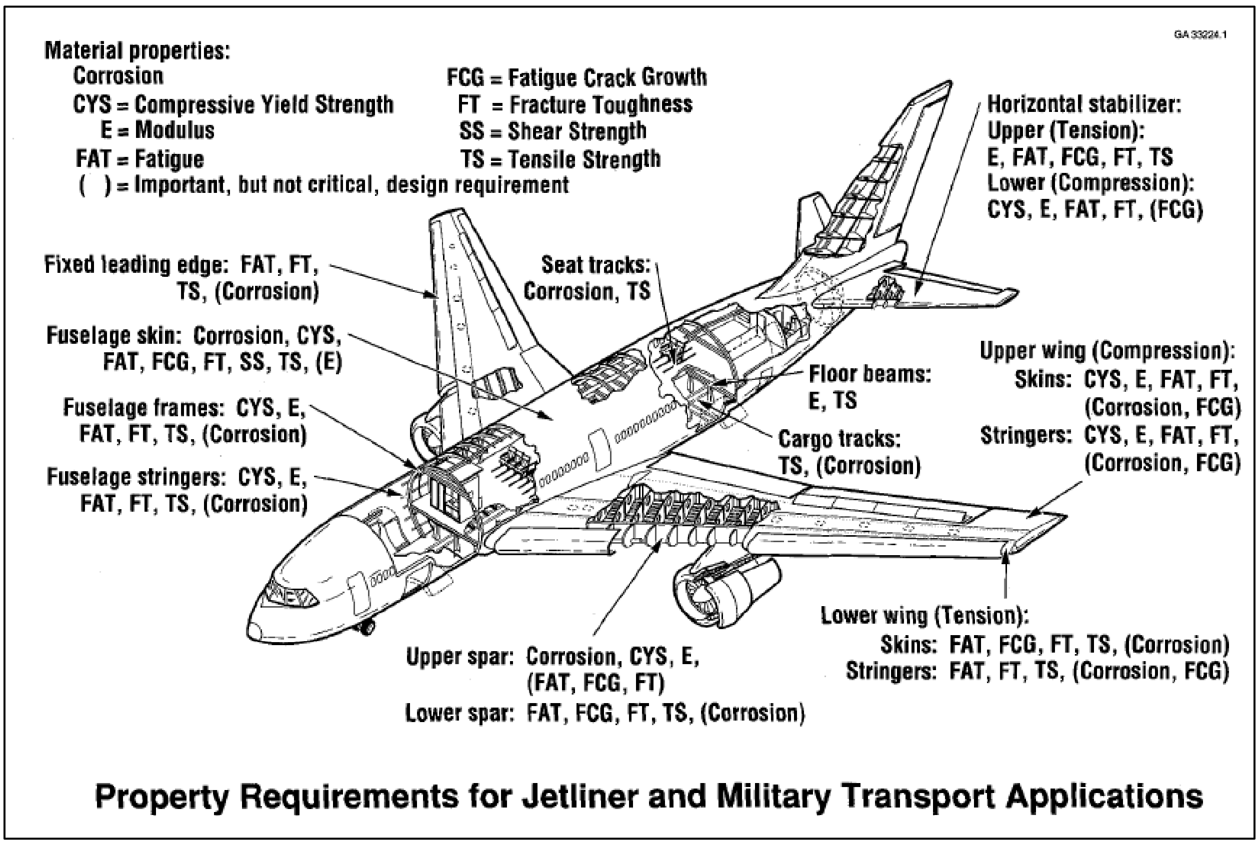


Figure 2.1-3: Property Requirements for Jetliner and Military Transport Applications[2]
http://hal.archives-ouvertes.fr/docs/00/25/19/21/PDF/ajp-jp4199303C728.pdf.

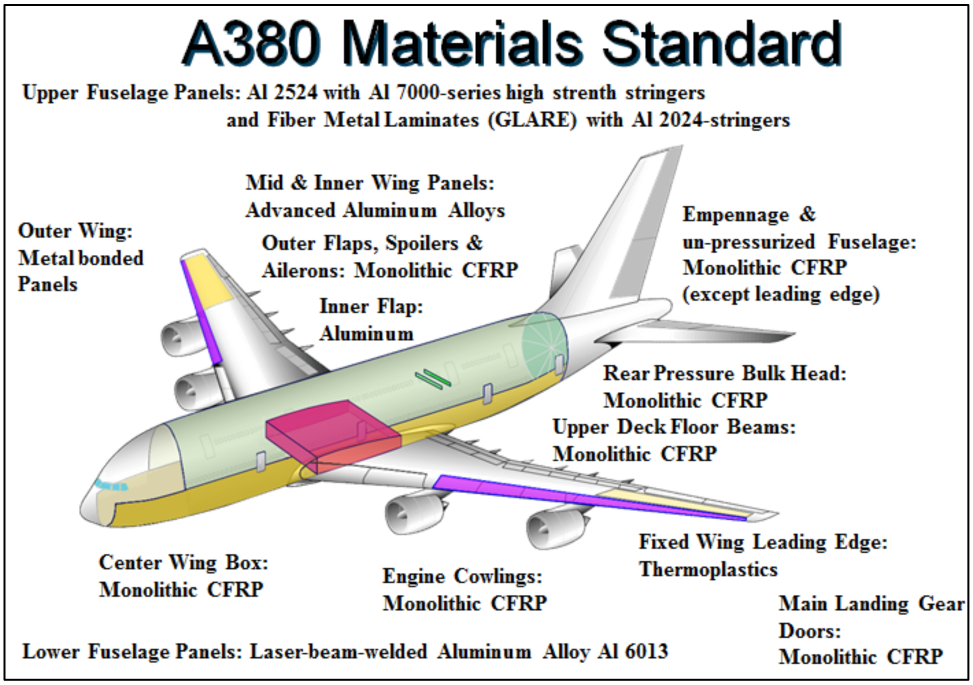


Figure 2.1-4: Materials Used in Airbus A380.[4]

Materials used on the Airbus A380 are shown in **Figure 2.1-4**. It should be noted that new Al alloys and fiber metal laminates (GLARE) are being used for portions of the fuselage.

Structures and materials research carried out at Langley on aircraft structures was focused in three primary areas: (1) structural concept design and analyses, (2) durability and damage tolerance, (3) environmental degradation expected for typical aircraft service life environments. Limited work was also performed in cooperation with the airframe companies and metals industry on alloy development for subsonic, supersonic, and hypersonic aircraft. This research included work on steels for landing gears, aluminum alloys for fuselage and wing structures, titanium for highly loaded components and for elevated temperature applications, metal matrix composites (Gr/Al, B/Al, Borsic/Al, SiCp/Al, SiC/Ti, and selected others) for airframe applications, and superalloys for heat shield applications on hypersonic vehicles. Selected examples of the excellent work performed in these areas will be presented in later sections of this report. However, in this section, one particular issue associated with widespread fatigue damage is highlighted because of the importance of the work NASA did in helping the Federal Aviation Administration (FAA) and aircraft manufactures first to understand the fatigue issues involved and then to develop analyses and nondestructive evaluation (NDE) inspection techniques to help prevent future failures of fuselage structures particularly on older aircraft.

Aircraft aging is a safety concern throughout all classes of aircraft. NASA, in conjunction with the FAA, Sandia Laboratory and the University of Idaho, developed nondestructive evaluation methods, metal fatigue analyses and structural modeling to help operators ensure that older aircraft are as structurally sound as new ones. NASA has also developed new airframe manufacturing techniques to monitor the "health" and safety of aircraft structures.

NASA Langley was a major contributor to the detailed analyses conducted on this type of failure and conducted extensive research on widespread fatigue damage in a cooperative program with the Department of Defense (DoD) and the FAA. The results of this research formed the basis for the FAA issuing a new rule on airworthiness pertaining to inspection for widespread fatigue damage and steps to repair damaged structure.

2.1.1. NASA LaRC Aging Aircraft Program 1990s

The NASA Langley Research Center initiated an aging aircraft research program in 1989 (**Figure 2.1-5**) that was in response to the structural failure an Aloha Airlines 737 commercial transport aircraft during the previous year (**Figure 2.1-6)**. This aircraft experienced widespread fatigue damage (WFD) where small cracks developed at multiple, adjacent rivet holes in the metallic fuselage skin. These small cracks grew undetected until the near-catastrophic link-up into a single large crack that caused the loss of a large section of the fuselage. The development of WFD had previously been postulated,[5] but had never been observed occurring in-service. This damage mechanism caused alarm in the commercial airline industry because of the aging of the fleet, the inability to detect WFD before the cracks became critical, and the inability to predict the onset of WFD.

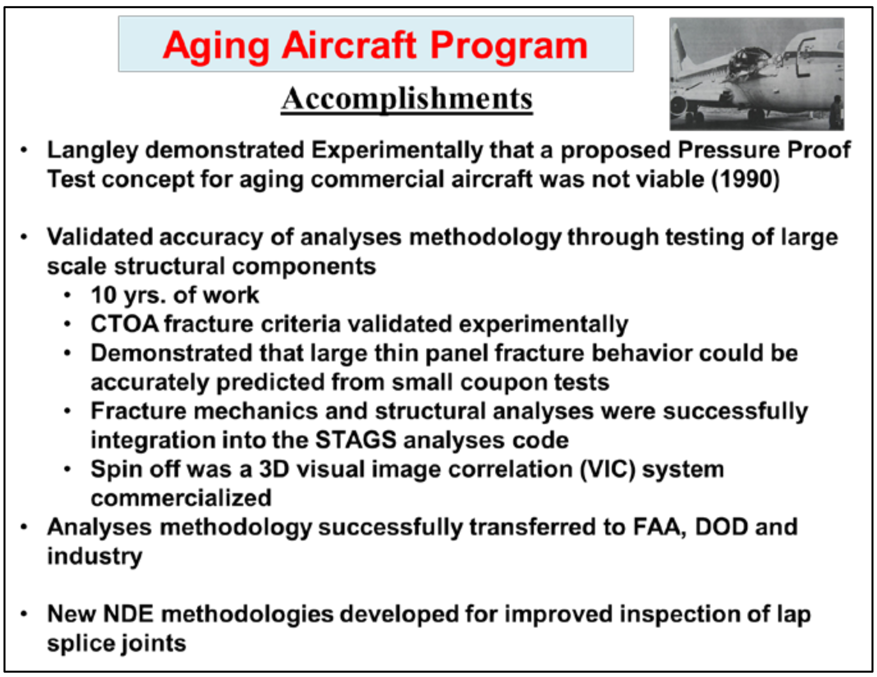


Figure 2.1-5: Major Accomplishments from the NASA Aging Aircraft Program.

The NASA Langley Research Center's Aging Aircraft Program[6] responded to this challenge by leveraging decades of research in the areas of fracture mechanics, structural analysis, and NDE. This multidisciplinary program had the following goals:

- Prediction of the onset of WFD
- Development and validation of elastic-plastic fracture mechanics techniques
- Development and validation of nonlinear structural analysis techniques
- Development and commercialization of NDE tools that can detect WFD

This program was planned and executed with coordination of elements of the FAA, DoD, and industry that were also performing WFD research. This coordination facilitated collaboration, reduced duplication of effort, and allowed efficient dissemination of research findings. The program culminated in the advancement of the state-of-the-art in a number of areas:

- An experimentally validated prediction of the onset of WFD in a large scale structural component
- The creation, enhancement, and validation of a number of fracture mechanics and structural analysis tools
- A database of experimental WFD data from the coupon level to large structural components
- A detailed characterization of WFD through the teardown inspection of a 747 aircraft
- The development of three NDE prototype instruments (two eddy current probes and a thermal image system) that have been licensed and commercialized
- A joint NASA/FAA program to infuse the developed technology into the standard industry practice

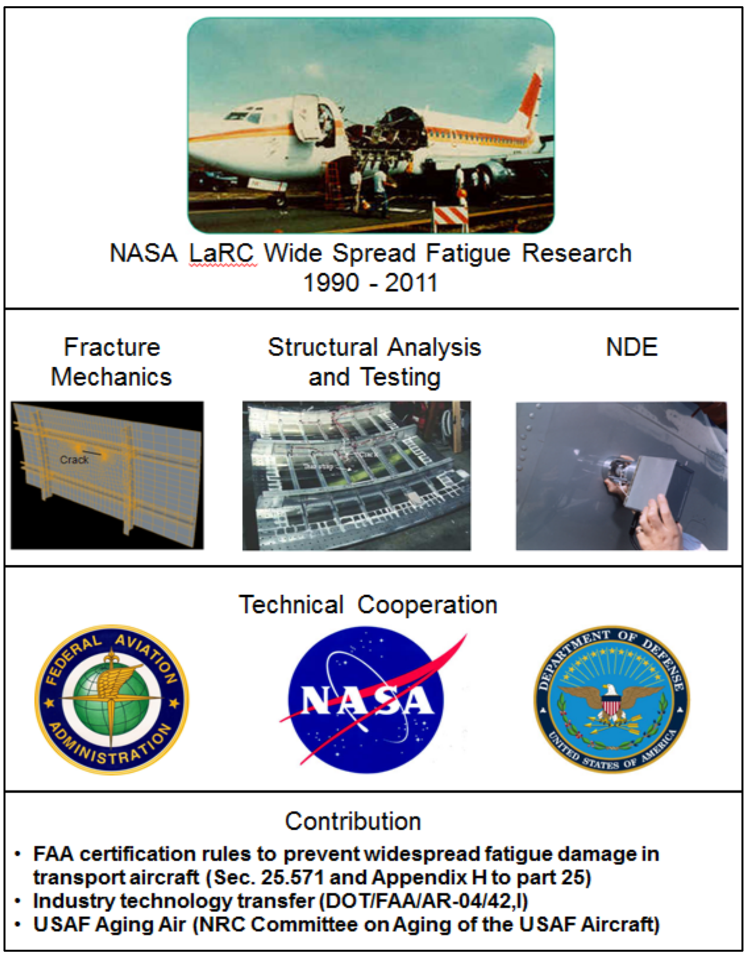


Figure 2.1-6: Widespread Fatigue Damage R&D.

NASA has developed many of the key human factors concepts underlying cockpit resource management and has played a pivotal role in coordinating the efforts of industry and the military to develop effective training Programs. A senior United Air Lines executive has credited NASA's Cockpit Resource Management Program with saving "hundreds of lives" in emergencies such as the loss of the cargo door on Flight 811 out of Honolulu, and an uncontained failure of the #2 engine on Flight 232 at Sioux City. The teamwork exhibited by both flight crews was directly attributable to the training they received as a result of the efforts of many NASA personnel.

References

[1] http://www.nasa.gov/centers/langley/news/factsheets/AvSP-Accom.html.
[2] Staley, J.T. anti Lege, D.J. (1993); "Advances in aluminum alloy products for structural applications in transportation," J. Phys. IV, Colloque C7, 3, 179–190.
[3] E. A. Starke, J. T. Staley,; "Application of modern aluminum alloys to aircraft," Progress in Aerospace Sciences (Impact Factor: 2.4). 01/1996; 32(2):131–172.
[4] Hinrichsen, Jens; "Airbus A380: Materials for the Flagship of The New Millennium," 7th Japan International Symposium and Exhibition (JISSE-7), Tokyo, November 13th, 2001.
[5] Swift, T.; "Damage Tolerance in Pressurized Fuselages," 14th International Conference on Aeronautical Fatigue, 1987.
[6] Harris, C. E., Newman, J. C., Jr., Piascik, R. S., and Starnes, J. H., Jr.; "Analytical Methodology for Predicting the Onset of Widespread Fatigue Damage in Fuselage Structures," Proceedings of the FAA-NASA Symposium on Continued Airworthiness of Aircraft Structures, July 1997, pp. 63–88.

2.2. General Aviation

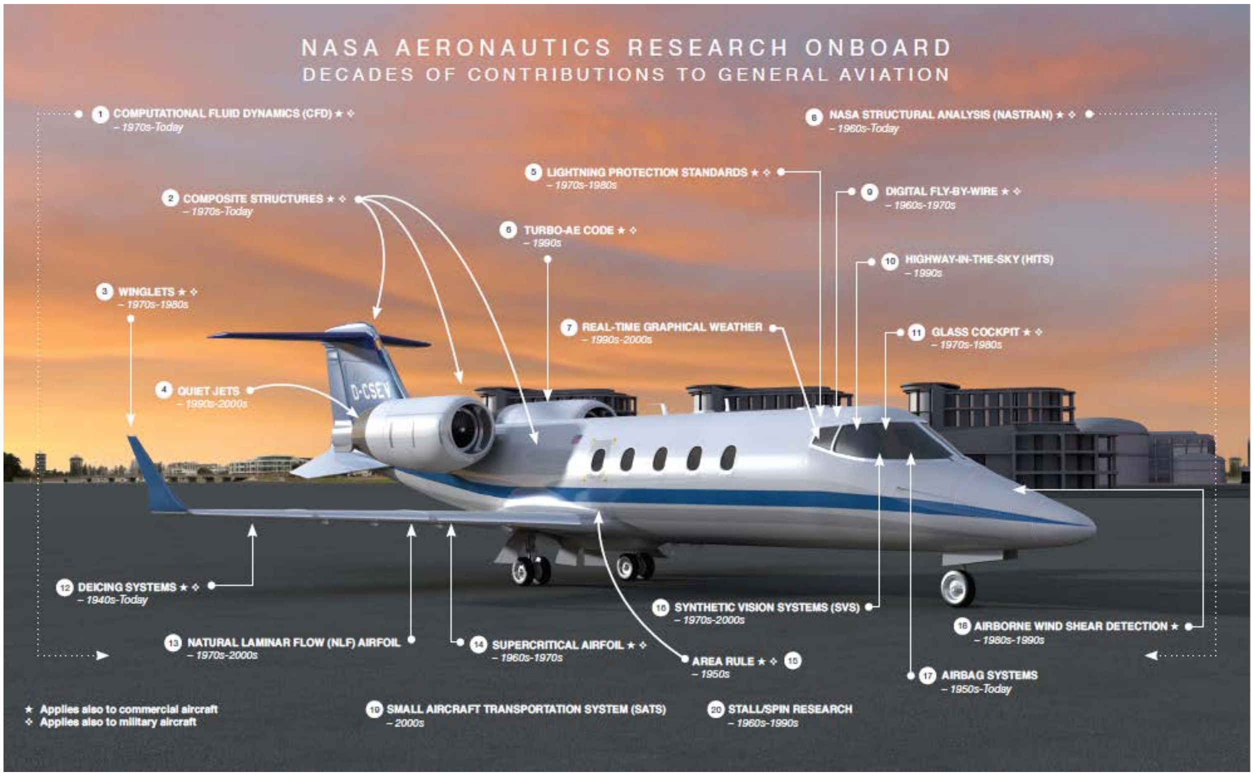


Figure 2.2-1: NASA Contributions to General Aviation.
http://www.nasa.gov/pdf/381579main_General_Contributions_h.pdf.

The reader is referred to the web site noted in the caption of **Figure 2.2-1** for a listing of some 20 different technologies where NASA has made very significant contributions to general aviation. Clearly, much of the work NASA did in structures and materials, including durability and damage tolerance of aircraft structures; corrosion data and test methodologies for Al, Ti, and steel aircraft components; structural analyses codes such as NASTRAN and ABACUS (modules from Langley); methods for crack detection; structural panel buckling criteria; and numerous fatigue and fracture codes such as FASTRAN and NASGRO (Stress Intensity Factors from Langley), and test data and crashworthiness testing and analyses have significantly contributed to the safety of flight of general aviation aircraft. Three notable contributions will be singled out here as examples of structures and materials success stories for the safety of general aviation aircraft.

2.2.1. NASA Structural Analysis (NASTRAN)

In the 1960s, NASA partnered with industry to develop a common generic software program that engineers could use to model and analyze different aerospace structures, including any kind of spacecraft or aircraft. Today, NASTRAN is an "industry-standard" tool for computer-aided engineering of all types of structures. More details on this development are presented in a later section.

2.2.2. Airbag Systems

In the 1950s, NASA explored a variety of crew protection systems including airbags. Later adapted to protect robotic spacecraft during landings, they have now been further tested by NASA and adapted for use as an airbag system on passenger aircraft (as seen on the ATI RT-700, a twin-engine business aircraft).

2.2.3. Crashworthiness of General Aviation Aircraft

The major facility used for this research was the Impact Dynamics Research Facility (IDRF) a 240-foot-high gantry structure located at NASA Langley Research Center located in Hampton, Virginia. The gantry facility was originally built as a lunar landing simulator during the Apollo Program and was used by the Apollo astronauts to practice lunar landings under realistic conditions. In 1972, the facility was converted to a full-scale crash test facility for light aircraft and rotorcraft. Since that time, the IDRF has been used to perform a wide variety of impact tests on full-scale aircraft and structural components in support of the general aviation (GA) aircraft industry, the U.S. Department of Defense, the rotorcraft industry, and NASA in-house aeronautics and space research programs.

A photograph of the IDRF is shown in **Figure 2.2-2**. The gantry structure is oriented in an east-west direction and is composed of truss elements arranged in three sets of inclined legs to give vertical and lateral support. An additional set of inclined legs located at the east end of the gantry provides longitudinal support. The legs are inclined at an angle of 25 degrees from vertical and they are 265 ft apart at the ground level. An enclosed elevator and a stairway provide access to the overhead work platforms. A movable bridge spans the gantry at the 217-foot level and runs the length of the gantry. In 1981, a 70-foot vertical drop tower, designated the Vertical Test Apparatus, was added beneath the northwest leg of the gantry, shown in **Figure 2.2-2**, for the purpose of conducting vertical drop tests of Boeing 707 fuselage sections. These tests were conducted in support of a full-scale crash test of a remotely piloted Boeing 720 transport aircraft that was conducted at Edwards Air Force Base in 1984.

Figure 2.2-2: Photograph of the IDRF Located at NASA Langley Research Center.

One of the important features of the IDRF is the ability to perform full-scale crash tests of light aircraft and rotorcraft under free-flight conditions, and, at the same time, to control the impact attitude and velocity of the test article upon impact. Also, full-scale crash tests can be performed for a wide range of combined forward and vertical velocity conditions. Most GA aircraft tests are performed with a higher forward velocity and a lower vertical velocity. For example, the 1994 crash test of a Lear Fan 2100 aircraft was performed at 82 fps forward and 31 fps vertical velocity. Conversely, helicopters are typically tested with a lower forward and higher vertical velocity. For example, the 1999 crash test of a Sikorsky prototype helicopter was performed at 31.5 fps forward and 38 fps vertical velocity. Currently, the IDRF is limited to test articles weighing 30,000 lbs or less.

Since the first full-scale crash test was performed in February 1974, the IDRF has been used to conduct 41 full-scale crash tests of GA aircraft including landmark studies to establish baseline crash performance data for metal and composite aircraft, 11 full-scale crash tests of helicopters including crash qualification tests of the Bell and Sikorsky Advanced Composite Airframe Program helicopters, 48 Wire Strike Protection System qualification tests of Army helicopters, 3 vertical drop tests of Boeing 707 transport aircraft fuselage sections, and 60+ drop tests of the F-111 crew escape module.

Figure 2.2-3: Photographs of Several GA Aircraft Full-Scale Crash Tests Performed at the IDRF.

Most of the full-scale crash tests of GA aircraft[1] were performed using the pendulum-swing technique (**Figure 2.2-3)**. This test method was sufficient to achieve impact velocities typical of the take-off and landing velocities of small GA aircraft (81 to 88 fps). Since it was not possible to evaluate all potential impact scenarios, most of the tests were performed for impact conditions that represented some of the more serious but potentially survivable GA airplane crashes. The data obtained during the GA aircraft crash test program was used to define the levels of acceleration typically experienced by the airframe structure and by the occupants during crash events. The occupant data were compared with different human injury prediction criteria to determine injury risk levels during airplane crashes. The structural data from this landmark crash test program was used to establish impact criteria for aircraft seats that are still used as the FAA standard for seat certification testing today. Later, the data were used as the foundation for the Crash Survival Design Guide for GA aircraft.[2]

An excellent article on the history of NASA's research on aircraft and rotorcraft crash testing and simulation is a paper[3] entitled *A History of Full-Scale Aircraft and Rotorcraft Crash Testing and Simulation at NASA Langley Research Center* by Karen E. Jackson, Richard L. Boitnott, and Edwin L. Fasanella, at the U.S. Army Research Laboratory, Vehicle Technology Directorate NASA Langley Research Center, Hampton, VA, and Lisa E. Jones and Karen H. Lyle at the Structural Dynamics Branch, Structures and Materials Competency NASA Langley Research Center Hampton, Virginia.

References

[1] Karen E. Jackson, Richard L. Boitnott, and Edwin L. Fasanella, Lisa E. Jones and Karen H. Lyle,; "A History of Full-Scale Aircraft and Rotorcraft Crash Testing and Simulation at NASA Langley Research Center," NASA Document ID 20040191337, 2004.

[2] Hurley, T. R. and Vandenburg, J. M., editors; "Small Airplane Crashworthiness Design Guide,"AGATE Report Reference No. AGATE-WP3.4-034043-036, Simula Technologies Reference No. TR- 98099, April 2002.

[3] http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.75.1605&rep=rep1&type=pdf.

2.3. Rotorcraft

The NASA Rotary Wing Project[1] research into materials and structures focuses on rotorcraft-specific issues in crashworthiness, advanced materials for airframes and engines, durability, and damage tolerance.

Work within the structures and materials discipline was focused on unique technology needs for future rotorcraft in the areas of durable propulsion materials, lightweight structure, and advanced acoustic materials/structures. Research on propulsion materials was focused on the need for materials that can withstand harsh cyclic loading and erosion conditions. Research on lightweight structures was focused on three areas: (1) the need for fatigue resistance and damage tolerance in extremely lightweight structures that are sometimes allowed to buckle in service, and (2) the need for reliable crash-simulation tools that will reduce reliance on expensive full-scale testing for evaluation of new materials and structural concepts to improve crashworthiness, and development of a technology base needed by the rotorcraft industry to develop an advanced finite-element-based dynamics design analysis capability for vibrations. Research on advanced acoustic materials/structures was focused on developing and evaluating materials with improved acoustic performance and integration of these materials into lightweight rotorcraft structures. This research was coordinated with research in the acoustics discipline.

One example of many NASA contributions to rotorcraft is the development of design analysis methods for vibrations. A NASA Langley-sponsored rotorcraft structural dynamics program, known as Design Analysis Methods for VIBrationS (DAMVIBS)[2], was initiated in 1984. The objective of this program was to establish the technology base needed by the industry to develop an advanced finite-element-based dynamics design analysis capability for vibrations. Under the program, teams from the four major helicopter manufacturers have formed finite-element models, conducted ground vibration tests, made test/analysis comparisons of both metal and composite airframes, performed "difficult components" studies on airframes to identify components which need more complete finite-element representation for improved correlation, and evaluated industry codes for computing coupled rotor-airframe vibrations. Studies aimed at establishing the role that structural optimization can play in airframe vibrations design work have also been initiated. Five government/industry meetings were held in connection with these activities during the course of the program. The fifth meeting included a brief assessment of the program and its benefits to the industry. The benefits cited at that meeting included the following:

1. Developed industry-wide standards for basic modeling of metal and composite airframes
2. Improved industrial finite-element modeling techniques for analysis of airframe vibrations
3. Resulted in changes/improvements in industrial design practice for vibrations
4. Reversed industry management perception of the utility of finite-element models for vibration predictions. For the first time, such models are being relied on for airframe vibrations design work
5. Identified critical structural contributors to airframe vibratory response which require better finite-element modeling
6. Showed that considerably improved correlation can be obtained if modeling details that have been historically regarded as of secondary importance are taken into account
7. Provided a unique leadership role and focal point for rotorcraft structural dynamics research in government, industry, and academia
8. Provided the basis for the industry to move forward aggressively on its own to further enhance its capabilities in the subject areas

References

[1] http://www.aeronautics.nasa.gov/fap/srw_materials_structures.html
[2] Kvaternik, Raymond G., "The NASA/industry Design Analysis Methods for Vibrations (DAMVIBS) Program: A government overview," AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference; Dallas, TX; 13-15 Apr. 1992; 33rd; United States (NASA-TM-107579; NAS 1.15:107579).

2.4. Supersonic Aircraft

During the 1960s Langley scientists and engineers put in a mammoth, Apollo-like effort in support of the government's proposed, but later cancelled, construction of a national supersonic transport or SST. Concurrently, they explored the potential of the variable-sweep wing and other aerodynamically and structurally novel wing shapes both for the SST and for advanced performance military aircraft. Noteworthy breakthroughs in aeronautics have included the improvement of vertical takeoff and landing capabilities, the design of the "supercritical wing" for more effective flight at high supersonic speeds, the enhancement of laminar flow in the boundary layer of a wing, and the refinement of energy-efficient engines and fuels. All of these research efforts-with the exception of SST, which was cancelled by the U.S. Congress in 1971, continued to yield valuable results into the 1970s and 1980s. But even the supersonic work did not really come to an end. From the early 1970s on, Langley managed to keep alive a low-level but determined program to develop the technologies required for the effective flight of a supersonic transport. By the mid-1980s, there was a renewed interest at the Center in the development of an American SST. According to estimates, new technologies, including those developed at NASA Langley, now make an SST a much better bet.

In addition to the environmental and economic questions that still remained when the National SST Program was cancelled in 1971, several technical questions needed satisfactory answers. In the structures area, the major unresolved problems were related to the poor flutter characteristics of the aircraft and the high-operating empty weight fraction which adversely affected the economics of the airplane. The Department of Transportation funded a follow-on technology program to complete selected tasks in the areas of flutter, titanium honeycomb panel development, and fuel tank sealants. Advanced structural concepts or high-temperature composite materials were not included and flutter investigations were limited to the delta wing-type configurations in the National SST Program.

2.4.1. Advanced Fabrication Technology for Increased Structural Efficiency

Significant advances have been made in the processing of titanium in recent years. Research studies have demonstrated that weldbrazing, superplastic forming (SPF), SPF/DB, and SPF/WB are viable processes for fabricating titanium structures that exhibit improved efficiency. The large reduction in manufacturing costs afforded by these processes will substantially reduce the finished-part cost of titanium components. This cost driver combined with the highly mechanical properties at temperatures up to 600°F and the excellent corrosion resistance of titanium should promote wider spread applications in industries involved with chemical processing, food handling and processing, manufacturing products exposed to a marine environment, and, possibly, components for high-performance internal-combustion engines.

The method for superplastically forming and codiffusion bonding titanium sandwich structure,[1] using the selective application of stop-off material is schematically represented in **Figure 2.4-1**. In the first step, both sides of the center sheet are selectively coated with a ceramic stop-off material. The three sheets are then stacked and placed in the tool. The assembly is then positioned between resistance heated ceramic platens that are mounted in a press or loading device. Load is applied and a gas-tight seal is established between the tool and the three titanium sheets due to the pinching action of the projections machined on the upper tool. The cavity of the tool is then purged with argon gas and the assembly is heated to 1700°F. Argon gas is then injected into the tool at a pressure of 300 psi to compress the three sheets against the flat side of the tool. Pressure is maintained for three hours to diffusion bond the titanium sheets together in the regions where stop-off was not applied. Gas pressure in the tool cavity is then released and inert gas is injected through the preplaced tubes into the stop-off material between the sheets. Once separation of the sheets occurs, the gas pressure is increased at a programmed rate to a pressure of 100 psi to superplastically form the outer sheets to the contour of the mold cavity. As the face sheets are separated by the gas pressure, the center core sheet is superplastically stretched to form the truss core configuration. Gas pressure is equalized within the sandwich during forming by means of pre-machined holes. Following SPF/DB the panel is chemically milled to remove surface contamination and to obtain the desired skin thicknesses. This process has been patented and has been used to fabricate a wide variety of large components.

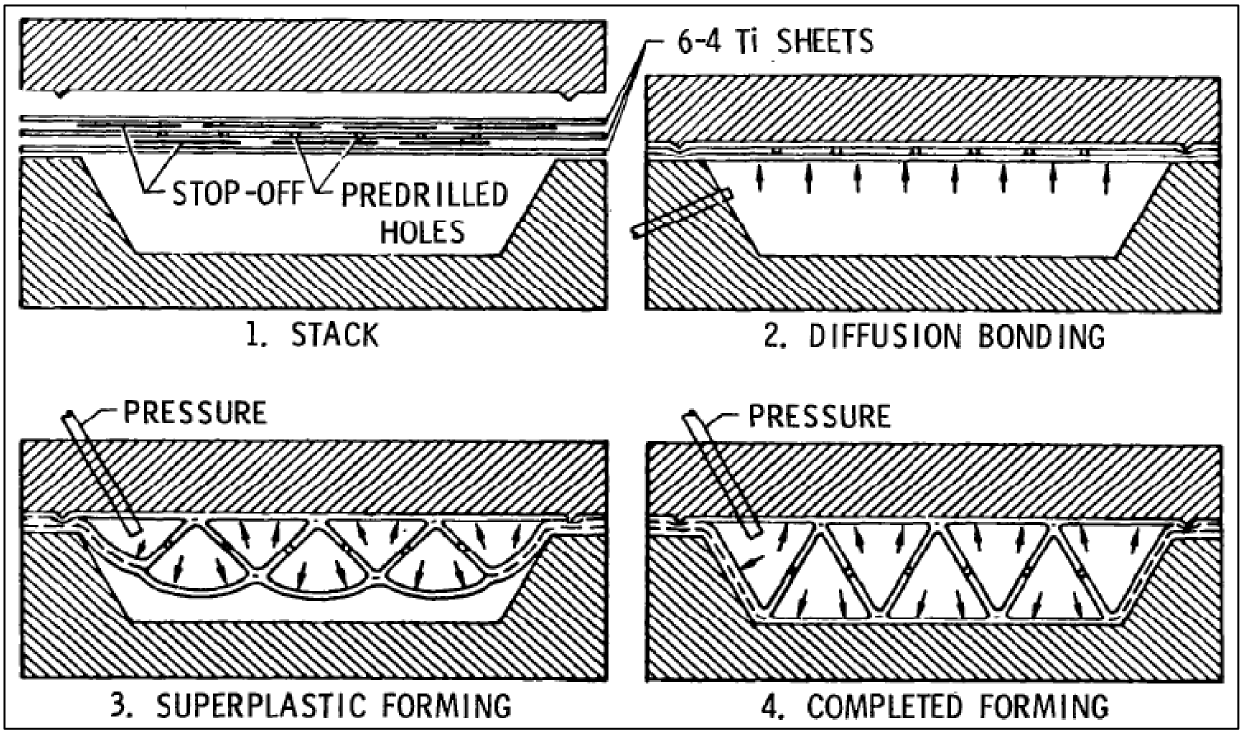


Figure 2.4-1: Superplastic Forming and Co-diffusion Bonding of Titanium Sandwich Panel.

2.4.2. Advanced Al Alloys for Supersonic Aircraft

NASA Langley has also been involved in the development of high-temperature aluminum alloys for use in structural components of high-speed aircraft. For example, in 1992 NASA initiated a program directed towards developing materials for the possible production of a high-speed civil transport (HSCT). Besides the researchers at NASA Langley, the research team also consisted of the Aluminum Company of America (Alcoa), Allied-Signal, Boeing, McDonnell Douglas, Reynolds Metals and the University of Virginia. Four classes of aluminum alloys were investigated: (1) I/M 2XXX containing Li (Reynolds) and I/M 2XXX without Li (Alcoa), (2) I/M 6XXX (Alcoa), (3) two P/M 2XXX (Alcoa and Allied-Signal), and (4) two different aluminum-base metal matrix composites (MMC) (Alcoa and UVA). The I/M alloys were targeted for a Mach 2.0 aircraft, and the P/M and MMC alloys were targeted for a Mach 2.4 aircraft. Although the HSCT Program was canceled the research that Langley did on the aluminum-lithium alloy 2098 was picked up and used in a new block of F-16 aircraft (**Figure 2.4-2**).

Most of the recent work on aluminum metal matrix composites has been focused on discontinuously reinforced Al (DRA). The development of affordable and scalable process and manufacturing techniques has been responsible for the widespread commercial usage of discontinuously reinforced MMCs with the development of the Duralcan liquid metal processing route and the DWA Al composites P/M process leading to many major automotive applications and most aeronautical applications. DRA has been successfully flight tested for use in a redesign of the F-16 ventral fins to overcome material failure in the original design. DRA was also used in an advanced actuator to replace titanium. In that application DRA provided a 25 percent reduction in piece part weight reduction while meeting elevated temperature strength, thermal expansion, stiffness and fatigue properties. Also, sharing of information for the F-16 applications led to the fan exit guide vanes of some Pratt & Whitney engines. In automotive applications DRA has been used for cylinder liners by Toyota, Honda, Daimler and Porsche and brake components in the Toyota RAV4-EV

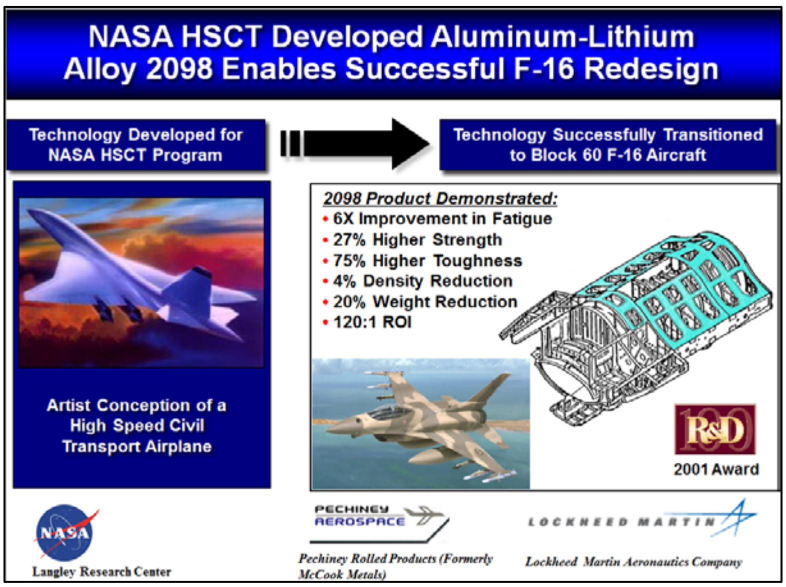


Figure 2.4-2: HSCT Developed Aluminum-Lithium Alloy 2098 Benefits New Fighter Aircraft.

Although the High-Speed Research (HSR) Program discontinued funding for the development of aluminum technology in December 1996, the alloys developed on the program had attractive properties and research and development work continued in-house at NASA Langley and at the aluminum companies. The research on two of the alloys, C415 and C416, resulted in the development of 2040 (C415), which is currently used for forged aircraft wheels; see **Figure 2.4-3** where elevated temperature properties are important. Aluminum aircraft wheels are subjected to demanding operating conditions during service such as heat, carbon dust, runway and aircraft fluids, and high-energy braking events. Alloy 2040 possesses an enhanced combination of desired materials' properties and produces wheel designs lighter in weight than those of other aluminum wheel alloys, e.g., 2014 and 7050. The demand for lighter structures and advanced manufacturing technologies has led to the development of AlMgSc alloys, which have a density similar to the latest aluminum-lithium alloys. They offer excellent fatigue and damage tolerance properties. These alloys are amenable to laser-beam and friction-stir welding, and parts can also be produced using additive manufacturing technology, which aligns well with NASA Langley’s program on advanced manufacturing technology.

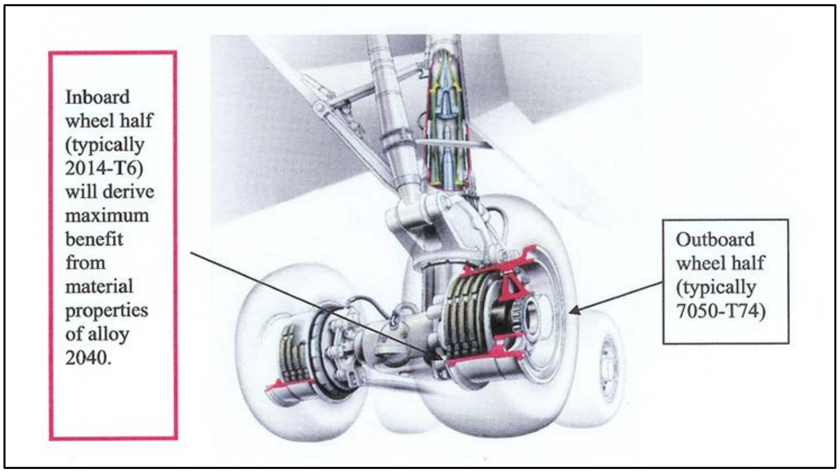


Figure 2.4-3: Alloy 2040 is targeted for use at the inboard wheel half, which is subjected to high thermal and mechanical loads.

2.4.3. Environmental Durability Testing

Environmental durability testing of materials and structures for aerospace applications has been, and continues to be, one of the major research thrust areas for Langley Research Center. A search of the technical literature will show reports from the early days on NACA to the latest efforts to test and evaluate new materials made by additive manufacturing. The structures and materials laboratories at Langley contain numerous specialized facilities and test chambers designed to evaluate the long term performance of materials and structures in simulated service environments. A search of the NASA Technical Report Server (NTRS) using just the two words “materials durability” will show more than 1100 NASA and journal reports on the work done at Langley or sponsored by Langley.

References

[1] C.P. Blankenship and Louis A. Teichman: “Advanced Materials Technology,”, NASA Conference Publication 2251, 1982.

2.5. Hypersonic

2.5.1. Structural Concepts for Hypersonic Aircraft Structures

One of the most significant contributions Langley made to Hypersonic Flight Vehicles was structural concepts for hot structures. Bob Jackson was a pioneer in structural concepts for metallic heat shields and vehicle structures. A key summary paper by Tenney, Lisagor, and Dixon, published in 1988, gives an overview of materials and structures research at Langley for hypersonic vehicles.[1]

2.5.2. High-Temperature Titanium Metal Matrix Composites and Titanium Aluminides

A paper by Johnson, Lubowinski, Highsmith, Brewer, and Hoogstraten reported on mechanical property testing of SCS-6/Ti-15-3 in 1988.[2] Another key paper was written by Hoffman, Bird, and Dicus on SCS-6/β21S.[3]

2.5.3. HYPER X

The purpose of the Hyper-X Program was to demonstrate the operation of an airframe-integrated scramjet engine at Mach 7 and Mach 10 flight conditions. Three Hyper-X vehicles were built and two were successfully launched setting world speed records. The Hyper-X vehicles were launched from NASA's B-52B mothership (**Figure 2.5-1**) and were accelerated to the test speed by a modified Pegasus booster. The second vehicle demonstrated that an integrated scramjet could produce more thrust than drag at a speed near Mach 7; the third vehicle was able to cruise at almost Mach 10. A NASA news release from Aug. 30, 2004 states, "On 27 March, 2004, NASA's unmanned Hyper-X (X-43A) airplane reached Mach 6.83, almost seven times the speed of sound. The X-43A was boosted to an altitude of 29,000 m (95,000 ft) by a Pegasus rocket launched from beneath a B52-B aircraft. The revolutionary 'scramjet' aircraft then burned its engine for around 11 seconds during flight over the Pacific Ocean." A later NASA press release states, "Guinness World Records recognized NASA's X-43A scramjet with a new world speed record for a jet-powered aircraft—Mach 9.6, or nearly 7,000 mph. The X-43A set the new mark and broke its own world record on its third and final flight on Nov. 16, 2004." Langley was the lead center for this very successful program.

Figure 2.5-1: Hyper-X experimental aircraft mounted under the wing of a B-52B airplane, ready to be carried to test altitude.

2.6. Space Launch Rockets

The lightweight alloys of preference for space launch vehicles have been and remain aluminum alloys. The use of aluminum alloys in early space rockets is shown in **Figure 2.6-1**. The information in this figure is from a book entitled "Structures Technology Historical Perspective and Evolution," edited by Ahmed K. Noor.[4]

Year	Vehicle	Type STR weld thickness	Alloy	Ult tens str / Weld str at room temp
1951–55	Redstone	doublers < 1/8″	5052-N22	31,000 psi / 26–31,000 psi
1954–60	Jupiter 'C'	butt welds < 1/4″	5036-N34	44,000 psi / 37–39,000 psi
1955–60	Jupiter	butt welds milling < 5/8″	early 5086-N34 / later 5456-N34	—— / ——
1955–60	Thor	butt welds < 3/8″	2014-T6	70,000 psi / ?–60,000 psi
1957–61	Titan	butt welds < 3/8″	2014-T6	70,000 psi / ?–60,000 psi
1959–62	Saturn C-1	butt welds > 3/8″	5456-N34	53,000 psi / 47–49,000 psi
1962	Saturn C-5	butt welds ≧ 2″	2219-T87	63,000 psi / 37–42,000 psi

Figure 2.6-1: Use of Aluminum Alloys in Early Space Vehicles.

2.6.1. Solving Apollo Titanium Fuel Tank Corrosion Cracking Problem

The Apollo tank story illustrates LaRC's ability to integrate the required knowledge and expertise to provide a total solution to a critical metallic material problem in an incredibly short time. LaRC engineers identified and demonstrated that an Apollo fuel tank failure was due to stress corrosion cracking. The stress corrosion cracking was demonstrated in a sample coupon, and the coupon test data was correlated with tests on tanks exposed to similar conditions. After evaluating different protective treatments, shot peening was shown to be an effective and viable treatment. Suitable shot peening equipment was built and the correct peening procedure was developed, eventually integrating the peening process into the manufacturing of titanium tanks.

2.6.1.1. Problem Description:

A reaction control system (RCS) oxidizer tank of the Apollo launch vehicle (**Figure 2.6-2** and **Figure** 2.6-3) failed during a test to demonstrate propellant compatibility with titanium tanks. This was the first of seven tanks to fail from a group of ten tanks tested to investigate a failure that occurred during February 1965. These results caused an intensive investigation to be undertaken.[5]

In August 1965, resident ASPO quality assurance officers at North American began investigating the recent failures of titanium tanks at Bell Aerosystems. The eventual solution (a change in the nitrogen tetroxide specification) was contributed to by North American, Bell Aero Systems, the Boeing Company, MSFC, MacNeal-Schwendler Corporation (MSC), Langley Research Center, and a committee chaired by John Scheller of NASA HQ The quality assurance people viewed the failures as quite serious since Bell had already fabricated about 180 such tanks.

Figure 2.6-2: Saturn V, Apollo Launch Vehicle.

Figure 2.6-3: Titanium Fuel Tank.

In December, ASPO Manager Joseph F. Shea informed North American, Grumman, and Bell Aerosystems Company that NASA's Associate Administrator for Crewed Space Flight, George E. Mueller, had requested a presentation on the incompatibility of titanium alloys and nitrogen tetroxide and its impact on the Apollo Program at the NASA Senior Management Council meeting in December 1965.

In light of recent failures of almost all titanium tanks planned for use in the Apollo Program when exposed to nitrogen tetroxide under conditions which might be encountered in flight, the matter was deemed to be of utmost urgency.

A preliminary meeting was scheduled at NASA Headquarters on December 16, and one responsible representative from each of the prime contractors and subcontractors was requested to be present. Prior to the December 16, 1965 meeting, it was necessary for each organization to complete the following tasks:

- Tabulate and analyze all tank tests to date and all related materials tests
- Establish a format for presentation of the effects of time, temperature, and stress levels on failure
- Obtain the best correlation between actual tank tests and related materials tests
- Establish limits of operation and confidence levels for all current titanium tanks and relate these to all planned flights
- Tabulate all titanium tank hardware in inventory and complete costs of development and manufacture of this hardware to date

- Consider and recommend a course of action which would alleviate problems for early flights using existing hardware with minimum cost and schedule impact
- Consider and recommend a course of action for future flights and indicate cost and schedule impact
- If recommendations for future action include coatings, surface preparation, or alternate materials, present component weight increase and overall spacecraft increase
- Consider changes in mission ground rules which would decrease time of tanks under pressure
- Consider possibility of venting and repressurization and impact on pressurization system design, weight, cost, and schedule
- Review all missions and present pressurization times, stress levels, and thermal environment of all Apollo titanium tanks which contain nitrogen tetroxide

NASA Langley took up this challenge, investigated and understood the stress corrosion cracking problem in titanium alloy and came up with an innovative practical solution of shot peening the tanks and thereby solved the problem to satisfaction of all parties involved.

2.6.2. Langley's Approach and Contributions

The Ti-6Al-4V titanium alloy in the solution-treated and aged condition is used as a structural material for liquid propellant tanks in many current aerospace vehicles because of its favorable strength-weight ratio and relative chemical inertness to highly corrosive liquid propellants. Recent experience, however, indicated that Ti-6Al-4V titanium-alloy tanks showed evidence of stress-corrosion damage when exposed to nitrogen tetroxide (N_2O_4) rocket propellant under pressure. Because this problem affected many tanks in existence as described above, an investigation was undertaken by Tom Bales, Barry Lisagor, and Charles Manning to obtain information on the nature of the stress-corrosion problem and to determine protective treatments which would make it possible to utilize the many existing propellant tanks.[6] The stress-corrosion tests were carried out on small self-stressed specimens at levels from 25 to 100 ksi exposed to four different N_2O_4 oxidizers and different temperatures (85°F to 165°F), followed by testing of tanks.

Several treatments were also applied to these specimens to investigate possible prevention of the corrosion attack. These treatments consisted either of a coating or different peening techniques. The coatings which were investigated included an aluminum coating which was deposited by a chemical vapor deposition process, a polytetrafluoroethylene tape coating which was tightly wrapped on the specimens, and a special polymer coating of the **"**Pyrrone" family.

The following conclusions were drawn from the investigation. Stress-corrosion cracking of Ti-6Al-4V titanium alloy in liquid N_2O_4 was demonstrated from tests of small self-stressed corrosion specimens and tanks. Results from corrosion tests of small specimens appear to correlate well with corrosion tests of tanks (**Figure 2.6-4**). There was little effect of applied stress on the time required for crack initiation. Tests conducted on specimens with the metallic and organic coatings were found to be unsatisfactory for protecting Ti-6Al-4V alloy against stress corrosion, but surface-induced residual compressive stresses produced by glass-bead peening were found to be effective. The magnitude of stress-corrosion damage appears to vary with chemical composition and source of oxidizer. Stress corrosion damage boundary for Ti-6Al-4V exposed to N_2O_4 oxidizer was established.

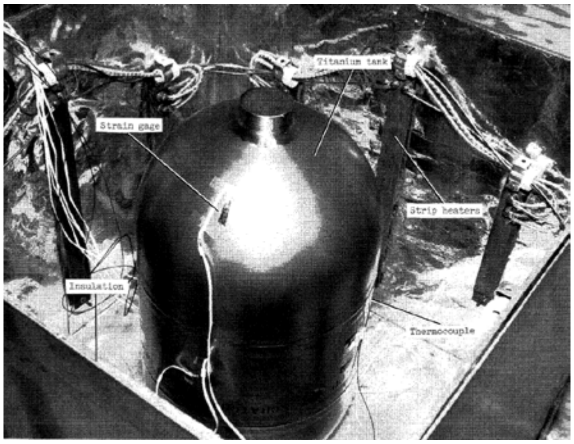


Figure 2.6-4: Stress Corrosion Testing of Titanium Alloy Tank.

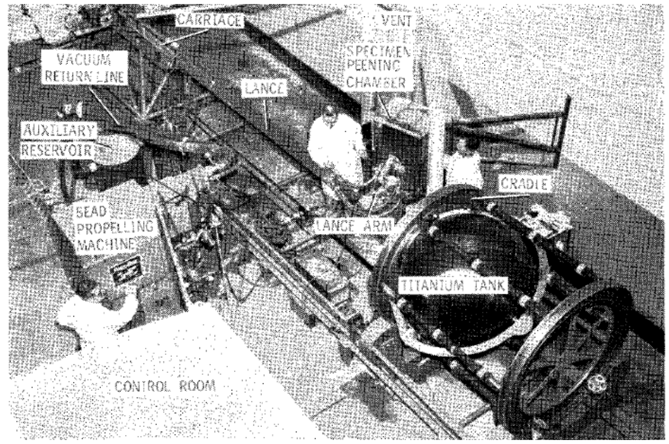


Figure 2.6-5: Glass Bead Peening Equipment and 51-inch Diameter Tank.

Glass-bead peening equipment, shown in **Figure 2.6-5**, which utilizes programed motions was developed and used to peen uniformly the inner surface of 26 titanium alloy spacecraft tanks for the alleviation of stress corrosion resulting from exposure to nitrogen tetroxide.[7] The tanks which were peened varied from 20 inches to 14 feet (0.5 to 4.3 m) in length and from 12.5 to 51 inches (0.3 to 1.3 m) in diameter. Glass-bead peening parameters have been investigated and parameters were established which produced a compressive stress of approximately 100 ksi on the peened surface of titanium test strips. It is noteworthy that a U.S. patent was issued for this invention relating to a method and apparatus for preventing stress corrosion in a pressure vessel, and more particularly to introducing a compressive stress in the inner surface of the pressure vessel by peening.[8]

Langley's contributions can be aptly summarized by quoting the memo from Apollo Program Director Samuel C. Phillips to the Director, Office of Advanced Research and Technology, NASA Headquarters pointing out that, in July 1965, the Apollo Program encountered stress corrosion of titanium tanks from nitrogen tetroxide propellant, and that through his auspices, Langley Research Center initiated a crash effort that had been a key factor in solving the problem.[9] Phillips said that Langley's effort had been vigorous, thorough, and of the highest professional caliber. An excellent team relationship had been maintained with MSC, MSFC, Kennedy Space Center, vehicle contractors, and tank subcontractors and LaRC personnel had given dedicated and outstanding support. He cited that

- within nine days from go-ahead, a test facility was constructed, equipped, and in operation;
- within one hour after the request from MSC, coupon tests were under way in support of the Gemini VII flight;
- glass bead peening was demonstrated as a solution, and many tanks were peened on a crash schedule for flight and test use;

- coupon tests in direct support of AS-201 were instrumental in providing confidence for proceeding with that flight.

2.6.3. Structural Concepts and Analyses Codes (NASTRAN)

Dr. Charles E. Harris was lead for the development of an implementation plan for the Structures and Materials Center of Excellence Plan for NASA as outlined in the 1998 NASA Strategic Plan.[10] In his NASA paper on this subject,[11] he noted that one of NASA's most significant and lasting technical contributions in the field of structures and materials was a direct result of a collaborative effort among all the NASA Field Centers. In January 1964, key personnel from all NASA Field Centers gathered at Headquarters in Washington, D.C. to discuss efforts underway to improve structural analysis methods, particularly as it applied to the shell configurations commonly used in aerospace structure. Each representative described how his group had written special-purpose computer programs to analyze particular shell configurations. After this meeting, NASA Headquarters commissioned an ad hoc committee, with a representative from each NASA Center, to investigate the state of analysis methods in the aerospace industry. The first action taken by the committee was to visit the aircraft companies which were doing prominent work in developing computer based advanced structural analysis methods. The committee's visits to the aircraft companies revealed that no single computer program incorporated enough of the best analysis features desired by NASA. Therefore, the committees recommended to Headquarters that NASA sponsor the development of its own computer program as a means to upgrade the analytical capability of the whole aerospace industry. Headquarters endorsed the recommendation and selected Goddard Space Flight Center (GSFC) to manage the development of the computer program. Under the leadership of GSFC, the ad hoc committee developed a visionary and thorough technical specification for the computer program and released a request for proposals in July 1965. Much of the eventual success of the project was directly attributed to the initial work of the NASA committee in developing the thorough specification for the computer program. In December 1965, NASA awarded two Phase I contracts for preparation of a Technical Evaluation Report, one to a team led by MSC[12] and one to the team led by Douglas Aircraft Company. After an evaluation of the two competing Phase I Reports and the associated Phase II proposals, MSC was selected as the recipient of the Phase II contract and began development of the computer program in July 1966. Shortly thereafter, NASA designated the name of the computer program to be the <u>NA</u>SA <u>ST</u>ructural <u>AN</u>alysis (NASTRAN) Computer Program. The contracting team completed the computer program in 1969 and delivered it to all the NASA Field Centers. In February 1970, the Program Office at Goddard was disbanded. Later that year, NASA Headquarters established the NASTRAN Systems Management Office (NSMO) at Langley Research Center. The NSMO had the dual mission of maintaining NASTRAN and developing new capabilities for the program. A NASTRAN Advisory Group was set up to provide guidance to the NSMO. This Advisory Group consisted of members from each of the NASA Centers and was, in effect, a continuation of the ad hoc committee which drafted the initial NASTRAN specification in 1964. In November 1970, NASTRAN was released to the public through the COSMIC Distribution Center at the University of Georgia for the price of $1750. Less than a year later, in September, the first NASTRAN Users Conference held at Langley Research Center was attended by about 200 representatives of the rapidly growing user community. Thus were the origins of the most successful finite element structural analysis computer code used throughout the world and in virtually all industrial sectors.

NASTRAN has emerged as truly general-purpose software by making the model input independent of the details of the mathematical operations internal to the software. It now contains extensive nonlinear analysis, heat transfer, aeroelasticity, and thermal analysis modules. It, in turn, provided the impetus for the development of such programs as the structural analysis programs series, ANSYS, and ABAQUS.

References

[1] Tenney, D. R., Lisagor, W. B., and Dixon, S.C.; "Materials and Structures for Hypersonic Vehicles", NASA Technical Memorandum 101501, Oct. 1988.

[2] Johnson, W. S., Lubowinski, S. J., Highsmith, A. L. ,Brewer, W.D., Hoogstraten; "Mechanical Characterization of SCS6/Ti15-3 Metal Matrix Composites at Room Temperature", NASP Technical Memorandum 1014, 1988.

[3] Hoffman, E. K., Bird, R. K. and Dicus, D.L.; "Effect of Braze processing on SCS-6/β21S Titanium Matrix Composites", Welding Research, supplement to the welding Journal, August 1994.

[4]Noor, Ahmed K., Editor of book entitled "Structures Technology-Historical Perspective and Evolution," Published by American Institute of Aeronautics and Astronautics, Inc., 1998. http://books.google.com/books?id=EQRfhBdrYGIC&pg=PA15&lpg=PA15&dq=William+Mrazek+nasa+Marshall+structures+and+materials&source=bl&ots=RxYaV2oWzu&sig=mIoXI23FIz3SOhVDaGTgsBbmKNc&hl=en&ei=rzNlTqXFN6ausALP9NG-Cg&sa=X&oi=book_result&ct=result&resnum=7&ved=0CD0Q6AEwBg#v=onepage&q=William Mrazek NASA Marshall structures and materials&f=true.

[5] "Advanced Design, Testing and fabrication, October 1965" section in "The Apollo Spacecraft-A Chronology," http://www.hq.nasa.gov/office/pao/History/SP-4009/v3n.htm.

[6] Bales, T.T, Lisagor, W.B, Manning, C.R. Jr, "Stress Corrosion Cracking of Titanium Aluminum Vanadium Alloy in Nitrogen Tetroxide under Pressure," NASA Document ID 19680003422, Jan. 1968.

[7] Bales, T.T, Lisagor, W.B, Manning, C.R. Jr, "Equipment and Procedures for Glass Bead Peening titanium-alloy Tanks," NASA Document ID 19680003421, Jan. 1968.

[8] Manning, C.R. Jr., Bales, T.T., and Lisagor, W. B., "Controlled Glass bead Peening," US Patent 3,531,964, Oct. 6, 1970.

[9] Memo, Phillips to Director, Research Div., NASA OART, "Compatibility of Titanium Propellant Tanks with Nitrogen Tetroxide," http://www.hq.nasa.gov/office/pao/History/SP-4009/v4p1a.htm, March 7, 1966.

[10] NASA Strategic Plan, NASA Policy Directive (NPD)-1000.1, National Aeronautics and Space Administration, Washington, D.C., 20546, 1998, page 15.

[11] Charles E. Harris. 1998. Implementation Plan for the NASA Center of Excellence for Structures and Materials. NASA/TM-1998-208714.

[12] The MacNeal-Schwendler Corporation, The First Twenty Five Years , by Dr. Richard H. MacNeal, The MacNeal-Schwendler Corporation, Major Aerospace and Defense Accounts, 1000 Howard Blvd., Suite 105, Mount Laurel, NJ 08054, 1988.

2.7. Shuttle and Beyond

2.7.1. Development of Super Lightweight External Tank

Langley played a key role in the successful development of the new aluminum-lithium alloy (2195) used for the super lightweight tank for the space shuttle. In 1986, Langley funded basic research on the fracture toughness of a new generation of Al-Li alloys known as Weldalite® at the Lockheed Martin Laboratories in Baltimore. The results of this early work gave birth to a new Al-Li alloy (2195) that was used for the SLWT project. Langley personnel worked closely with researchers at Marshall Space Flight Center and with personnel at Lockheed Martin during the maturation of the new 2195 alloy and subsequent development of the very successful SLWT for the shuttle. Additional details are included in section 5.2.

2.7.1.1. External Tank Development

The external tank (ET) was the only non-reusable major component of the Space shuttle system that consists of the ET, the orbiter, and the two solid rocket boosters. The ET was the single largest element at 154 feet long and 27.6 feet in diameter, and during launch it serves as the structural backbone of the shuttle, absorbing most of the 6 million pounds of thrust generated during flight and providing propellant to the orbiter's three main engines (**Figure 2.7-1** and **Figure** 2.7-2). The original version of the ET used on the first shuttle launches in the early 1980s weighed some 76,000 lbs. A program to redesign the ET yielded a 10,000 lbs weight savings. The resulting lightweight tank, introduced on the sixth mission (STS-6) in 1983, made possible substantial improvements in shuttle performance. Each pound removed from the structure of the ET means an extra pound of payload in the orbiter's cargo bay or the ability to go to a higher orbit and/or into an orbit more highly inclined to the Earth's equator.

However, when NASA committed to a new higher inclination orbit for the International Space Station a 15,000 lbs weight savings from the shuttle was required. The NASA External Tank Project was asked to provide 50% of the required savings (7500 lbs). The approach was to use a new material-aluminum-lithium (Al-Li) alloy 2195 combined with a new Orthogrid tank design for LH2. The 2195 Al-Li alloy is 30% stronger and 5% less dense than the aluminum alloy previously used in manufacturing ETs. The major work on the tank began in 1994 with Martin Marietta as the prime contractor on the project. The tank was reengineered to use Al-2195 and Al-2090 extensively, which were stronger and lighter than the Al alloys on Lightweight Tank (Al-2219, etc). Together with the first use of an orthogrid structure—on the LH2 tank's barrel—this lightened the structure and improved payload, especially to the high-inclination orbit of the ISS. Some 7500 lbs were saved by using the stronger, lighter aluminum-lithium alloy and incorporating weight-saving design changes, such as replacing machined longitudinal tee stiffeners in the liquid hydrogen tank barrels by an orthogonal waffle grid design. Additional weight savings were achieved by fine-tuning controls for the thickness of the spray-on thermal protection coating, machining this sprayed-on coating and optimizing tank structure not undergoing material change.

All Orthogrid Configurations were tested[1] in full size to failure. A design margin of 218% was

Figure 2.7-1: Space Shuttle *Discovery* Begins Liftoff at the start of STS-120.

Figure 2.7-2: Shuttle Super Lightweight LH2 Tank.

demonstrated vs. 140% required. Protoflight testing for the LH2 tank consisted of subjecting each flight LH2 tank to 115% Limit Load test. These tests demonstrated the structural stability margins of the new design and the processes and workmanship standards for the new material. A 7500 lbs weight savings was accomplished. The 7500-pound lbs weight savings resulting from the SLWT increases shuttle payload capacity by a similar amount. Weighing 58,500 lbs empty and 1.6 million lbs when filled with cryogenic propellants, the SLWT supplied over 535,000 gallons of liquid oxygen and liquid hydrogen to the orbiter's engines. The first SLWT flew June 2, 1998 on STS 91—6 months ahead of the official ISS need date. The development cost for the SLWT was ~$132 million which was $20 million under budget and these funds were returned to the Shuttle Program.

The performance increase was vital to the building and supplying of the ISS. The first shuttle flight that placed ISS components in high-inclination orbits took place on December 4, 1998.

2.7.1.2. Alloy Development Background

Langley has made extensive contributions to the development of cryogenic tanks for launch vehicles. Aluminum alloy 2219 is the material previously used for the pressurized portions of the ET structure. In 1986, the Lockheed Martin Laboratories in Baltimore undertook the challenge to develop a high-strength, low-density replacement for the 2219 alloy while retaining that alloy's excellent weldability, fracture toughness, and cryogenic properties. The result was a family of aluminum-lithium alloys called Weldalite®, from which the 2195 alloy was selected as the optimum replacement for the 2219 alloy on the ET. Dr. Joe Pickens[2] was funded by Langley to study the basic fracture toughness of this new generation of Al-Li alloys. His work combined with fracture toughness testing and examination of microstructural features was instrumental in the early development of Weldalite® and the ensuing development of the 2195 alloy optimized for the SLWT Project.

The 2195 aluminum-lithium alloy is weldable and has excellent fracture toughness at cryogenic temperatures down to –423°F, the temperature at which liquid hydrogen is maintained on board the ET. The nominal chemistry for the 2195 alloy is 1% lithium, 4% copper, 0.4% silver, 0.4% magnesium, with the remainder aluminum. Alcan, located in Ravenswood, West VA, provided Lockheed Martin with aluminum-lithium alloy for super lightweight tank production.

The first super lightweight tank lifted off June 2, 1998, with shuttle flight STS-91 (**Figure 2.7-3**).

- **Space Shuttle system redesigned to support space station launch requirement of 51.6° angle of inclination**
- **SLWT program requirement was an 8,000 lb. system weight reduction**
  - **System redesigned: T-stiffened → orthogrid**
  - **Material Replacement: Al 2219 → Al-Li 2195**
- **Program initiated in 1994; First SLWT flight was STS-91, June 1998**

Figure 2.7-3: Space Shuttle Super Lightweight External Tank.

Langley has worked with industry and cooperatively with other NASA centers to mature advanced technologies for higher performance cryotanks. **Figure 2.7-4** shows data generated on 2219 and Al-Li 2195 in biaxial testing at Langley.

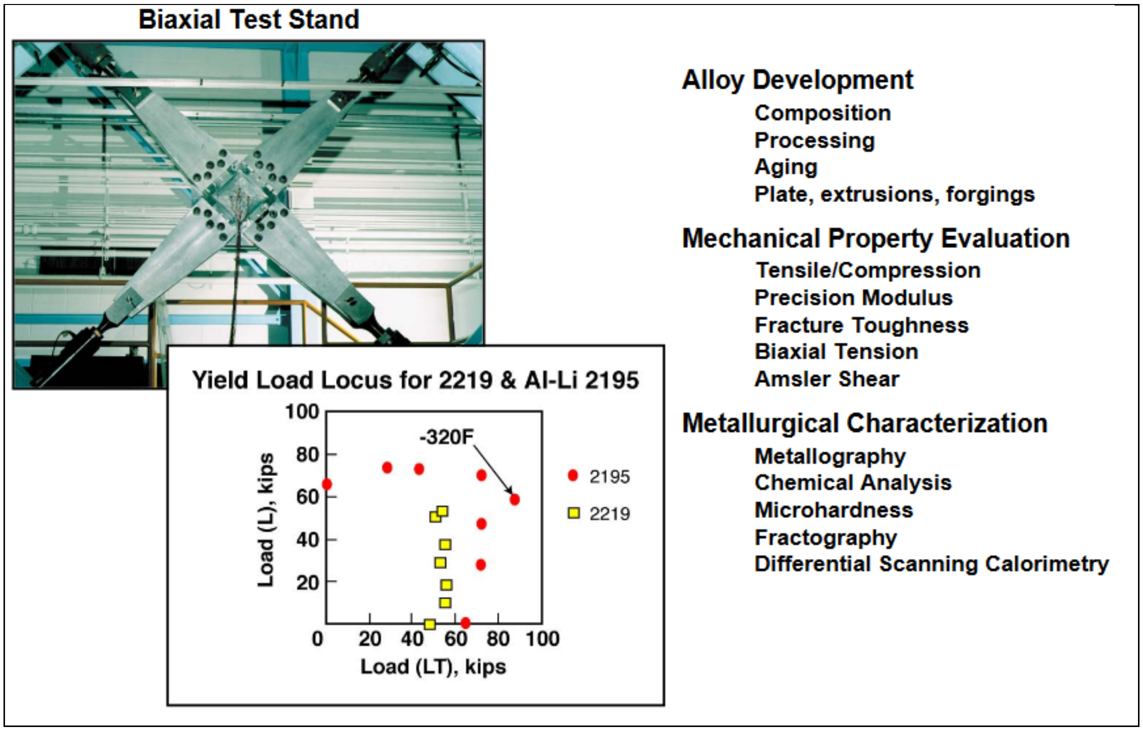


Figure 2.7-4: Materials Testing and Characterization Program conducted at NASA Langley Research Center.

The types of testing and metallurgical characterization performed at Langley in support of the Shuttle Tank project are also noted in **Figure 2.7-4**. **Figure 2.7-5** also shows some additional details on the different alloys and types of fabrication technologies worked at Langley for space transportation systems. These advanced processing technologies included near-net-extrusions, roll forming, shear forming, spin forming and friction stir welding. Targeted space launch vehicle application for components fabricated by these processes include cryotank barrel sections, adapter rings, cryotank domes, intertank, and other dry bay structures found on space launch vehicles. Development of these advanced processing technologies was done in cooperation with launch vehicle manufactures, metal producers and fabricators, and NASA partners MSFC and JSC. **Figure 2.7-6** also illustrates that Langley worked with its partners to not only research advanced technologies, but to also demonstrate that tanks could be fabricated using these new technologies. The tank shown was fabricated from 2195 Al-Li alloy also used for the SLWT. As a result of working these advanced development programs Langley was able to significantly contribute to the Space Shuttle Program in the foundational technologies required for the SLWT required to enable the shuttle to carry payloads to the ISS, as noted above.

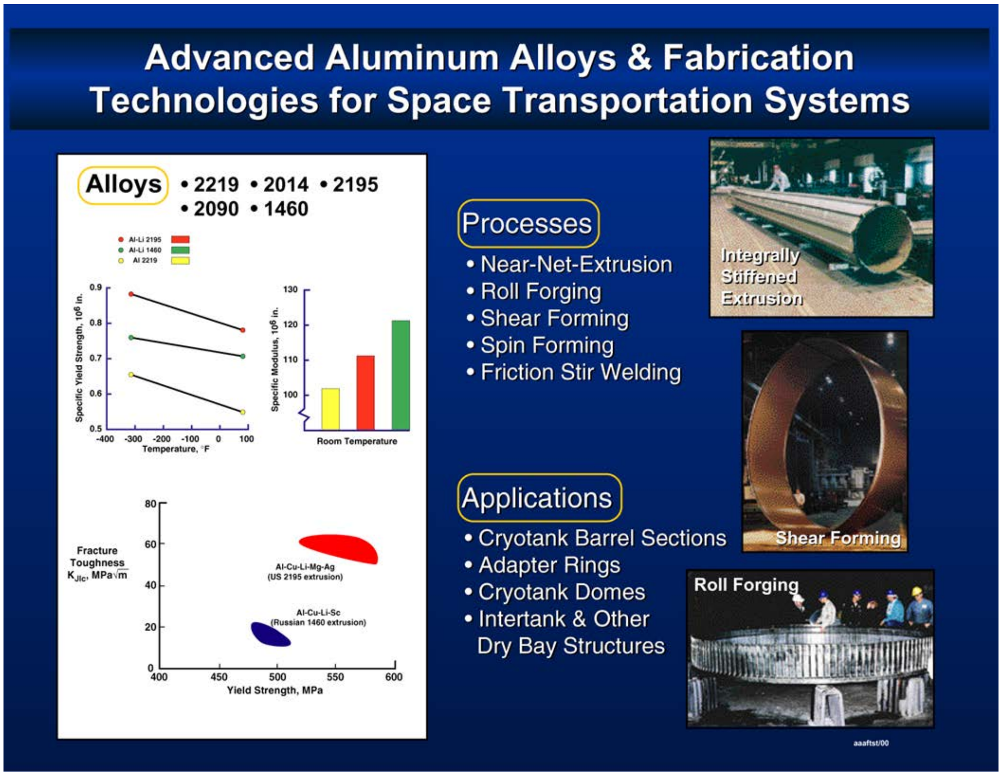


Figure 2.7-5: Advanced Aluminum Alloys and Fabrication Technologies for Space Transportation Systems.

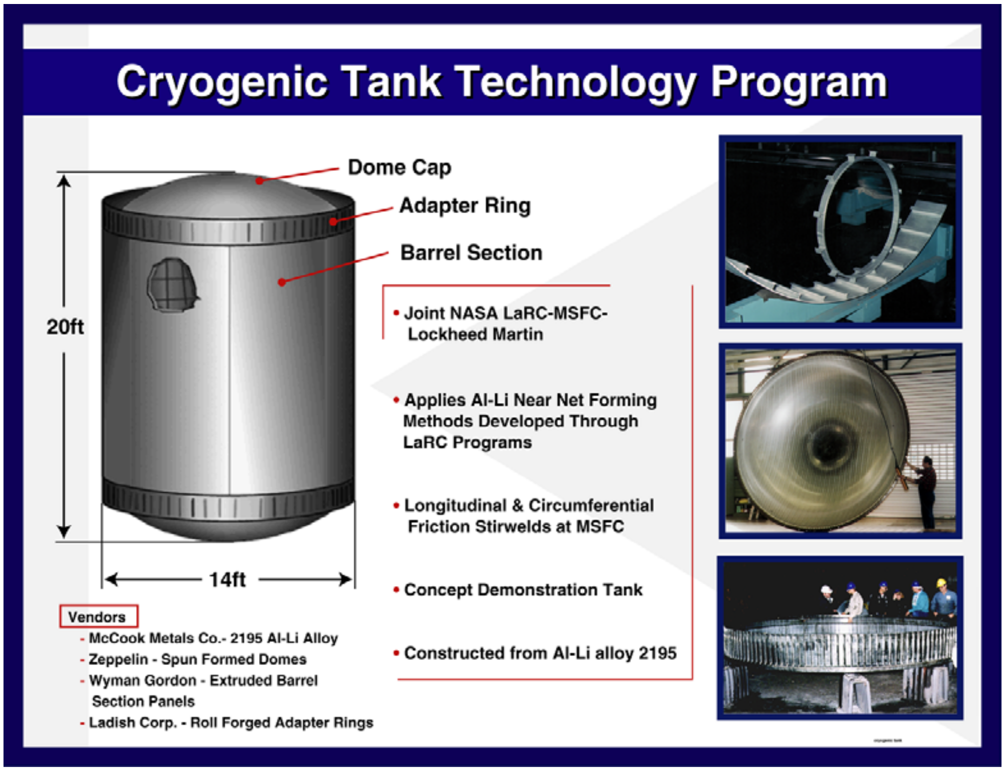


Figure 2.7-6: Metals Technology Advancement Championed by Langley Researchers.

Early pioneering work in the development of an Al-Cu-Li-Ag-Mg alloy that would be weldable and have improved short transverse fracture toughness was done by Dr. Joe Pickens at the Martin Marietta Research Laboratory. He was funded by Langley to investigate the effects of silver additions on the distribution of the T_1 phase in the alloy microstructure. Dr. Pickens' work demonstrated that a weldable Al-Cu-Li-Ag-Mg alloy could be produced with a uniform distribution of the T_1 phase which improved the short transverse fracture behavior and gave birth to a new alloy which he called Weldalite.[2] Weldalite 049 is an Al-Cu-Li-Ag-Mg alloy that is strengthened in artificially aged tempers primarily by very thin plate-like precipitates lying on {111} matrix planes.[3] Al-Li alloys are generally joined by friction stir welding. However, some Al-Li alloys, such as Weldalite 049, can be welded conventionally. The downside is that this property comes at the price of density; Weldalite 049 has about the same density as 2024 aluminum and 5% higher elastic modulus.

Additional research on similar alloy chemistries by Reynolds, Lockheed-Martin, Langley, and MSFC gave birth to the alloy variant now known as 2195 Al-Li from which the super lightweight tank for the shuttle was fabricated. An extensive R&D program was funded by NASA to bring 2195 to the maturity level where highly reliable cryogenic tanks of the size required for the Shuttle Program could be fabricated with the required fracture toughness and strength at cryogenic temperatures to give safe and affordable lightweight tanks for the Shuttle Program.

The third and final version of the U.S. space shuttle's External Tank was principally made of Al-Li (2195 alloy). In addition, Al-Li alloys are also used on both the Atlas V and Delta IV Evolved Expendable Launch Vehicle rockets, and before its cancellation were to be used by NASA for Project Constellation, primarily, on its Ares I and Ares V rockets, as well as the Orion spacecraft.

2.7.2. Shuttle Fracture Control Methodology

Structural flaws and cracks may grow under fatigue inducing loads and, upon reaching a critical size, cause structural failure to occur. The growth of these flaws and cracks may occur at load levels well below the ultimate load bearing capability of the structure. The Fatigue Crack Growth Computer Program, NASA/FLAGRO, was developed as an aid in predicting the growth of preexisting flaws and cracks in structural components of space systems. The earlier version of the program, FLAGRO4, was the primary analysis tool used by Rockwell International and the shuttle subcontractors for fracture control analysis on the space shuttle. NASA/FLAGRO is an enhanced version of the program and incorporates state-of-the-art improvements in both fracture mechanics and computer technology. NASA/FLAGRO provides the fracture mechanics analyst with a computerized method of evaluating the "safe crack growth life" capabilities of structural components. NASA/FLAGRO could also be used to evaluate the damage tolerance aspects of a given structural design. The propagation of an existing crack is governed by the stress field in the vicinity of the crack tip. The stress intensity factor is defined in terms of the relationship between the stress field magnitude and the crack size. The propagation of the crack becomes catastrophic when the local stress intensity factor reaches the fracture toughness of the material. NASA/FLAGRO predicts crack growth using a two-dimensional model which predicts growth independently in two directions based on the calculation of stress intensity factors. The analyst can choose to use either a crack growth rate equation or a nonlinear interpolation routine based on tabular data. The growth rate equation is a modified Forman equation which can be converted to a Paris or Walker equation by substituting different values into the exponent. This equation provides accuracy and versatility and can be fit to data using standard least squares methods. Stress-intensity factor numerical values can be computed for making comparisons or checks of solutions. NASA/FLAGRO can check for failure of a part-through crack in the mode of a through crack when net ligament yielding occurs.

Dr. Jim Newman made major contributions to the Shuttle Program by generating stress intensity factor solutions for Royce Forman at JSC which were used in NASA/FLAGRO. The NASA/FLAGRO (NASGRO) computer program was developed for fracture control analysis of space hardware and is currently the standard computer code in NASA, the U.S. Air Force, and the European Space Agency for this purpose. The significant attributes of the NASGRO program are the numerous crack case solutions, the large materials file, the improved growth rate equation based on crack closure theory, and the user-friendly promptive input features.[4]

NASA/FLAGRO 2.0 [5] developed as analytical aid in predicting growth and stability of preexisting flaws and cracks in structural components of aerospace systems. It has been extensively used for fracture-control analysis of space hardware. It is organized into three modules to maximize efficiency in operation. NASA/FLAGRO is useful for (1) crack-instability/crack-growth analysis, (2) processing raw crack-growth data from laboratory tests, and (3) boundary-element analysis to determine stresses and stress-intensity factors. It is written in FORTRAN 77 and ANSI C.

References

1.http://appel.nasa.gov/wpcontent/uploads/sites/2/2013/04/553074main_Super_Light_Weight_Tank_Counts.pdf

[2] Pickens, J. R., Heubaum, F. H., Langan, T. J., and Kramer, L.S.; 1989. Proc. Fifth International Aluminum-Lithium Conf. T.N. Sanders and E. A. Starke, eds. MCE publications Ltd., Birmingham, U.K. pp. 1397–1414.

[3] R. A. Herring, F. W. Gayle, and J. R. Pickens; J. Mater. Sci. 28, 69 (1993).

[4] Foreman,R.G.; "NASA/FLAGRO - FATIGUE CRACK GROWTH COMPUTER PROGRAM," MSC-21669, Jan. 01, 1994.

[5] Forman, Royce G.; Shivakumar, Venkataraman; Newman, James C., Jr.; "Updated Fatigue-Crack-Growth And Fracture-Mechanics Software," NASA Tech Briefs (ISSN 0145-319X); 19; 12; P. 74, Dec.01, 1995.

2.8. Metallic Materials for Launch Vehicles beyond Shuttle

NASA Langley Research Center has been a key player in the development of improved alloys for future space launch vehicles beyond the space shuttle (**Figure 2.8-1**). Research on materials for future launch systems has included work on near-net-shape fabrication of cryogenic tank structures, development of advanced metallic thermal protection systems, and development of high-temperature materials including metal matrix composites and many others that will be discussed in later sections.

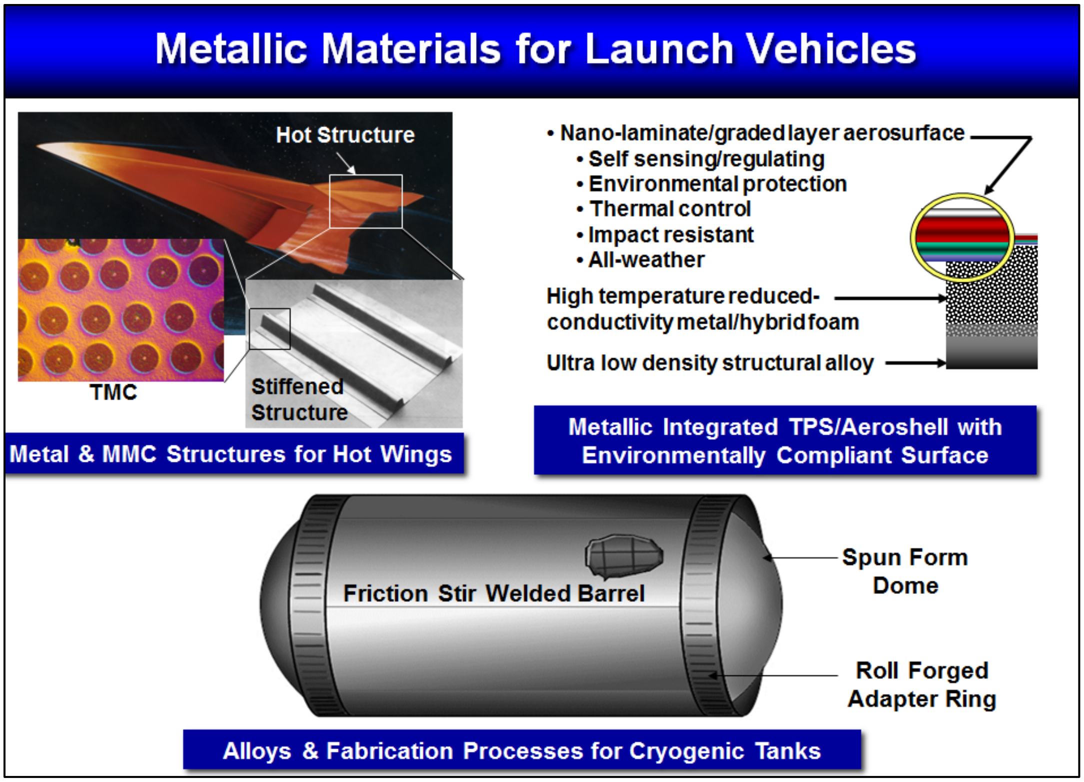


Figure 2.8-1: Metallic Materials for Launch Vehicles.

2.8.1. SLS Contributions: Shell Buckling Knockdown Factors (SBKF)

In 1998, after a challenging four-year development program that kick-started NASA's knowledge about Al-Li alloys, STS-91 flew the first SLWT. This tank had been reengineered to use Al-2195 and Al-2090 extensively, which were stronger and lighter than the Al alloys on LWT (Al-2219, etc.). However, those new alloys were also more brittle and difficult to weld, and experience showed high-maintenance overhead. All of the dome and ogive sections were reverted back to aluminum 2219 over three subsequent revisions first flown on STS-116, -119, and -130 respectively. At the same time, SLWT experience allowed the LH2 orthogrid to be further optimized and lightened from STS-119. NASA also experienced additional problems with Al-Li the 2090 intertank stringers failed during STS-133 tanking and had to be reinforced.

The space launch system (SLS) Program Office decided to move away from the stringer design for its intertank, which carries much higher loads supporting a larger LO2 tank, an upper stage, payload, and PLF all at higher Gs, and with greater aero and bending loads than the ET. The new design will have integrally machined stiffeners instead of riveted sheet metal stringers.

Beginning in 2007 NASA Langley under the direction of Mark Hilburger conducted a study to better define and understand shell buckling of large cylinders. (Hilburger published an excellent paper[1] in 2012 giving a review of relevant past work.) This project has been funded by the SLS Advanced Development Office since Q3 FY12. Launch vehicles need to allow substantial margins to avoid their tanks, intertanks, and interstages buckling during launch. Rules for this were set by experiments in the sixties, but the state-of-the-art in analysis and construction has moved on a long way since then. The engineering team is rewriting the rules for large vehicles via a combination of analysis and experimental verification, leading to a 2011 "can crush" test[2] where they used 1 million lbs of force to buckle an "External-Tank-like Test Article," which was 8.4 m in diameter and 6.1 m tall,[3] (**Figure 2.8-2)**.

Figure 2.8-2: "External-Tank-like Test Article," 8.4 m in diameter and 6.1 m tall, tested at NASA Langley Research Center.

Since early 2012, the Langley team has been working closely with the SLS team on design of the new SLS core.[4] A first draft of their new Shell Buckling Knockdown Factors guidelines has already been produced. Based on the success of the team the SLS Program recently reported a wholesale switch from Al-2195 to Al-2219 on the core. The key technical factor for making the switch away from 2195 Al-Li alloy is its brittleness. The higher ductility of 2219 made it a better choice when trying to beef up the structure for SLS.

Orthogrids or possibly isogrid (as shown in **Figure 2.8-3**) on the tank barrel are machined from flat plates, leaving stiffening ribs that, ideally, are tall (for strength, or more accurately, stiffness), allowing them to be thin (for lightness). However, the ET was already using the thickest plate that could survive being formed to the tank's 8.4 m diameter. Al-2219 is less quench sensitive, so thicker plate can be reliably formed, and the thicker orthogrid actually results in a lighter structure overall.

The Shell Buckling Knockdown Factors (SBKF) project has also been doing preliminary work on a new alloy. AL-2050 adds magnesium for an Al-Mg-Li mix, and "is already used extensively in several commercial aircraft." This promises plates and orthogrids three times thicker than Al-2195 up to six inches with weight savings of as much as 20–30 percent. Research is underway to characterize material properties and structural design optimization for possible future heavy lift cryotanks. The work could lay the foundation for a future upgrade to a "super lightweight tank" for future SLS vehicles.

Figure 2.8-3: Isogrid Structure Machined from Flat Plate of Al-2219.

References

[1] Hilburger, M. W.; "Developing the next generation shell buckling design factors and technologies," 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 23-26 Apr., Honolulu, HI, 2012.

[2] Thornburgh, Robert, P.; and Hilburger, Mark, W.; "Design of the Space Shuttle External-Tank-Derived Test Articles for the Shell Buckling Knockdown Factor Project," NASA/TM-2011-217074, ARL-TR-5485, March 2011

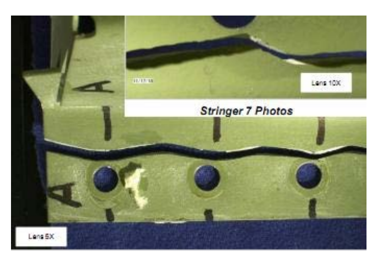
[3] Thornburgh, Robert, P.; and Hilburger, Mark, W.; "Pre-Test Analysis of 45-Percent-Scale Ares-1 Liquid Hydrogen Barrel Test Article," NASA/TM-2011-217073, ARL-TR-5486, March 2011.

[4] Thornburgh, Robert, P.; and Hilburger, Mark, W.; "Design of Orthogrid Cylinder Test Articles for the Shell Buckling Knockdown Factor Assessment," NASA/TM-2010-216866, ARL-TR-5122, November 2010.

2.9. Expert Analyses and Test for NASA Engineering and Safety Center

The NASA Engineering and Safety Center (NESC) was established in 2003 in response to the Space Shuttle *Columbia* accident. The purpose of the NESC was to create an Agency-wide technical resource to provide independent assessment of technical issues for NASA programs and projects. The NESC achieves independence through funding from the Chief Safety and Mission Assurance Office and draws upon the best engineering expertise from across the Agency and from other government agencies, universities, and industry. NESC activities generally consist of Technical Assessments, Technical Inspections, Technical Consultants, and Technical Support.

The NASA Langley Research Center has leveraged its expertise in fracture mechanics, structural analysis and testing, nondestructive evaluation, structural dynamics, and material science to supported NESC activities that involve metallic materials. **Figure 2.9-1** contains selected examples of some of the NESC activities that LaRC has supported in the area of metallic materials.

Fracture Mechanics Assessment of LH2 Feed Line Flow Liners Inspections revealed small cracks growing from slots in the IN 718 liners. LaRC performed structural dynamics analyses to develop a flight rationale, developed an inspection method capable of detecting cracks as small as 0.001 inches, developed an inspection criteria, and lead the assessment team that inspected almost 2000 flowliner slots. The inspection identified about 50 cracks that had been missed by conventional techniques	
Critical Flaw Size Analysis for Ares I-X Upper State Simulator (USS) The Ares I-X was a development flight test vehicle that was designed to obtain performance data for the first stage. The USS was composed of segments that were bolted together through welded flanges. The NESC performed an independent assessment and prediction of the critical crack size. LaRC performed fracture tests on flight production weld material, performed structural analyses to determine stresses in the vicinity of the weld, and predicted the critical flaw size.	
Assessment of the Orbiter Gaseous Hydrogen Flow Control Valve Poppet Cracking A gaseous hydrogen (GH2) flow control valve poppet experienced an uncommanded transition from low- to high-flow position during the assent of STS-126. Post-flight inspection found that a fatigue failure had occurred and a piece of the poppet was liberated, creating a potential for the explosive loss of the vehicle. LaRC provided fractography, fracture mechanics, and NDE inspections support for the NESC assessment. A poppet simulator was developed and fatigue cracks as small as 0.001 inches were nucleated for an NDE probability of detection (POD) study.	
STS-133 External Tank Stringer Cracking Assessment Several cracks were detected in stringers in the intertank region of the space shuttle external tank during the filling of the LH2 and LOX tanks, causing the launch to be scrubbed. The NESC performed an independent root cause investigation. LaRC performed structural analyses to simulate the cryogenic loading of the flanges, performed material characterization tests, and performed high-fidelity microstructural analyses to assess stringer material differences.	

Shell Buckling Knockdown Factor (SBKF) Project
The NESC conducted a program to develop and validate new analysis-based shell buckling design factors for metallic and composite launch vehicle structures. LaRC performed detailed structural analyses, structures and materials trade studies, and supported validation tests on subcomponent structures that included 8-foot-diameter Al-Li orthogrid barrel test articles and 27-foot-diameter orthogrid barrel.

Figure 2.9-1: Examples of LaRC Support to NESC Activities.

Another example of where Langley has played a leadership role was in exploring new processing approaches to fabricating space hardware. **Figure 2.9-2** shows a spin-formed single-piece Al-Li Orion Multi-Purpose Crew Vehicle (MPCV) crew module (CM)-like forward pressure vessel bulkhead. Spin forming the bulkhead can eliminate multipiece fabrication and assembly methods currently used to construct the MPCV CM bulkhead, cone, and barrel regions. The design trade and materials/process studies were conducted at JSC, LaRC, and MSFC to identify the benefits and limitations associated with the one-piece Al-Li bulkhead design. Preliminary results suggest bulkhead spin forming could simplify fabrication, reduce processing cost, and lower system weight, while maintaining or increasing reliability and safety.

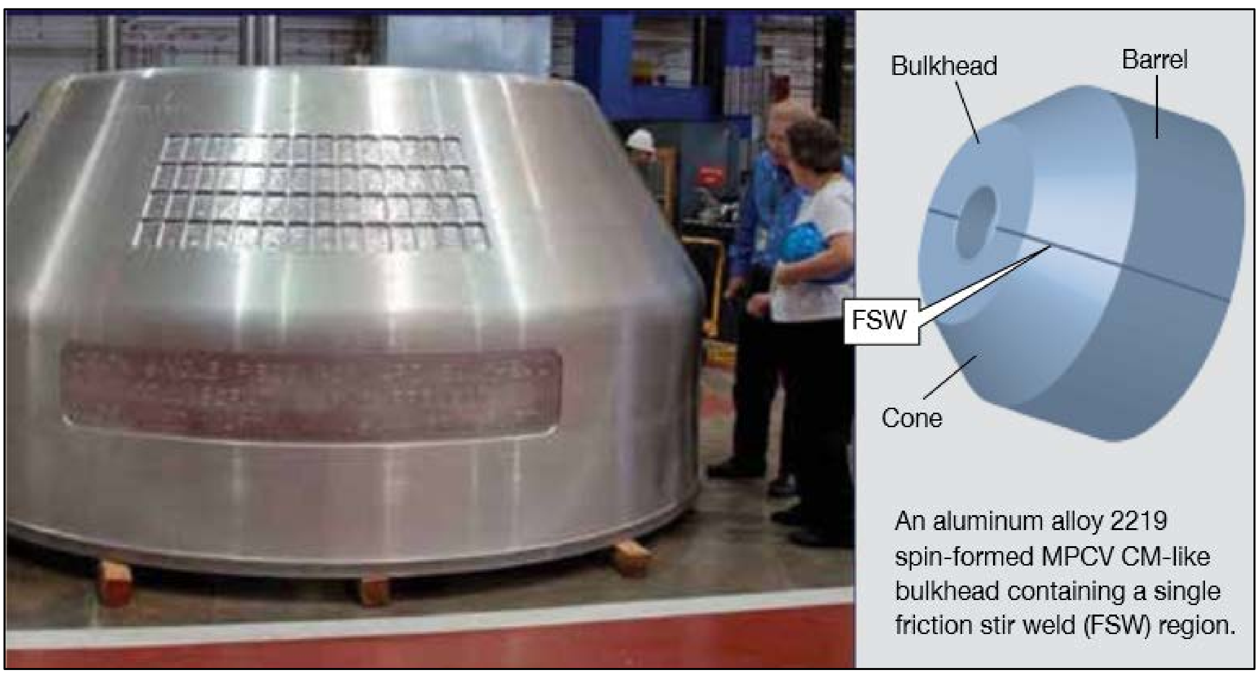


Figure 2.9-2: Spin forming a complex-shaped, single-piece aluminum-lithium Orion multi-purpose crew vehicle crew-module-like forward pressure vessel bulkhead.

2.10. Metallic Materials Failure Analysis

The metals research group at Langley performed more than 200 failure analyses investigations of parts, equipment, test models, and in support of other government agencies over the past several years. These expert analyses were done in response to requests from facility operators if there had occurred either a structural failure in the test equipment or in the test model being examined. Many of these required examination not only of the metallurgical features of the failure surfaces but detailed analyses to establish critical structural loads leading to failure. Repeatedly the individuals conducting these analyses have been praised for the expert work they performed and for shedding light on the factors leading up to the failures and suggestions on corrective action to be taken to prevent similar future failures. In each case detailed failure analyses reports were prepared and delivered to responsible parties and key center management teams. The number of personnel involved in conducting these failure analyses would range in the 20–50 range over the years Langley has been operating. Although the list of names of researchers who have helped perform these studies is too long to include in this section, some are deserving of mention here. They include Bland Stein, W. Barry Lisagor, Thomas T. Bales, John Wagner, Marcia Domack, James Starnes, and Robert Edahl.

2.10.1. Selected Examples

A few examples of the types of failure analyses performed by the metallic materials experts at NASA Langley are presented to illustrate the professional nature of the studies performed generally in support of operating a research center that contains cutting edge major facilities for aeronautics and space research. Records show that well over 200 failure investigations were conducted.

2.10.1.1. NTF Mishap Damages Blades

Analyses performed by: Marcia Domack, Ann C. Van Orden, and William T. Drummond with support from other members of the Metallic Materials Branch.

The National Transonic Facility (NTF) (**Figure 2.10-1**) was completed in 1983. Its test section measures 8 by 25 feet. It was at that time a new kind of wind tunnel capable of accurately testing models of advanced aircraft and spacecraft designs that must fly in the transonic speed range. Gaseous nitrogen or dry air can be used as the tunnel’s test medium. When the tunnel is operated cryogenically with gaseous nitrogen, heat is removed by evaporating liquid nitrogen, which is sprayed into the tunnel circuit upstream of the fan. When air is used for ambient temperature operations, heat is removed by a water-cooled heat exchanger (cooling coil). The NTF was built to research the development and evaluation of aeronautical systems including studies of components, development of aircraft configurations, assessing and then evaluating aerodynamic designs, and performing research and technology studies of fluid mechanics and aeroelasticity.

Figure 2.10-1: National Transonic Tunnel located at NASA Langley Research Center.

At approximately 3 p.m., January 18, 1983 a mishap occurred at the NTF wind tunnel. No personal injury was reported. Upon initial inspection, it was observed that one or more metal parts of the tunnel just upstream of the fan blades came loose during a routine test run and damaged several of the tunnel's 25 fiberglass fan blades. The metal parts were from a thermal barrier assembly surrounding the main drive shaft. At the time of the mishap, the tunnel was running in the "air" mode, without supercold cryogenic nitrogen. Tunnel speed was about Mach 0.7 (approximately 500 mph) and pressure was about 2.5 atmospheres, both well within operating capabilities of the tunnel. The tunnel was being used to test a model of a military aircraft at the time of the incident. (This accident caused $3.2 million in damage to the tunnel and caused an eight-month delay in returning the tunnel to operation.)

A NASA Accident Investigation Board was formed to investigate the mishap and make recommendations on changes to prevent this type of mishap from occurring again. A note was sent to Dr. Darrel R. Tenney, then Chief of the Materials Division, from Dr. Buddy Young requesting technical support from the metals experts in the Metallic Materials Branch and from fatigue and fracture researchers in the Fatigue and Fracture Branch. Marcia Domack was selected for this assignment and led the materials investigations in support of this mishap. The Metallic Materials Branch was asked to provide metallurgical analyses of failed components and also to assist the accident investigation board in identifying suspect components and consult regarding possible failure paths. The failure analyses investigation involved a general survey of the debris and its relative location in the tunnel, identification of critical components for analyses, compositional verification of all hardware from the external thermal barrier assembly, evaluation of metallurgical structure and mechanical properties of suspect components, and evaluation of fracture surfaces with optical and scanning electron microscopy.

Extensive investigation into the failure included chemical analyses of all failed parts, metallurgical examination of failed parts, tensile testing to measure strengths of steel and studies of failure surfaces to identify locations where fatigue had initiated. The cause of the failure was determined to be fatigue and fracture of a 4-foot-diameter stainless steel band, the thickness of sheet metal, which caused the metal retention clamps to break free. The steel band was used to hold insulation in place to shield the main drive shaft of the tunnel from the extreme temperatures of the tunnel. The extreme operating temperatures of the tunnel were a contributing factor in the failure of the stainless steel band. Debris from the failed structures passed through the fan blades causing major damage to all 25 blades and minor damage to other internal tunnel components. All of the blades in the propulsion system were damaged beyond repair and had to be replaced.

It should be noted that as a result of this investigation and additional study it was determined that the main drive shaft did not need to be insulated thus eliminating the need for the steel bands that held the insulation. The tunnel has now operated successfully for many years without any additional failures like this one and is a national asset that is extensively used by NASA and industry.

2.10.1.2. Aircraft Landing Dynamics Facility (ALDF): Corrosion of Valve Body and Nozzle

Analyses performed by: M.S. Domack, Metallic Materials Branch, MD and A.C. Van Orden, Analytical Services and Materials

Figure 2.10-2: Aircraft Landing Dynamics Facility, NASA Langley. Also shown in the photo is Tom Yeager, who became well known for his pioneering work using the facility.

The Aircraft Landing Dynamics Facility (ALDF) successfully operated at NASA Langley for more than 50 years from 1956 until 2015). The major components of the ALDF are the pressurized air and water propulsion system, a 54-ton (49-metric-ton) tubular steel carriage and the arresting gear at the end of the railroad-like tracks the carriage runs along. The "water gun" that propels the carriage is comprised of an L-shaped container that holds 26,000 gallons (98,410 liters) of water, three air tanks pressurized at up to 3150 lbs per square inch (2,214,669 kg/m2) and a high-speed shutter valve that controls the water jet.

Several MMB researchers have evaluated corrosion damage in the ALDF propulsion control valve and L-vessel since our first inspection in 1986. In addition, Professor Glenn E. Stoner from the University of Virginia inspected the system in 1987 and summited a report with his findings and recommendations. The study results by the various examiners were in agreement, and a summary of their findings is presented below.

The L-vessel is SA 516 GR 70 carbon steel and is painted on both the inside and outside. The existing valve body is SA 508 CI-2 standard pressure vessel steel, with a 0.0008–0.0010 inch thick electroless nickel coating. Internal components contained within the valve body include the nozzle (304 SS), safety shutter (17-4PH SS), and armature to rotate the safety shutter (17-4 PH SS). The nozzle is joined to the L-vessel by a stainless weld overlay which forms a smooth joint to facilitate water flow. The valve body is bolted to the L-vessel through a flanged seal ring. The facility is maintained filled with city water and pressurized with air at all times.

Corrosion damage has occurred at several locations within the system, both in the valve body and the L-vessel. Pitting corrosion is observed over the entire inside surface of the valve body, with the most significant damage around the water exit orifice at the location which forms a seal with the safety shutter in the closed position. A greater density of pits occurs near the armature assemblies that rotate the safety shutter.

The pitting was made worse by the nickel coating. Point defects in the coating resulted in more localized damage than if no coating were present.

The pitting corrosion at the valve orifice was accelerated by galvanic and crevice corrosion. The galvanic couples occur between the 304 SS safety shutter and the carbon steel valve body, as well as between the Ni coating and carbon steel due to small defects in the coating. The effect of the crevice formed by contact between the valve body and safety shutter is to generate a more corrosive condition by altering the chemistry of the small volume of water contained within the crevice. The pitting has progressed to an interconnected network that covers the entire circumference of the exit orifice and bridges the seal area, resulting in a breach of the seal. The water leakage has increased as the damage has progressed, but the condition does not limit the operating capacity of the facility.

Additional corrosion damage in the valve included pitting over the entire interior surface. A greater density of pits occurs in patterns around the armature assemblies that rotate the safety shutter. Additional pitting corrosion was observed in the L-vessel, with the most significant occurring at the joint between the L-vessel and the valve body. This joint was smoothed to facilitate laminar water flow by application of a stainless steel weld overlay. The carbon steel L-vessel is painted inside. There is uniform pitting over the surface at local paint defects with enough general corrosion to cause large regions of paint to spall off.

At the time of this failure analyses plans were being made to replace the valve with a 17-4 PH stainless steel valve which was thought to alleviate the galvanic condition and provide better overall corrosion resistance. To minimize costs, the valve was to be machined to the same design. MMB was asked to review the benefit of the selected material and identify issues for further consideration. Domack and Ann Van Orden reviewed the selection and pointed out that stainless steels will suffer crevice corrosion. 17-4 PH stainless steel is susceptible to slow pitting and crevice corrosion in seawater. The extent of damage is probably five times less than for carbon steel in seawater, and the city water supply for the ALDF is low in chloride, suggesting that the corrosion rate for 17-4 in this application should be very small. Van Orden made use of a model developed to predict crevice corrosion in stainless steels, which has been empirically shown to predict the behavior of carbon steel, to assess the benefit of 17-4. The model is able to account for the water chemistry, oxygen level after pressurization with air, as well as some galvanic effects.

2.10.1.3. F-18 Aircraft Mishap

Analyses performed by: M. S. Domack, T. T. Bales, W. B. Lisagor, R. A. Edahl

Metallic Materials Branch, MD, NASA-LaRC

Figure 2.10-3: NASA Armstrong F-18 Mission Support Aircraft.

On October 7, 1988, an F-18 assigned to the Armstrong Flight Research Facility experienced an apparent failure of the leading edge flap system while performing a safety chase mission. The aircraft was in a left bank at an altitude of 17,000 feet and travelling about 350 knots when failure of the left leading edge flap occurred. The pilot brought the plane to a level flight attitude and observed that the inboard surface was deflected upward about 70 degrees. He made contact with the ground control facility and continued to fly the plane for over a minute before ejecting. The plane impacted the ground in a nearly vertical attitude and was totally destroyed. The investigation board recovered nearly all of the significant portion of the wreckage along with the maintenance signal data recorder.

The Metallic Materials Branch was asked to evaluate the failure mode of several parts from observation of the fracture surfaces. The failure analysis investigation involved photographic documentation of the failed components, verification of material hardness to estimate strength levels and evaluation of the fracture surfaces with optical and scanning electron microscopy. Fortunately, the left flap actuator system was not compromised by the post-crash fire, and the fracture surfaces were sufficiently preserved to facilitate fractographic analysis.

The leading edge flap actuation system consists of mechanical transmissions driven by a hydraulic drive unit through rotating torque shafts. The aircraft has a single hydraulic drive unit to symmetrically operate the transmissions on both sides of the aircraft. The hydraulic drive unit includes a brake that is activated upon loss of hydraulic pressure. Asymmetry sensors and control brakes are installed on the outboard transmission. The sensor monitors flap rotation rate and will lock the brake if the rate exceeds 58 degrees per second. The maximum rate during normal operation is 18 degrees per second. If a shaft breaks, the system outboard of the break will rotate rapidly due to aerodynamic loading and will be stopped when the brake locks. If a yielding type failure occurs, the brake will lock when the asymmetry sensor detects a difference between the inboard and outboard surfaces exceeding 3 degrees. Torque limiters, located on the inboard transmission, will lock the flaps in the event of excess torque in the shaft connecting the inboard and outboard transmissions. Overtravel stop modules are installed on the torque limiters to limit the flap deflection to 1 degree beyond the maximum range, which can be commanded by the flight control computers.

The left inboard transmission ring gears were fractured into several pieces which were inspected to determine the mode of separation. The gears are forged from HP-9-4-30, which is a 9% Ni, 4% Co, and 0.3% C steel with high strength and toughness. All fractures were the result of overload and probably occurred on impact. One suspect fracture surface, examined in the scanning electron microscope (SEM), revealed features typical of ductile overload fracture over the entire surface (**Figure 2.10-4)**.

Figure 2.10-4: Typical Fracture Surface of Transmission Ring Gear.

The right inboard transmission was also recovered from the crash site and was damaged but still assembled, although it had been burned in the post-crash fire. The ring gears coupling the transmission to the wing were intact, but those coupling the transmission to the flap were fractured. Fracture surfaces were cleaned and examined to attempt to determine the direction of separation of the flap, i.e., upward or downward with respect to the wing. The location of shear lips on the fracture surfaces indicate that the flap separated from the aircraft in an upward direction over the top of the wing.

Fracture surfaces from several components from the drive system were evaluated, including rotating drive shafts, torque tubes, and drive gears. These included the torque tube, which transmits torque from the hydraulic drive unit to the angle drive unit, and the spur gear, which transmits torque into the transmission from the torque shaft. This shaft is driven by the angle drive unit and terminates with the spur gear at the torque limiter. The coupling tube from the output side of the torque limiter to the stop module was also evaluated. No evidence of fatigue was found in any of the drive system components.

The spline end of the torque tube showed extensive spline wear with fracture of the tube end. Hardness of the 4130 tube was Rc 33.8, which indicates material ultimate strength of nearly 170 ksi, and was measured on the inside of the tube and corrected for surface curvature. Metallurgical sections prepared through both the worn and intact splines revealed the splines were not case hardened, which is allowed for this part but might result in greater wear than case hardened splines.

The failed coupling tube exhibited very little macroscopic plastic deformation, and the fracture surface was nearly flat. Much of the surface was mechanically damaged, but the visible microscopic features indicated the tube failed in a ductile manner, with shear dimples indicative of shear or torsional loading. A metallurgical section of the tube revealed an abundance of stringer particles, but was not excessive for 4340 steel of this quality. Hardness measurements of Rc 39 indicated material ultimate strength to be approximately 195 ksi. Traces of the stringer particles being pulled out during fracture and marks in the mechanically damaged areas follow a roughly circumferential pattern, suggesting a torsional loading mode. The center of rotation of these features is off center from the axis of the tube. The elongated appearance of the ductile dimples observed at high magnification suggests loading in shear, but may also be the result of torsional loading. The mechanical damage on the fracture surface appeared to be due to repeated contact between the fracture surfaces rather than by a single contact, indicating the part failed before impact. It is difficult to explain failure of the tube by purely shear or torsional loading due to the small amount of plastic deformation in the tube body, however the ductile fracture surface features exclude failure by a brittle mode. No evidence of fatigue cracking was observed on the undamaged fracture surface, nor was there any evidence to indicate that fatigue damage has been masked by the regions of mechanical damage. Conducting laboratory tests to simulate failure in torsion and in shear would demonstrate the expected tube fracture surface morphology associated with these modes of failure and would indicate the amount of plastic deformation which might be expected in the tube body. No evidence of material irregularities or preexisting defects was found which would compromise the tube and permit failure at loads below that which should be transmitted by the torque limiter. A functional check of the torque limiter indicated the unit operated properly when torque was applied at the service rate, but failed to limit when torque was rapidly applied.

The right side coupling tube failed in tensile overload, probably on impact, and exhibited the characteristic cup and cone shaped fracture surface. SEM evaluation of the surface revealed ductile dimples usually associated with tensile overload fracture.

The spur gear was separated from both the solid torque shaft and the hollow drive shaft. The spur gear is a 4340, case hardened part. The fracture surface from separation of the spur gear from the torque shaft exhibited a distinct case hardened layer, a large region of ductile tearing, and a large shear lip. Chevron marks seen in the case hardened layer clearly identified the fracture initiation site. SEM evaluation of the fracture surface revealed no evidence of fatigue loading and indicated ductile overload to be the failure mode. The large shear lip occurs opposite from the initiation site, and is an indication that the overload likely occurred in bending. The fracture surface from separation of the spur gear from the hollow drive shaft exhibited a cone shape typical of tensile overload failure. SEM examination found only ductile dimple morphology, confirming the tensile failure mode.

Several components from the left side flap actuation system were evaluated to determine the mode of failure of each, and in some cases were compared with failures from the right side system. The failure mode of the ring gears, the torque tube, spur gear, and torque limiter-stop module coupling tube are summarized:

1. All fractures of the ring gears were by tensile overload, and probably occurred on impact. No evidence of fatigue damage was found on any of the fracture surfaces.
2. The torque tube failure was likely due to stripping of the splines and subsequent fracture of the tube by motion of the drive gear. Hardness measurements indicated adequate material strength. Measurements of the amount of spline wear were not made.
3. The torque limiter-stop module coupling tube failure mode is not well defined, but it is apparent from the regions of mechanical damage that the failure occurred prior to impact. It is likely the tube failed by ductile overload under very complex loading conditions. Fracture surface features indicate the tube failed in a ductile manner, probably in shear or torsion. The tube body, however, exhibits almost no macroscopic plastic deformation, which would be expected for pure shear or torsional loading. No evidence of fatigue or other preexisting damage was observed, and hardness measurements indicated adequate material strength.
4. The spur gear fractured from the torque shaft by bending overload and from the hollow shaft by tensile overload, and both fractures probably occurred on impact.

2.10.1.4. Naval Weapons Station: Cracking of Tail Cone Sections of Rockeye Missile

Analyses performed by: John Wagner, Thomas T. Bales and Robert A. Edahl

The metallic materials branch at NASA Langley Research Center not only did failure analyses for NASA, but also supported other government agencies. An example is the work that Langley did for the Naval Weapons Station located near Langley on the Virginia Peninsula.

On September 11, 1987, John A. Wagner was contacted by Junilla Applin from the Naval Weapons Station and requested to examine two cracked tail cone sections from MK20 MOD7 Rockeye Missiles (**Figure 2.10-5**). This missile is an air-to-ground weapon which was/is part of the armament of F-18 aircraft. Mr. Wagner was asked to conduct an analysis to determine factors contributing to the cracking. John Wagner led the investigation and was assisted by Tom T. Bales and Robert A. Edahl.

Two cast aluminum tail cone sections (Alloy 356), two parts each, were submitted to the Metal1ic Materials Branch for analysis. Each tail cone section exhibited cracks which had propagated through the thickness of the part in the region of a fastener boss, illustrated in **Figure 2.10-6**. Dye penetrant had been applied to the cracked regions at the Naval Weapons Station to assess the severity of cracking.

Figure 2.10-5: Rockeye II Mark 20 Photo from U.S. Navy Museum of Armament & Technology.

Figure 2.10-6: Region of a Fastener Boss Exhibiting Cracking.

One tail cone was sectioned at NASA to facilitate further metallurgical examination. Analysis of the cracked surface was conducted using optical microscopy and scanning electron microscopy with associated energy dispersive X-ray analysis (EDAX). The microstructure of the 356 aluminum alloy in the vicinity of the crack was dendritic with constituent particles rich in iron and silicon and is typical for cast aluminum. However, extensive regions of crack-like voids were also found in the microstructure.

Optical and fractographic analysis of the exposed crack surfaces revealed a layer of oxidized material in the crack and a mechanically damaged region adjacent to the crack. Windowless EDAX of the cracked surface showed a high concentration of oxygen.

The cracking in the fastener boss region was most likely due to a combination of shrinkage and hot tearing. The section thickness where the cracks appeared was much greater than adjoining sections and, therefore, probably cooled at a slower rate than the remaining part. Such a scenario could lead to a structure characterized by localized shrinkage cavitation if not adequately considered in design of the mold for casting. When applied loads are of sufficient magnitude, stress concentration associated with these cavities could lead to part failure. The morphology of the cracked surface suggested the possibility of hot tearing. Hot tearing occurs at discontinuities when tensile stresses, which arise during cooling, are large enough to cause cracking. The fracture surface was typical of a hot tearing fracture exhibiting an oxidized surface and dendritic pattern.

Also numerous internal defects in the wall of the tail cone were apparent on sectioning of the parts. Further examination of this region using nondestructive X-ray analysis revealed a large population of casting defects some of which had diameters greater than half the wall thickness. These defects would appear to be related to shrinkage due to improper mold design or poor casting practice. However, without detailed information on this procedure a single mechanism responsible for defect formation cannot be identified.

Although specifications were not reviewed with respect to acceptance or rejection, it would appear that the size and number of observed defects would not be allowable. Review of the specifications and procurement procedures is recommended to determine if the observed defects form the basis for acceptance or rejection.

This failure analysis was done nearly 30 years ago and, a search of the literature[1] reveals that more than 28,000 Rockeye missiles were used in the IRAQ War which would suggest that production issues such as those uncovered in this study were corrected.

References

[1] http://www.chinalakemuseum.org/exhibits/rockeye.shtml.

2.11. Common Success Factors

In reviewing and analyzing the success stories from past work at Langley related to metallic materials, some common elements were evident and are noted in **Figure 2.11-1**. In all cases there emerged a champion for the work that recognized the opportunity and formulated a plan to solve the issue. These were generally the technical engineers that were doing experimental and analytical research. In particular, they were technical experts in the discipline areas. The technical skills and facilities required to solve the problem were available in-house at Langley. Because Langley had a base R&D program the engineers were able to do pre-work to validate their proposed solution (no half-baked ideas) before promoting their proposal to line management or to headquarters. Another critical factor was that researchers were given the opportunity to interface directly with the person(s) who owned the problem. Another key was the direct interaction with system level designers responsible for the hardware designs. Even for highly visible agency level issues, the technical experts make the technical presentations on their ideas and the results of their investigations. The program plan was developed to the point of scoping the resources required to do the work including personnel and facilities. All the successful projects had another key attribute of keeping line management fully informed on their work.

Common Success Factors

1. Opportunity Identified
2. Technical Excellence Established in Past R&D
3. Critical Skills and Facilities Available – In-House (Best)
4. Champion Motivated to Lead
5. Sufficient Pre-work to Validate Proposed Solution to Problem
6. Opportunity to Directly Interface With Person(s) Who Own the Problem
7. Interface With Designers who Need a Solution
8. Technical Expert Makes the Presentation of Proposed Work
9. Program Plan Developed to the Point of Scoping the Level of Effort Required
10. Keep Line Management Informed (No Lone Ranger)

Figure 2.11-1: Common Success Factors of the Metals R&D Projects.

3. LANGLEY'S ENGAGEMENT IN METALLIC MATERIALS RESEARCH: THE EARLY YEARS

3.1. The Metal-Skinned Aircraft

The transition from the wood-and-fabric airplane to the all-metal airplane was essentially complete by World War II. The late 1920s and early 1930s are said to have witnessed a structural revolution in aeronautics with the appearance of streamlined metal aircraft with such features as tightly cowled multiple engines, variable-pitch propellers, retracting landing gear, and stressed-skin aluminum construction. The reader is referred to an interesting article published by Peter L. Jakeb[1] on the transition from wood to metal.

Figure 3.1-1: The Junkers J.L. 6 represents an important step forward in technology. It was probably the first plane with the fuselage, wings, and skin all constructed of metal.

Junkers' work on Reissner's *Ente* design convinced him to use metal as the main structural material, but since the apparently "ideal" metal alloy for aircraft construction, duralumin, had only been invented some six years earlier in Germany, and was initially prone to flaking and other undesirable characteristic flaws when worked in sheet metal form, Junkers had to use sheets of heavier electrical steel instead for his first all-metal aircraft designs, similar to the types of ferrous sheet metals used in laminated-core AC electrical transformers.

The Junkers firm got its first aircraft construction contract in July 1915 from the German government to produce an example of a two-seat all-metal aircraft that would be capable of a 130 km/h (81mph) top speed, wing loading of 50 kg/m² (10.2 lb/ft²), and use a 75 kW (100 hp) engine for power. Junkers engineers Otto Mader, head of Junkers' *Forschungsanstalt*, and Hans Steudel, director of Junkers' structural materials and testing department, started the work on the design of what would become the Junkers J 1 in September of that year, and by November 1915 the completed J 1 was ready for her first attempts at flight testing.

Duralumin (also called duraluminum, or dural) is the trade name of one of the earliest types of age-hardenable aluminum alloys. The main alloying constituents are copper, manganese, and magnesium. A commonly used modern equivalent of this alloy type is AA2024, which contains 4.4% copper, 1.5% magnesium, 0.6% manganese, and 93.5% aluminum by weight. Typical yield strength is 450 MPa (65 ksi), with variations depending on the composition and temper.[2]

Figure 3.1-2:The Junkers J.L. 6 was probably the earliest all-metal plane, built in Germany in 1919 as the F 13 and imported to the United States by John Larsen to be used as a mail plane.

Most of the 170,000 airplanes built during World War I were constructed of wooden frames with fabric coverings. These materials were relatively lightweight and available. Anthony Fokker, a Dutch entrepreneur working in Germany during the war, developed a welded-tube steel fuselage to take the place of wood. German manufacturers built more than 1000 of these aircraft, which had wooden wings. After the war, Junkers developed several all-metal passenger transports.

In the spring of 1920, the American pilot John M. Larsen began demonstrating an imported Junkers all-metal passenger plane designated the JL-6, shown in **Figure 3.1-1** and **Figure** 3.1-2. It created much excitement within the American aviation community. The U.S. Postal Service bought six of the aircraft. The enthusiasm over the JL-6 caused many aviation leaders to call for the development of all-metal aircraft. NACA declared in its 1920 *Annual Report* that metal was superior to wood because "metal does not splinter, is more homogeneous, and the properties of the material are much better known and can be relied upon. Metal also can be produced in large quantities, and it is felt that in the future all large airplanes must necessarily be constructed of metal.” NACA immediately began research into all-metal construction, and the U.S. Navy developed duralumin fabrication techniques at the Naval Aircraft Factory. In 1924, the first all-metal commercial airplane, called the Pullman, was produced by William Stout. Glenn Martin Aircraft also developed all-metal aircraft for the U.S. Navy in 1923–1924, where the only wooden structure was the engine mount.

Airplane designers also felt that metal offered other significant advantages over wood, including protection from fire, but in reality, early aircraft metals provided little protection against airplane fires. In fact, despite the enthusiasm over the JL-6, the aircraft had a faulty fuel system causing it to catch fire in flight, and the thin aluminum skin between the engine and cockpit melted, allowing flames to burst through at the pilots’ feet. Two airplanes were lost within months, and the Post Office quickly sold the remaining four at a huge loss.

Despite the initial great enthusiasm over all-metal construction within the U.S. aviation community and the widespread belief among designers in the superiority of metal in the early 1920s, engineers soon found that metal was not inherently superior at the time. Wood was still lightweight and easy to work with. Over the next decade, aeronautical engineers had a difficult time designing metal wings and airframes that weighed as little as wood.

In late 1920, the Army Air Service contracted with the Gallaudet Aircraft Company for a monoplane bomber with an all-metal fuselage and metal framework wings. The prototype, designated the DB-1 and delivered in late 1921, was grossly overweight and considered a miserable failure. It was quickly retired. By 1929, nine years after the JL-6 had created so much excitement about all-metal airplanes, an aeronautical textbook estimated that metal wings still weighed 25% to 36% more than wood wings. By 1930, a decade after NACA declared metal superior to wood, only 5% of the aircraft in production were of all-metal construction.

One of the big problems with metal was that it buckled when compressed, just like a piece of paper will bend when its ends are pushed together. In comparison, wood does not buckle as easily. By the 1930s, another aircraft design trend known as stressed-skin structures made this problem more acute. Before this time, aircraft achieved much of their structural strength through their internal frameworks. But in a stressed-skin structure, the covering contributed much of the structure’s strength and the internal framework is reduced. This provided a streamlined external surface for the airplane, but made metal buckling failures more likely.

In order to combat the problems of compressive buckling, metal structures had to be complex, with curves and riveting and reinforcement. This dramatically increased the costs of such an aircraft. By 1929, some manufacturers were making metal wings that were as light as wooden ones, but by the end of the 1930s, all-metal airplanes were significantly more expensive than wood and fabric airplanes.

Metal also presumably was more durable than wood, which warped, splintered, and was eaten by termites. But duralumin also had severe corrosion problems. It turned brittle. Unlike iron or steel, which rusted from the outside in, duralumin weakened internally and could fail suddenly in flight. Duralumin corroded even more in salt spray and the U.S. Navy eagerly sought a solution. The Aluminum Company of America (Alcoa) and the Federal government cooperated to develop a material known as Alclad, which consisted of an aluminum alloy bonded to pure aluminum. Alclad solved many of the corrosion problems of duralumin. Soon other alloys were developed that proved effective as well and during the 1930s, all-metal airplanes became much more common.

By the mid-1930s, wood was no longer used on American multi-engine passenger aircraft and U.S. combat aircraft. But in 1938, the British airplane company, de Havilland, began work on a fast, unarmed bomber named the Mosquito. It was one of the most successful British aircraft of World War II, able to fly faster and higher than most other aircraft. More than 7700 Mosquitoes were built. They were made of spruce, birch plywood, and balsa-wood, proving that even in the era of all-metal planes, older materials could still achieve impressive results.

The lesson of the development of all-metal airplanes is that just because engineers may think that a new material is superior that does not mean that it will be immediately useful. It may take many years before designers and materials specialists are able to adapt a new material to a new task.

Additional information on the historical development of all metal aircraft can be found in an excellent book authored by Peter Brooks.[3] Additional details on NASA's role in development of all metal airframes can be found in NACA Technical note[4] by Unger and Schmidt and a NASA Technical Memorandum[5] by Warner. Membership of the National Advisory Committee for Aeronautics in 1938 directing NACA Research can be found in Government archives.[6]

References

[1] Jakab, Peter L.; "Wood to Metal: The Structural Origins of the Modern Airplane," JOURNAL OF AIRCRAFT Vol. 36, No. 6, November–December 1999.

[2] http://www.centennialofflight.gov/essay/Evolution_of_Technology/metal_plane/Tech15.htm

[3] Brooks, Peter W.; "The Modern Airliner: Its Origins and Development. London," Putnam, 1961.

Schatzberg, Eric; "Ideology and Technical Choice: The Decline of the Wooden Airplane in the United States, 1920-1945". Technology and Culture, January 1994, 34-69.

[4] Unger, E. and Schmidt, E. "Duralumin," NACA Technical Note 8, July 1920. http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19930080804_1993080804.pdf

[5] Warner, Edward P.; "Metal Construction of Aircraft," NACA Technical Memorandum 153. November 1922. http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19930083158_1993083158.pdf

[6] http://www.archive.org/details/GPN-2000-001554

3.2. Aluminum Alloys

For 60 years, aluminum alloys[1] have been the primary materials for airframes. No other single material has played as major a role in aircraft production as aluminum, specifically, the 2000 and 7000 series ingot alloys in various heat treatments.

Starting in 1917 Alcoa produced a 2000 series alloy 17S which contained the same alloying elements as the newer 24S (Al-Cu-Mg-Mn) alloy formulated with different proportions of the alloying elements for higher strength, which has been the principle aluminum alloy since 1945. The 17S was Alcoa's version of Duralumin patented by Alfred Wilm in Germany in 1908.Wilm's Dural aluminum alloy was used for the Zeppelin structure in 1911. Alcoa's 17S was used in construction of the U.S. Navy airship Shenandoah, which first flew in 1923. This alloy began the U.S. stressed metal skin semimonocoque structure revolution.

Other countries were also quick to adopt Duralumin monocoque fuselage construction. In England, the Short Brothers Company built the metal Silver Streak biplane in 1919, which was all Duralumin except for the wing spars, which were steel. The wing consisted of round steel tube spars and Duralumin ribs, with right angle flanges, to which riveted Duralumin covers were joined.

Over the many years of utilizing aluminum materials, several important lessons have been learned.[2] In 1954, the Boeing 367-80 became America's first jet transport prototype. The KC-135 was a derivative of the Boeing 367-80 (Dash 80), as was the 707, but the lower wing skin of theKC-135 was initially 7178-T6 Al. A small critical crack length for this material, at the KC-135 wing limit load level, led to cases of in-service rapid fracture. The concern about loss of an aircraft from degradation of fail safety from widespread fatigue cracking motivated the U.S. Air Force to make a costly modification. The lower wing skins were replaced with 2024-T3 aluminum.

In 1982, 14 years of service experience with the C-5A resulted in greater emphasis being placed on fracture toughness, corrosion resistance, and durability in selecting materials for the C-5B: 7075-T6 fuselage skin and cargo door skins were changed to 7475-T761 where corrosion was a problem. The wing plank material was changed from 7075-T6 to 7175-T73 for increased toughness. Predictions as early as 1985 were that, "lithium-containing aluminum alloys (Al-Li) would find significant use in both military and civil aircraft," and that the "ultimate level of utilization of carbon fiber reinforced polymer matrix composites may be somewhat less than predicted, in view of the potential of Al-Li alloys." By the early 1990s, however, the realization set in that Al-Li was not ready to be a wide-scale direct substitute for conventional aluminum aerospace alloys, although it was being used in some production airframe applications in the United States and Europe. At present, it is the high-strength aluminum alloys such as 7150 and 7055 with increased compression strength and balanced fracture toughness and corrosion resistance that are enabling aluminum to maintain its high level of use in the aerospace industry.

Today Al alloys still play a critical role in the modern aircraft. The many different uses of metals in modern aircraft are illustrated in **Figure 3.2-1**. This chart was taken from an Alcoa Aerospace briefing[3] given in June 2011. Even in "an all-composites" aircraft nearly half the structure is metallic. The Boeing 787 uses Al-Li plate for multiple applications, Al-li extruded floor structure is found on the Airbus A380, and Al-Li extruded floor structure has been selected for the Airbus A350 (EIS 2015). Aluminum continues to be a material of choice for the new Bombardier CSeries aircraft and the Mitsubishi Regional Jet, which was initially designed with a composite wing, but was redesigned in Sept. 2009 with an aluminum wing. And the AVIC ARJ-21 aircraft makes extensive use of aluminum in the airframe. Gerson Lehrman Group Inc. concludes that new aluminum-lithium alloys will be "the material of choice over composites" for narrow-body airliners, citing aluminum's damage tolerance, manufacturability and recyclability."

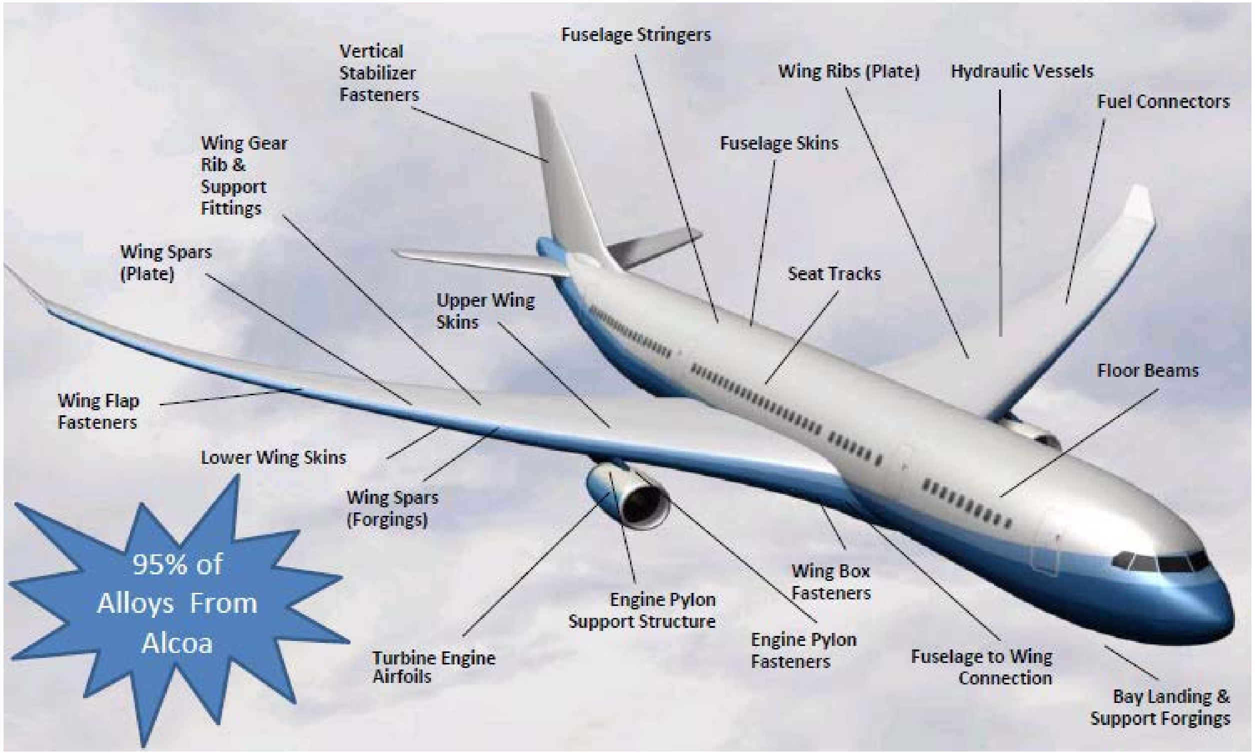


Figure 3.2-1 Light alloys are found in modern aircraft from nose to tail. http://www.alcoa.com/aerospace/en/pdf/Alcoa_Aerospace_Briefing_June92011.pdf.

References

[1] D. Paul, L. Kelly, V. Venkayya, and Thomas Hess; "Evolution of U.S. Military Aircraft Structures Technology", Journal of Aircraft Vol. 39, No. 1, January–February 2002.
[2] Lincoln, J.; "Life Management Approach for USAF Aircraft," AGARD CP 506-Structures and Materials Panel, Fatigue Management Conf., Bath, U.K., Dec. 1991, pp. 17–2.
[3] http://www.alcoa.com/aerospace/en/pdf/Alcoa_Aerospace_Briefing_June92011.pdf

3.3. Titanium Alloys

The history and early use of titanium was driven by the aerospace industry. The first major structural application of titanium was the Douglas X-3 that utilized 629 lbs of Rem-Cru, Inc., titanium. This was a commercially pure material used for the aft fuselage boom and stabilator portions of the aircraft. One of the first airframe production applications was the F-86 Sabre Jet. This aircraft, which flew as the XP-86 in 1947, employed 600 lbs of titanium in the aft fuselage and engine areas.

The annealed alpha–beta alloy Ti 6Al-4V has been the workhorse of the industry. This alloy has been utilized on aircraft from the B-52 to the F-22. This specific alloy composition was first melted and evaluated in 1953, at IIT Research Institute, under a U.S. Air Force contract.[1] The Mallory Sharon Titanium Corporation version of this alloy (MST 6Al-4V) was selected shortly thereafter (1954) for use in Pratt and Whitney's J-57 turbojet engine (disks, blades, and other parts) for the B-52. The first commercial production of titanium began in 1946. Titanium was pushed into commercial production as a structural material, in unprecedented time by the combined efforts of industry and Government to meet military requirements.

In 1956, 90% of the titanium market was for military aircraft production. By 1980, less than 20% of aerospace grade was used for military aircraft. The majority of titanium sponge is processed into titanium dioxide pigment for use as filler in paint, paper, plastics, and rubber. The use of titanium has been increasing, at the expense of both aluminum and composites, and will continue to increase in more unitized assemblies facilitated by combined superplastic forming / diffusion-bonding welding and casting.

The most famous U.S. titanium airplane, the YF-12A/SR-71, first flew as the A-12 in 1962 and was fabricated from primarily beta-120 VCA alloy (Ti-13V-11Cr-3Al). Selected highlights of NASA work on Ti alloy structural panels will be discussed in a later section. NACA and NASA conducted extensive research on titanium fabrication technology for aircraft and space launch vehicles. Several different structural concepts were fabricated using competing processes in an effort to improve structural efficiency. Panels were flight tested on the YF-12 aircraft for validation of the fabrication technology developed.

The most widely used Ti alloy isTi-6Al-4V. This alloy is particularly amenable to fabrication by superplastic-forming/diffusion-bonding (SPF/DB) processes and, therefore, was the subject of a systematic well-planned research and development (R&D) thrust by the U.S. Air Force, the U.S. Navy, and NASA over a 20-year period from 1965 to 1985. The use of SPF/DB titanium for the aft fuselage of the F-15E resulted in 726 fewer components and 10,000 fewer fasteners and achieved 15% weight savings over the C/D models.[2] Large forgings and castings have facilitated the creation of one-piece substructures. The aft-fuselage frame for the F-22 is a Ti-6Al-4V forging The F-22 wing carry-through bulkhead is fabricated from the largest titanium forging, by surface area, to date (96 ft^2, 6560 lbs). Four bulkheads in the mid-fuselage are made of titanium. The forward and aft boom structures on either side of the aircraft's empennage section are formed from integrally stiffened titanium isogrid panels that are electron beam welded to forged titanium frames. The wings attach fittings and rudder actuator supports are hot isostatically pressed (HIP) titanium castings. The A-6E composite wing rear spar is a 27-foot titanium forging, and large one-piece titanium bulkhead forgings are employed by the F/A-18 E/F aircraft.[1]

Recently, RMI Titanium of Ohio developed a stronger, more damage-tolerant alloy (Ti-6-22-22S) that is finding application on the F-22 joint strike fighter and X-33 reusable launch vehicle.

Timet Corporation alloy 10–2–3 is being used in the main landing gear and Timetal 21S (Ti-15Mo-3Nb-3Al-0.2Si, ASTM Grade 21) for the nacelle cowl, plug nozzle, and Pratt and Whitney Aircraft engine components of the Boeing 777 aircraft. Titanium usage on Boeing aircraft has increased from 2% empty weight of the 737 to 8% of the 777. The McDonnell Douglas C-17 transport also utilizes alloy 10–2–3 for landing gear components. Titanium has grown in use partly because of its compatibility with composites both from a thermal expansion characteristic and resistance to galvanic corrosion when in contact with carbon epoxy.

The focus of titanium alloy development, however, has shifted from aerospace to industrial applications. New product forms are emerging rapidly. Titanium is growing in use for everything from golf clubs, skis, tennis rackets, bicycles, pots and pans, and jewelry to even hip and knee replacements.

References

[1] Crossly, F.; "Aircraft Applications of Titanium: A Review of the Past and Potential for the Future," AIAA Paper 81-0893, May 1981.
[2] Tuegel, E., Pruitt, M., and Hefti, L.; "SPF/DB Takes Off," Advanced Materials and Processes, Vol. 136, July 1989, p. 37.

3.4. NACA Airplane Testing

Wind tunnel testing of airfoils[1] and airplanes was a major thrust of NACA. The history of NACA aerodynamics has been documented in several publications and will not be covered in this monograph, but airfoil research was a major focus.[2] A specific example of this focus is the fact that in Technical Report No. 460[3] "The Characteristics of 78 Related Airfoil Sections from Tests in the Variable-Density Wind Tunnel" issued in 1933 NACA engineers tested 78 airfoil shapes in its wind tunnel. The authors of this report described a four-digit scheme that defined and classified the shape of the airfoil. The testing data gave aircraft manufacturers a wide selection of airfoils from which to choose. The information in this report eventually found its way into the designs of many U.S. aircraft of the time, including a number of important World War II-era aircraft.

The Langley laboratory continued to design new wind tunnels that added to its capabilities, building about a dozen tunnels by 1958. In 1928, the first refrigerated wind tunnel for research on prevention of icing of wings and propellers began operations. In 1939, NACA constructed a new low-turbulence two-dimensional wind tunnel that was exclusively dedicated to airfoil testing. A transonic tunnel in the early 1950s provided data for Richard Whitcomb's research into supersonic flight.

In December 1951, Richard T. Whitcomb[4] verified his "area rule" in NACA's new transonic wind tunnel. Useful in the design of delta-wing planes flying in the transonic or supersonic range, the rule stated that, to reduce drag, the cross-sectional area of the aircraft should be consistent from the front of the plane to the back. The resulting "Coke bottle" or "wasp waist" fuselage shape was contrary to the design customary at that time that had the cross-section much greater where the wings were attached to the fuselage. Designers quickly applied the supersonic area rule to the design of new supersonic aircraft.

NACA was also considering flight beyond the atmosphere. In 1952, the laboratories began studying problems likely to be encountered in space. In May 1954, NACA came out in favor of a piloted research vehicle and proposed to the Air Force the development of such a vehicle. NACA also studied the problems of flight[5] in the upper atmosphere and at hypersonic speeds,[6] which would lead to the development of the rocket-propelled X-15 research airplane (**Figure 3.4-1**).

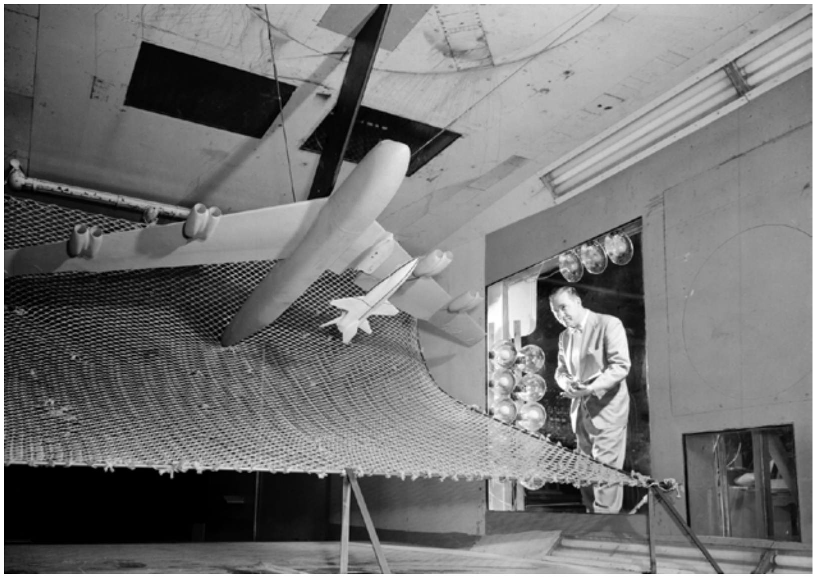


Figure 3.4-1: A one-twentieth scale model of the X-15, originally suspended beneath the wing of a B-52 was tested in the Langley High-Speed 7 × 10 Foot Tunnel, Around 1957. http://www.archive.org/details/GPN-2000-001882.

References

[1] The development of aerofoils and aerofoil technology www.century-of flight.net/Aviation%20history/.../Airfoils.htm. http://crgis.ndc.nasa.gov/crgis/images/2/2f/Century_in_Flight_-_Airfoils.pdf

[2] Ronald, Alex.; Model Research: The National Advisory Committee for Aeronautics, 1915-1958. NASA SP-4103. Washington, D.C.: U.S. Government Printing Office, 1985.

[3] The creation of NACA - Century of Flight; www.century-of flight.net/Aviation%20history/.../NACA.htm, http://science.ksc.nasa.gov/shuttle/nexgen/Nexgen_Downloads/FirstCenturyofFlight.pdf

[4] The Whitcomb Area Rule; NACA Aerodynamics Research ...history.nasa.gov/SP 4219/Chapter5.html

[5] Pattillo, Donald; "Pushing the Envelope", Ann Arbor, Mich.: The University of Michigan Press, 1998.

[6] Gorn, Michael H.; "Expanding the Envelope: Flight Research at NACA and NASA", Lexington: University Press of Kentucky, 2001.

3.5. First NACA-Dedicated Structures and Materials Research Laboratory (B-1148)

The history of Langley Research center has been documented in a number of excellent reports[1] which contain interesting photos and references[2] to early NACA reports[3] and briefings. Perhaps the first facility in which structures and materials work was done at Langley[4] was the patternmakers shop shown in **Figure 3.5-1**. Wood was being shaped in aircraft models for testing in the wind tunnels. It was not until 1940 that a major facility was built on the west side of Langley Airfield. Ground breaking for this facility is shown in **Figure 3.5-2**. A photo of the completed structures and materials research laboratory is shown in **Figure 3.5-3**. An adjacent model shop was built to support the facility and take some of the work burden the East Area Model Shop was carrying. This second building in the West Area became known as the West Area Model Shop.

Figure 3.5-1: Workmen in the Patternmakers' Shop manufacture a wing skeleton for a Thomas-Morse MB-3 Airplane for pressure distribution studies in flight, June 1922.[5]

Figure 3.5-2: Clearing for Structures and Materials Research Facility Building 1148; October 27, 1939.

Figure 3.5-3: Completed Structures and Materials Research Facility Building 1148; 1940.

The structures and materials research laboratory was equipped with specialized equipment uniquely designed for testing built-up structural panels where very high stresses were required to study the ultimate load carrying ability of aircraft structures. One such piece of equipment was the "million pound" loading machine shown in **Figure 3.5-4**. This machine is still in use today (2016) for structures testing.

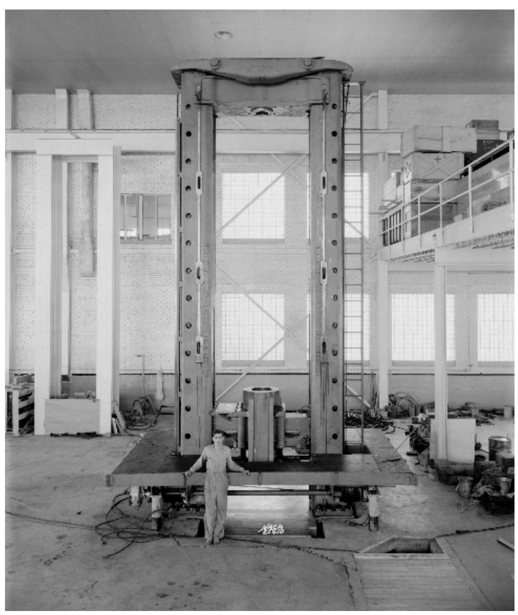


Figure 3.5-4:Million Pound Machine Assembly in the Structures and Materials Research Facility Building 1148; 1941.

A photo taken in 2007 after the latest upgrade of the Structures and Materials Laboratory (building 1148) is shown in **Figure 3.5-5.** Over the years many other testing machines were added to the facility. Cyclic load testing was carried out in this laboratory before other dedicated fatigue and fracture laboratories were built. Materials and structural analyses were conducted to help design the best structures for aircraft, and to develop new structural concepts for aeronautical and space vehicles. Experiments were done in metallurgy, mechanical property testing, fatigue testing, creep testing, corrosion and oxidation testing, environmental effects studies, and manufacturing technology to develop materials that could withstand mechanical, thermal, chemical, and radiation conditions. The facility also had the support of a next door model shop that helped in the construction of the materials and models that needed to be tested.

Figure 3.5-5: Exterior View of the Structures and Materials Research Facility Building 1148; 2007.

References

[1] Hansen, James. R. Engineer in Charge; A History of the Langley Aeronautical Laboratory, 1917-1958. NASA SP-4305, Washington, D.C.: U.S. Government Printing Office, 1987.

[2] Pamela E. Mack, editor, *From Engineering Science to Big Science: The NACA and NASA Collier Trophy Research Project Winners.* Washington, D.C.: Government Printing Office, NASA SP-4219, 1998

[3] Pattillo, Donald. Pushing the Envelope. Ann Arbor, Mich.; The University of Michigan Press, 1998.

[4] Bilstein, Roger E.; "The American Aerospace Industry", New York: Twayne Publishers, 1996. Orders of Magnitude: A History of the NACA and NASA, 1915-1990. NASA SP-4406. Washington, D.C.: U.S. Government Printing Office, 1989. Also at http://www.hq.nasa.gov/office/pao/History/SP-4406/cover.html

[5] http://www.archive.org/details/GPN-2000-001376.

3.6. Unique Structures and Materials Test Capabilities

Although wind tunnels have been the dominant facilities at Langley since its formation in 1917, there are many other facilities and laboratories associated with both the aeronautical and space research missions of the center. The scope of Langley's structures and materials research is shown in **Figure 3.6-1**. A detailed listing of the structures and materials test facilities located at Langley Research Center is given in a review paper by Charlie Harris.[1] A select few have been highlighted in this section to illustrate either the historical significance of these facilities or their importance in the metallic materials R&D conducted at Langley over the past several decades. Over the years, unique test capabilities were developed when necessary to perform critical tests to validate a new analysis capability or for experimental validation of a new structural concept or materials form.

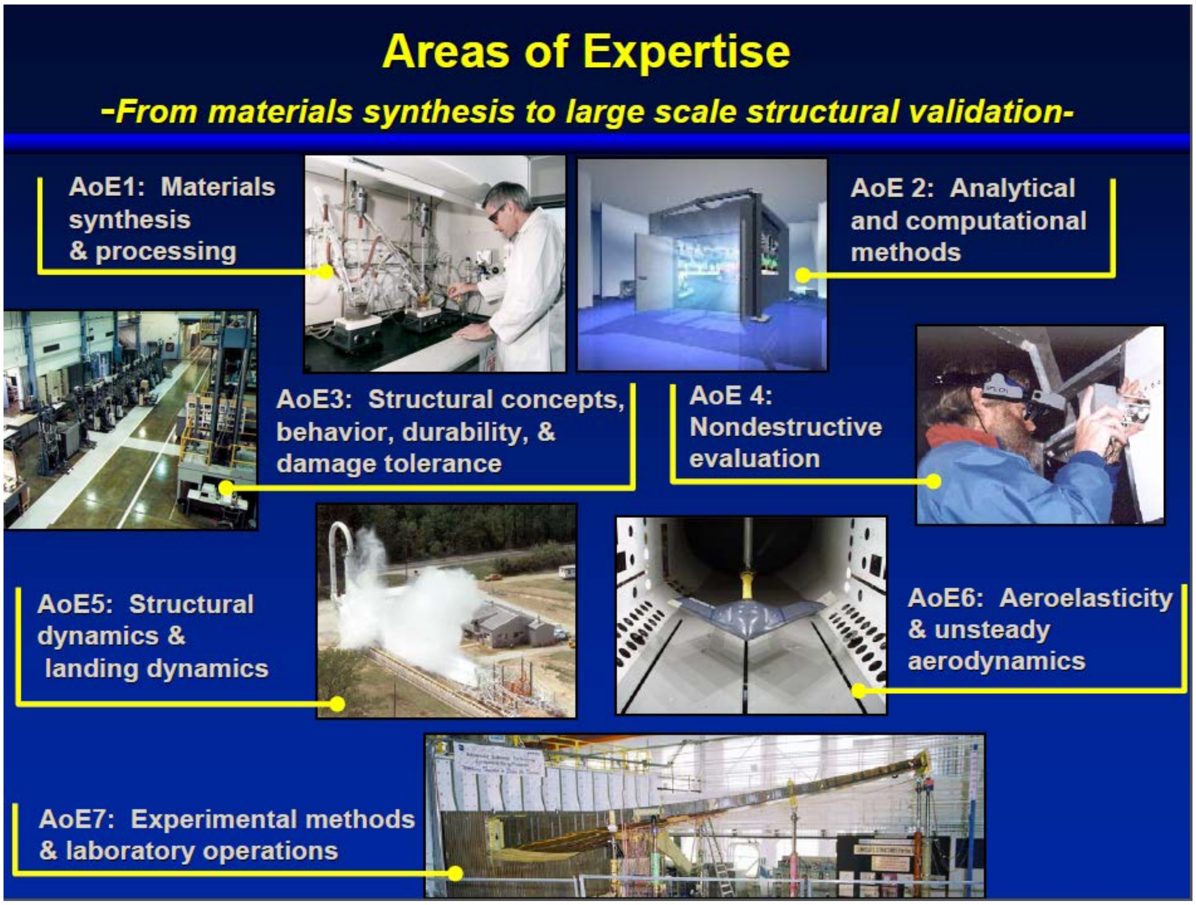


Figure 3.6-1: Areas of Expertise in Structures and Materials at Langley.

Langley has, over the years, been able to have excellent R&D testing capabilities to do structures and materials research. This has included numerous mechanical test frames, analytical tools for metallurgical analyses, environmental test chambers equipped with capabilities to simulate loads, temperatures, and pressures representative of aircraft and space launch vehicle environments.

NASA Langley has excellent laboratory and test capabilities to evaluate lightweight structures and materials. A few examples[2] are presented to illustrate the scope of capabilities of structures, materials, and non-destructive evaluation facilities and laboratories.

3.6.1. James H. Starnes Structures and Materials Lab

Figure 3.6-2: James H. Starnes Structures and Materials Lab.

For structures research, the James H. Starnes Structures and Materials Laboratory, shown in **Figure 3.6-2**, is a several thousand square foot laboratory with a wide range of mechanical-load test machines capable of testing specimens at loads ranging from 1 lb to 1,000,000 lbs. The lab is regularly used to test both small and large metallic and composite test specimens. It is equipped with state-of-the art data acquisition systems. The lab also has a large double-sided backstop with a reinforced floor for testing of full-scale structures and models.

A listing of some of the primary experimental test machines in this laboratory is as follows:

- Bending, torsion, and shear loads machine (Combined Loads Test Machine)
- 1-Kip Instron Load Frame with Environmental Chamber
- 6 Kn Instron Test Machine with Environmental Chamber
- 120-Kip Southwark-Emery Test Machine
- 300-Kip Southwark-Emery Test Machine
- 1200 Kip Southwark-Emery Test Machine
- Static Indentation Test Facility
- HyMETS (Hypersonic Materials Environmental Test System)
- 10 ft x 30 ft T-Slotted Structural Backstop
- 100 Kip MTS Closed Loop Hydraulic Test Machine
- 50 Kip MTS Closed Loop Hydraulic Test Machines with Environmental Chamber

These facilities allow the testing of specimens ranging in size from material coupons to full-scale structural components and can accommodate a wide range of tests applicable to validating the structural concepts to be developed in the proposed effort. Several of the machines allow for the testing of specimens at elevated temperature. The tests that can be performed with these facilities include the following:

- axial tension and compression
- short beam and interlaminar shear
- buckling and crippling
- damage propagation
- multi-point flexure
- load cycling
- thermal response
- load to failure/postbuckling
- low speed impact test machines

3.6.2. Multi-parameter Laboratory

The Multi-parameter Laboratory (**Figure 3.6-3)** contains four multi-parameter test stands to provide the ability to evaluate materials in simulated realistic vehicle mission environments. The three variables of temperature, pressure, and load can be controlled simultaneously in three of the stands.

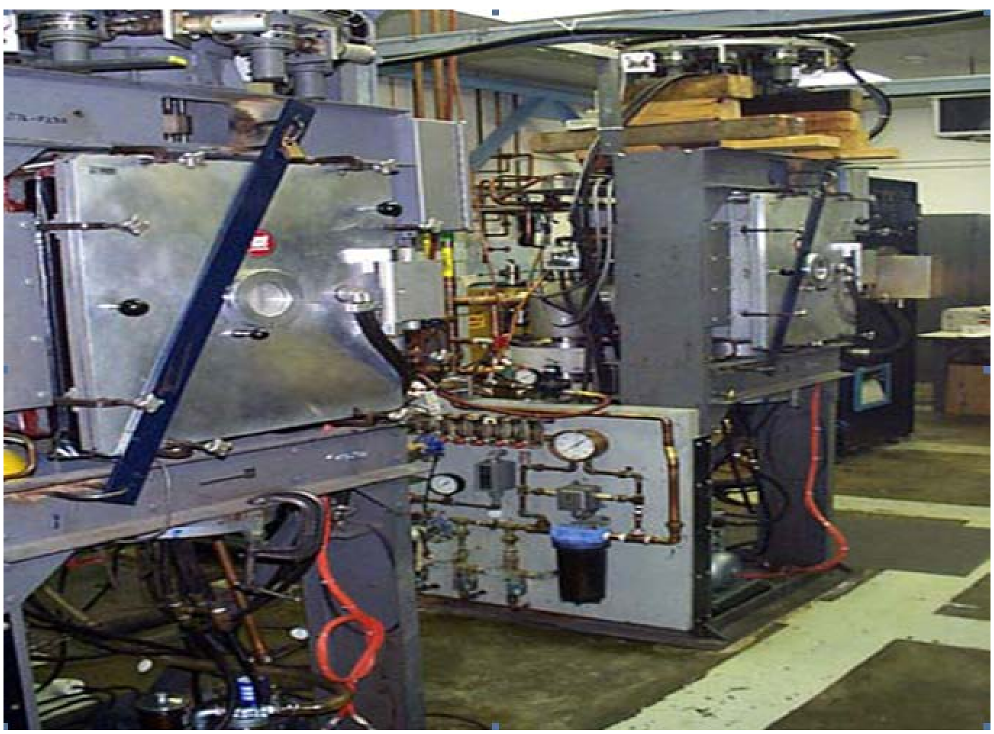


Figure 3.6-3: Multi-Parameter Test Machines.

Only temperature and pressure parameters can be controlled in the fourth test stand. Temperatures can range from room temperature to 3000°F, pressure can range from atmospheric to 1×10^{-6} torr and loads can range from no load to 2000 lbs. The tests can be run in either inert or oxidizing atmospheres. To date, most of the research has been conducted on high-temperature materials for various hypersonic vehicle applications. An Instron test machine is available for mechanical testing at elevated temperatures up to 3000°F.

Twelve creep stands are also available in this lab. There are two 50-channel data acquisition systems which can take up to 3 scans per second. The stands are capable of testing up to 1500°F. Creep tests are currently being conducted on metal matrix composites.

3.6.3. Light Alloy Laboratory

Figure 3.6-4: Light Alloy Laboratory.

The Light Alloy Laboratory (**Figure 3.6-4)** is an integrated facility for light alloy research focusing on alloy syntheses, development, and testing including innovative processing and joining, coating technology, and complex materials analysis with state of the art electron optics techniques. Emphasis is on titanium, aluminum, magnesium, and beryllium alloys and various combinations of these materials including whisker, particulate, and fiber reinforcement for application to subsonic, supersonic, and hypersonic airframe structures, launch vehicles, and space transportation.

Equipment and instrumentation are available to conduct surface analysis, thermal analysis, metallurgy, microscopy, X-ray, and dimensional stability studies. Capabilities for processing include electron beam freeform fabrication and plasma processing. The complex is divided into separate, enclosed discipline-oriented laboratories. Each laboratory has independent environmental control and a distribution system for laboratory gases and liquid nitrogen.

3.6.4. Metals Processing Laboratory

This laboratory has these capabilities:

- RF plasma spray: Plasma spray processing used to produce thin coatings of various metals on fabrics and fibers for hybrid composites.
- Electron beam freeform fabrication: Portable electron freeform fabrication equipment permits near-net-shape fabrication of various alloys.
- Vacuum hot press: 100-ton capacity compressive load frame, 2200°F temperature capability, 1×10^{-6} torr vacuum chamber. Used for consolidation of fiber-reinforced metal matrix composites.
- Beryllium laboratory: Capability to develop radiation shielding materials.
- Superplastic forming: Press with 1000°F maximum temperature and a forge force of up to 300,000 lbs. Used to superplastically form aluminum alloy sheet for incorporation into skin-stiffened and sandwich sub-elements.
- Surface processing: Performs chemical and electro-chemical surface preparations for metallic materials including cleaning, etching, milling, passivating polishing, plating, and anodizing in support of center-wide research activities.
- Resistance welding: Fabrication of air-tight bags to allow hot isostatic pressing of fiber-reinforced metal matrix composites.
- Hot/Cold isostatic press: 30,000-psi isostatic pressure system (Ar gas), 2300°F maximum temperature. Used for fabrication of powder metallurgy (PM) compacts and metal matrix composites.
- Heat treatments: Ovens capable of heat treating materials up to 1800°F

3.6.5. Materials Research Laboratory

The Materials Research Laboratory (**Figure 3.6-5**) houses experimental facilities for conducting a wide range of research to characterize the behavior of advanced structural materials under the application of mechanical and thermal loads. This research encompasses the study of deformation characteristics and damage mechanisms leading to the development of nonlinear constitutive models, strength criteria, and durability and damage-tolerance criteria. A high bay area surrounded by 8 enclosed laboratories house 59 servo-hydraulic controlled testing systems (1-kip to 400 kips), 3 X-ray radiography systems, 13 high-temperature creep frames, and 4 multi-parameter test facilities. An environmental fatigue laboratory has dedicated test facilities for aqueous environments, inert gases and ultra-high vacuum. The environmental durability test capability includes 20 load frames with temperature chambers for testing materials under synchronized cyclic thermal and mechanical loads to simulate supersonic flight conditions.

Covering the largest area in the lab is the biaxial test stand with two axis programmable load capacities of 165 and 225 kips. Multi-axis loading is also available on three tension-torsion test stands and the axial tension-bending test stand.

Figure 3.6-5: Materials Research Laboratory.

A more detailed discussion of the materials and structures research facilities and capabilities can be found in the references cited at the end of this section.

3.6.6. Lead Center Roles

In the 1998 NASA Strategic Plan,[3] each of the NASA Field Centers were assigned lead responsibilities in different disciplines. Langley was designated the lead center for the Center of Excellence (COE) in Structures and Materials. Further guidance and responsibilities are outlined in the NASA Strategic Management Handbook.[4] The NASA Center partners in this COE are illustrated in **Figure 3.6-6**. The scopes of the technologies worked by each COE partner are illustrated in **Figure 3.6-7**.

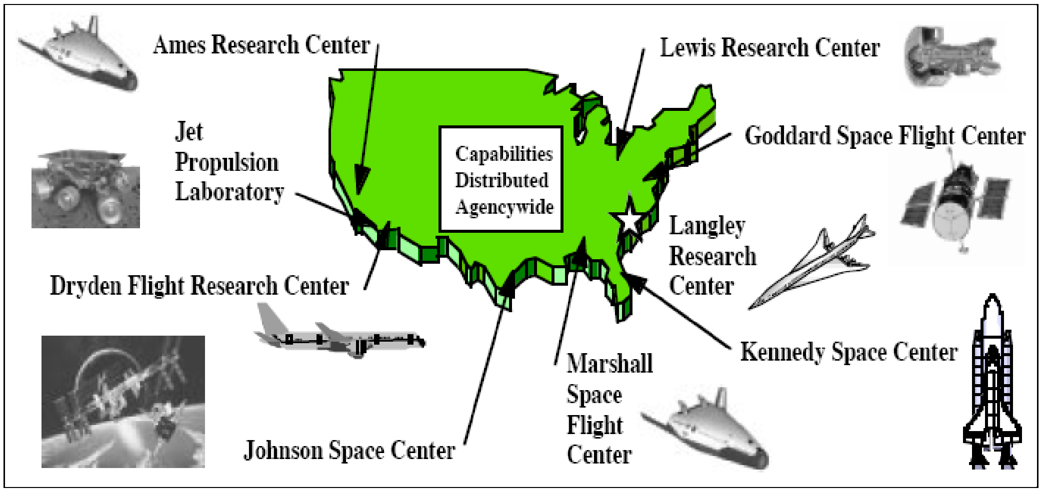


Figure 3.6-6:NASA Center Partners in the Materials and Structures COE Community.

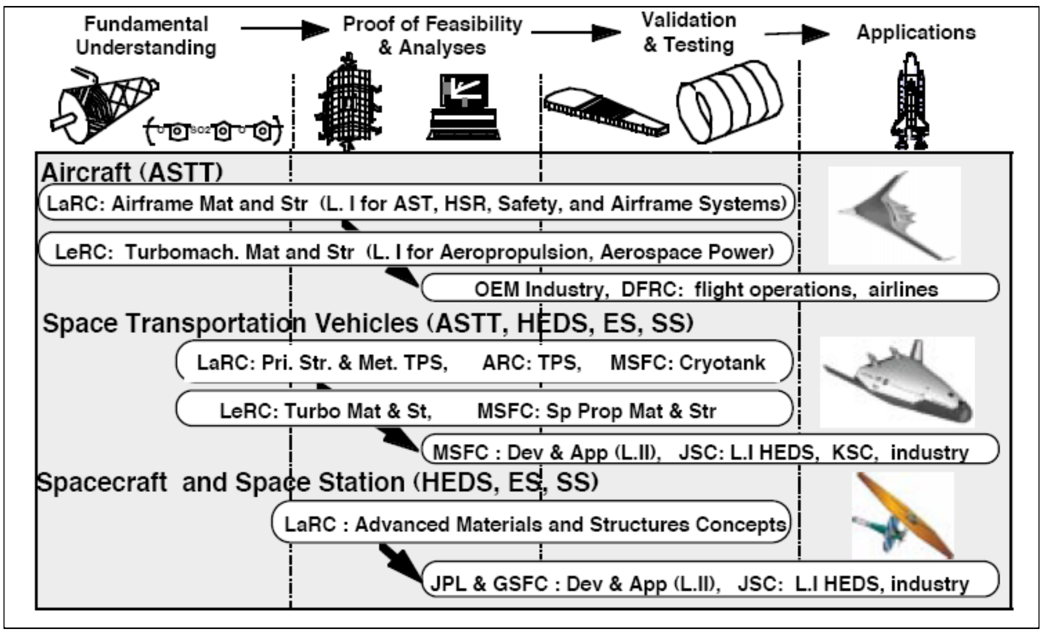


Figure 3.6-7: The COE Technology Scope.

3.6.7. Mission

The mission of the Structures and Materials COE was defined in a publication[5] by Charles E. Harris. It is outlined here to illustrate the importance of Structures and Materials research to the execution of agency programs. The Structures and Materials COE was to provide the leadership for coordination, planning, advocacy, and assessment of the structures and materials research and technology development activities throughout the Agency. The COE promoted the development of new material systems and processes, innovative structural mechanics and dynamics design and analysis methods, experimental techniques, and advanced structural concepts through technology validation for aircraft, space transportation vehicles, science instruments and spacecraft. The COE addressed technology challenges to enable more affordable, lighter weight, higher strength and stiffness, safer, and more durable vehicles for subsonic, supersonic, and sustained hypersonic flight, Earth and other planetary atmospheric entry, and for spacecraft flight throughout the solar system.

The effort was led by the COE office at Langley Research Center with strategic partnerships established among the other NASA Field Centers. The COE office provided the strategic leadership required to implement its functional responsibilities. The COE community was responsible for maintaining and enhancing the preeminent technical and programmatic expertise and ground test facilities and laboratories distributed throughout the Agency. The COE community developed and maintained partnerships with industry, academia, and other government agencies to leverage external programs and resources to achieve NASA strategic objectives.

Although centers of excellence are not officially defined today (2016) Langley is still recognized as a leader in aerospace materials and structures research.

References

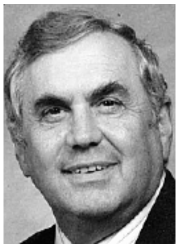
[1] Charles E. Harris; "Structures & Materials Facilities at the NASA Langley Research Center" http://researchtech.larc.nasa.gov/facils/SM_Facilities.pdf
[2] [DOC] RFI_capability_S&M+NDE_RD - NASA Langley . - + LaRC https://procurement.larc.nasa.gov/RFI/RFI_capability_S&M+NDE_RD.doc
3 NASA Strategic Plan, NASA Policy Directive (NPD)-1000.1, National Aeronautics and Space Administration, Washington, D.C., 20546, 1998, page 15.
4 NASA Strategic Management Handbook, National Aeronautics and Space Administration, Washington, D.C., 20546, 1996, pp. 14–15.
[5] Charles E. Harris; "Implementation Plan for the NASA Center of Excellence for Structures and Materials", NASA, TM-1998-208714.

4. CORE COMPETENCIES AND FOCUSED VEHICLE PROGRAMS

W. Barry Lisagor 1962 - 1998	**Thomas T. Bales 1962 - 1998**	**Bland A. Stein 1956 - 1992**	**C. P. Blankenship 1962 - 1997**

NASA has attracted exceptional engineers that have made outstanding contributions in advanced materials and lightweight structures for aircraft and spaceflight vehicles. The current research staff at Langley are making excellent contributions and helping to advance aerospace materials and structures to meet current and future need for our nation. Three of the past contributors deserving of special recognition are shown above. Barry Lisagor, Thomas Bales, Bland A. Stein, and Charles Blankenship all made outstanding contributions to Langley's metallic materials and structures program during their years of service at NASA. Blankenship is singled out here because of his outstanding leadership in forming the metallic materials branch, for hiring highly skilled researchers, and for his visionary guidance at the Materials Division and Structures Directorate levels. Barry Lisagor was an outstanding researcher excelling in testing technology, in-depth understanding of the metallurgy of light alloys, for his mentoring of young engineers, and for his leadership of metals research at Langley. Tom Bales is singled out for his many contributions in fabrication technology where he was a true visionary breaking new ground in processing, joining, and manufacturing new structural concepts generally where little or no guidelines were available.

4.1. Tribute to W. Barry Lisagor



A special tribute is given to W. Barry Lisagor who passed away on Nov. 29, 2007, for his untiring dedication and many technical contributions to the development and use of lightweight metallic materials in aerospace applications. Barry was a graduate of Virginia Polytechnic Institute and State University with B.S. and M.S. degrees in Metallurgical Engineering. He was commissioned as a Lieutenant in the U.S. Army and was assigned to support research at the NASA Langley Research Center.

Including his two-year assignment with the Army, Barry conducted or managed research at NASA Langley from 1962 to1998. Barry was an outstanding contributor, mentor, and leader in the light alloy research programs carried out at NASA over 36 years. Barry worked on structural materials development and application for subsonic, supersonic, and hypersonic aircraft and launch vehicle structures including cryogenic tank development. His technical areas of interest and experience have included aluminum-lithium alloy technology development, powder metallurgy aluminum alloy development, metal matrix composite development, coatings development for titanium alloys, superalloys, and coated refractory metals, and environmental effects on structural materials for the full range of aerospace vehicle application. During his NASA career, Barry’s areas of responsibility encompassed active technical research, technical leadership, and program management at all levels of proficiency.

At NASA, he planned, organized, conducted, and led research on the synthesis of advanced aluminum and titanium alloys and the development of innovative fabrication processes to provide for the manufacture of lightweight aerospace structures. He conducted personal research and was a key member of a team that identified and provided a solution to a stress corrosion problem which threatened the Apollo Program. He managed programs on the development of high-temperature metallic structural concepts for the space shuttle. He served as head of the Metallic Materials Branch and later as Associate Division Chief of the Materials Division. As Branch Head, he led a team of researchers to develop advanced metallic materials and innovative fabrication processes for NASA programs including the National Supersonic Transport, the National Aero Space Plane, Commercial Transport Aircraft, High-Speed Research Aircraft, and the Advanced Launch System Program. In the course of his career he received national and international recognition for his research and was frequently requested to chair sessions at national and international symposiums He met and interacted with Russian experts in aluminum technology and fostered cooperative research projects. He served as a key member of a national team that developed advanced Al-Li alloys for the Super Lightweight Tank for the space shuttle. He received many outstanding performance awards during his career and was honored with two NASA medals: one for Exceptional Service and one for Outstanding Leadership. He was a life member of the American Society for Metals. He was an ASTM Fellow and an ASTM Award of Merit recipient. He was honored with the prestigious Francis L. LaQue Memorial Award in 2002 for his contributions to corrosion research and service.

Following retirement he was employed as a Senior Scientist by Analytical Services & Materials (AS&M) Inc., located at 107 Research Drive in Hampton VA. As a Senior Scientist at AS&M, he supported research at NASA on the development and testing of advanced aluminum alloys.

4.2. Base and Focused Research Projects that Funded Metals R&D

4.2.1. Base and Focused Research Projects

The base and focused programs and projects that funded materials and structures work on metallic materials for subsonic, supersonic, and hypersonic aircraft development are shown in **Figure 4.2-1**.

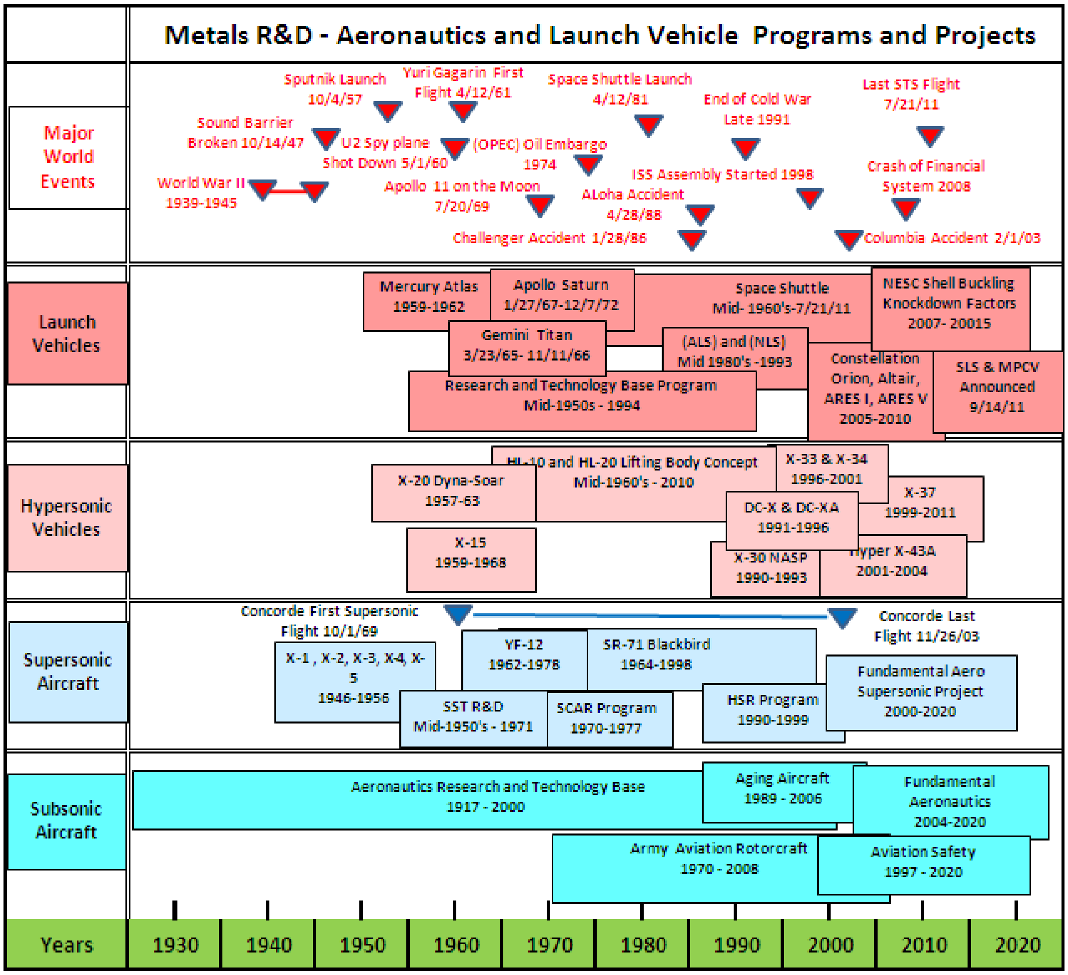


Figure 4.2-1: Programs that Funded Metallic Materials and Structures R&D for Aircraft at Langley.

The Aeronautics and Space Technology (OAST) base program in structures and materials was a primary source of funding for basic research on aerospace metallic material and structures for the past several decades. The research helped to develop the foundational base on which more focused projects were built. Although the name of the base program has changed several times, it has continued to provide resources for fundamental aeronautical research generally at the technology readiness levels (TRL) from 1 through 4–5. The base research and technology (R&T) program has primarily been focused on problems for subsonic flight vehicles including subsonic transports, general aviation, rotorcraft, and support for military aircraft. The material systems studied in the base program were for the most part focused on advanced aerospace alloys of aluminum and titanium. However, high-strength steel for landing gears was also researched for fracture toughness properties and corrosion durability. Disciple driven research was conducted in topics ranging from basic alloy development to fatigue and fracture studies aimed at insuring the safety of older aircraft. NASA has a rich history of working with other government agencies and industry to advance technologies of interest to the whole community. These partnerships included (1) partnering with universities to promote engineering education and basic research; (2) working with the basic material suppliers to develop new materials or test methods; (3) working jointly with the Department of Defense to solve problems for existing military aircraft and on development of advanced new materials and structures technology to enable the next generation of fighter or military transport aircraft; (4) working with the FAA on safety related technologies; (5) working directly with the aircraft manufactures to advance technologies that contributed to all the manufactures; and (6) actively participating with national technical societies such as ASTM on test standards, ASM on material development or service performance, SAMPE on processing and fabrication, and the American Institute for Aeronautics and Astronautics (AIAA) on structural mechanics and structural dynamics.

In the discussion above it is critical to recognize that the successful development of useful engineering materials for aerospace applications was done in a multidisciplinary environment where to property requirements, product forms, fabrication technologies, shapes required and service environments are defined by related disciplines. Multidisciplinary interaction has always been deemed critical for the efficient development of safe, reliable, and affordable flight vehicles. Materials research was guided by soliciting inputs from all the different groups required to develop a new airplane or space launch vehicle. Structures and materials disciplines are critical elements in the overall design process of flight vehicles. NASA has used advisory councils and technical advisory committees to guide its investment in advanced technologies. In addition to these committees, NASA has consistently made use of peer review committees to guide the R&D projects.

The focused projects that funded work on metallic materials and structures at Langley are shown in **Figure 4.2-1**. It should be noted that most of these projects were in supersonics, hypersonics, and space transportation. These vehicle-focused projects were and continue to be critical to the development of new vehicle capabilities. The structural concepts, material forms, and properties must be derived from multidisciplinary design optimization where vehicle performance must be traded versus what can be produced. Defining future requirements and product forms required for future vehicle concepts is invaluable to defining the goals for materials and structures research projects. The past NASA-focused projects provided guidance to the base R&D research and in many ways was the guiding criterion in the selection of what research was funded in the base program. These projects also helped to define the tough issues that required more time and effort than were available for the focused projects. Many times these tough problems became the subject of R&D in the base. There has been a very healthy partnership between technical experts working fundamental core competencies and practicing engineers working the vehicle development projects. This has been one of NASA's core strengths.

The Federal Government's involvement with aeronautics preceded NASA's establishment by many years. In 1915, Congress mandated that NACA "supervise and direct the scientific study of the problems of flight, with a view to their practical solution." In the National Aeronautics and Space Act of 1958 that established NASA, Congress stated that NASA would be involved in "aeronautical and space activities" using "aeronautical and space vehicles." The law defined aeronautical and space activities as

(a) research into, and the solution of, problems of flight within and outside the Earth's atmosphere; (b) the development, construction, testing, and operation for research purposes of aeronautical and space vehicles;(c) the operation of a space transportation system including the Space shuttle, upper stages, space platforms, and related equipment; and (d) such other activities as may be required for the exploration of space

The Space Act also defined aeronautical and space vehicles as "aircraft, missiles, satellites, and other space vehicles, crewed and uncrewed, together with related equipment, devices, components, and parts." It can safely be said that NASA OAST activities have covered all these areas.[1]

OAST's aeronautics research and technology program from 1979 to 1988 was derived from several technological disciplines and spanned the flight spectrum from hovering to hypersonic aircraft. OAST provided technology results well in advance of specific applications needs and conducted long-term independent research without the payoff of known immediate mission applications. The disciplinary research applied to all classes of vehicles and related to capabilities that were yet undefined. In addition, OAST's technology research enhanced the capabilities of specific classes of vehicles, such as subsonic transport, rotorcraft, high-performance military aircraft, and supersonic and hypersonic vehicles. Space research and technology took both a disciplinary approach and a vehicle-specific approach. Disciplines represented in the program included propulsion, space energy, aerothermodynamics, materials and structures, controls and guidance, automation and robotics, space human factors, computer science, sensors, data and communications systems, and spaceflight systems. The space research and technology program developed and improved technologies and components for the space shuttle and for the future space station and also participated in missions and experiments launched from and conducted on the shuttle.

OAST's fundamental involvement with other agencies and with industry differed from other NASA organizations. In the area of general aviation, OAST worked with the FAA, the Department of Transportation, and aircraft manufacturers to improve aircraft and aviation safety and to lessen any harmful impact of flight on the environment. In the area of high-performance aircraft, OAST research supported the needs of the military, and NASA continually participated in joint projects with the Department of Defense (DoD) and sometimes shared the financial costs of these projects.

OAST's activities have benefited the U.S. economy. Congress regularly, in its deliberations on NASA's budget, noted that aeronautics was one area in which the United States had a positive balance of trade and also created a large number of jobs. Congress generally deemed NASA's aeronautics deserving of steady support.

An example of the type of studies sponsored by the OAST Base Research Program is a study[2] performed by I. Frank Sakata, Lockheed-California Company, Burbank, California, and Contract NAS1-16434, entitled "Systems Study of Transport Aircraft Incorporating Advanced Aluminum Alloys" (Final Report published, January 1982). The study program identified weight and economic benefits that might result from the incorporation of advanced aluminum alloys in future commercial aircraft. The study utilized aircraft configured considering fuel-efficient technologies that could reasonably be available in new aircraft with a 1990 in-service date. A long-range advanced trijet, a short-medium range advanced twinjet, and a short-haul super-commuter aircraft were used for the investigation. Structural weight savings of 16% and an annual operational cost savings in excess of $1million per aircraft were shown for the long-range aircraft using a fuel price of $1.00/gal. Fuel prices of $2.00/gal and $3.00/gal were also considered in the economic analyses. Comparable savings were also realized for the short-medium range and short-haul super-commuter aircraft.

Over the past several decades NASA has sponsored these types of studies on different aircraft concepts to help define the critical technology needs and to identify emerging high-payoff technologies.

Although aeronautics has been downsized within the NASA budget, it still is making important contributions to the Nation. The NASA Aeronautics Research Mission Directorate research portfolio for 2010-2011 included 10 projects organized into three programs:

- Fundamental Aeronautics Program
    - Subsonic Fixed Wing Project
    - Subsonic Rotary Wing Project
    - Supersonics Project
    - Hypersonics Project
- Airspace Systems Program
    - NGATS ATM-Airportal Project
    - NGATS ATM-Airspace Project
- Aviation Safety Program
    - Integrated Vehicle Health Management (IVHM) Project
    - Integrated Intelligent Flight Deck Project
    - Integrated Resilient Aircraft Control Project
    - Aircraft Aging and Durability Project

Structures and materials research is funded by each of the projects in the Fundamental Aeronautics Program and in the Aircraft Aging and Durability Project and IVHM Project in the Aviation Safety Program.

The research focus in these projects related to metallic includes the following challenges:

- Develop lightweight sensor networks that characterize the state of materials and structures over large areas.
- Develop very-low-power or self-powered wireless sensors capable of operation in harsh environments.
- Develop artificial intelligence to automatically assess structural integrity from sensor responses and implement damage mitigation protocols.
- Develop components and sensors that are cost-competitive and available from multiple vendors.

- Flight test full-scale IVHM systems to detect multi-site damage.

Early detection of impending failures in aircraft materials, structures, and wiring is critical for avoiding fatalities as a part of the aging aircraft program.

Research on Adaptive Materials and Morphing Structures includes the following challenges:

- Identify new morphing missions and designs for reconfigurable civil aircraft, including supersonic aircraft with low sonic boom.
- Develop the next generation of high-strain, adaptive materials or devices that can be activated and deactivated for repositioning, with actuation deformation up to 100 percent.
- Develop novel integrated adaptive materials that allow wing surfaces and fuselages (including inlets) to rapidly change shape or alter load paths.
- Conduct scaled wind tunnel and flight tests on active, morphing aircraft to enable innovative, lightweight designs.
- Develop new, structurally integrated adaptive devices for flow control on a commercial aircraft to, for example, reduce drag and improve performance in off-design conditions.
- Develop analysis and design tools that account for and accurately predict nonlinear behaviors of adaptive materials and morphing structures.

Research on innovative high-temperature metals and environmental coatings is addressing the following challenges:

- Define required models and a model integration strategy to provide necessary functionality for simulations.
- Select models for further development, based in part on how well they are aligned with materials systems that provide the greatest benefit for propulsion systems.
- Develop models for selected substrates and associated environmental coatings; determine all the physical parameters required by the models.
- Validate the models by applying them to the development of new materials that are selected in concert with industry.

The challenges being addressed for multifunctional materials are as follows:

- Develop a comprehensive analysis to predict the performance of selected monolithic and composite multifunctional materials.
- Use this analysis to guide parametric studies to explore and optimize material response with the goal of understanding the combined response of the multifunctional material.
- Fabricate materials according to model predictions.
- Evaluate material performance, both coupled and structural, and compare with analytical predictions.
- Integrate multifunctional materials into a structural component for benchtop verification.
- Conduct flight tests on a structural component.

4.2.2. Graduate Education Program

NASA has a long history of developing strong ties with leading academic universities that pursue excellence in academics and graduate level research. Although a large number of grants with universities having Metallurgical Engineering or Materials Engineering Departments were funded by NASA Langley on many different topics related to metallic materials and structures areas, in this monograph we have chosen to single out one particular grant which was exceptionally productive in both educating students and generating excellent research results.

The NASA-UVA Light Aerospace Alloy and Structures Technology Program (LA^2ST); Research NASA Grant NAG1-745 was funded by NASA Langley from 1986 through 2004. Research on this grant was conducted by graduate students and faculty advisors in the Department of Materials Science and Engineering at the University of Virginia. The fundamental objective of the LA^2ST Program was to conduct interdisciplinary graduate student research on the performance of next generation, lightweight aerospace alloys, composites and thermal gradient structures. The LA^2ST Program was structured to produce relevant data and basic understanding of material mechanical response, environmental/corrosion behavior, and microstructure; new monolithic and composite alloys; advanced processing methods; measurement and modeling advances; and a pool of educated graduate students for aerospace technologies. The scope of the LA^2ST Program was broad. Research areas included mechanical and environmental degradation mechanisms in advanced light metals and composites, aerospace materials science, mechanics of materials for aerospace structures, and thermal gradient structures. A substantial series of semi-annual progress reports issued from 1987 through 2004 documents the technical objectives, experimental or analytical procedures, and detailed results of graduate student research in these topical areas.

As documented in the final progress report,[3] LA^2ST productivity since 1986 includes 143 publications (103 archival journal or reviewed book publications), 31 PhD dissertations or MS theses, 147 external technical presentations, 34 NASA progress reports, and 5 NASA Contractor Reports. Since 1986, 42 graduate students, including 38 citizens of the United States, have been involved with LA^2ST research; 34 have received the MS or PhD degree. Seven post-doctoral research associates have participated in LA^2ST research. A total of 13 different faculty worked on the LA^2ST Program since 1986.

As an example of the productivity of this grant, the introduction section of a progress report[4] from July 1997 is presented.

"In October of 1991, E.A. Starke proposed a substantial supplement to the base LA^2ST Program. The objective of that research was to involve UVA faculty with engineering scientists from aluminum alloy producers and airframe manufacturers in a broad research program to develop light aluminum alloys and composites for elevated temperature-long time high-speed civil transport (HSCT) applications.[5,6] NASA Langley Research Center (LaRC), Alcoa, Allied-Signal, Boeing, McDonnell Douglas, Reynolds Metals and UVa joined in an effort to identify the most promising aluminum based materials with respect to major structural use on the HSCT and to further develop those materials. This research began in January of 1992 and results were reported separately from the LA^2ST Program.[7] In 1994 HSCT research at UVa was expanded to include titanium alloys, and collaborations were implemented with RMI Titanium Company and TIMET. These titanium projects were reported in base LA^2ST progress reports, as was aluminum HSCT work performed during 1995 and beyond. In mid-1996, NASA requested that those LA^2ST

dealing with HSCT materials issues be reported separately.[8] Three HSCT research projects were conducted at UVa in 1996, involving two PhD graduate students, Sean P. Hayes (advised by Professor Gangloff) and Susan M. Kazanjian (advised by Professor Starke), as well as a Post-doctoral Research Associate supervised by E.A. Starke. The value of these types of grants cannot be over emphasized. Not only were significant new discoveries made that contributed to NASA R&D programs, but students were educated in a discipline area that the nation needed. Graduates from this grant are now making major contributions at NASA, in the aerospace industry, and in universities where they are teaching and conducting research."

References

[1] http://history.nasa.gov/SP-4012/vol6/vol_vi_ch_3.pdf "AERONAUTICS AND SPACE RESEARCH AND TECHNOLOGY Chapter Three".

[2] I. Frank Sakata, "Systems Study of Transport Aircraft Incorporating Advanced Aluminum Alloys",Contract NAS1-16434, Jan. 1982. http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19820009279_1982009279.pdf

[3] NASA-UVA Light Aerospace Alloy and Structures Technology Program (LA2ST); Research on Materials for the High Speed Civil Transport, Progress Report; 1 Jan.–31 Dec. 1999, NASA Grant NAG-1-745.

[4] R.P. Gangloff and E.A. Starke, Jr.; NASA-UVA Light Aerospace Alloy and Structures Technology Program, Report No. UVA/528266/MS97/123, University of Virginia, Charlottesville, VA, February, 1997. http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19980000333_1997049152.pdf.

[5] R.P. Gangloff, E.A. Starke, J.M. Howe and F.E. Wawner; NASA-UVa Light Aerospace Alloy and Structures Technology Program: Supplement on Aluminum Based Materials for High Speed Aircraft, Proposal No. MS NASA/LaRC-5215-92, University of Virginia, 1991.

[6] R.P. Gangloff, E.A. Starke, J.M. Howe and F.E. Wawner; NASA-UVa Light Aerospace Alloy and Structures Technology Program: Supplement on Aluminum Based Materials for High Speed Aircraft, Proposal No. MS NASA/LaRC-5691-93, University of Virginia, 1992.

[7] 4 E.A. Starke, Jr.; NASA-UVa Light Aerospace Alloy and Structures Technology Program: Supplement on Aluminum Based Materials for High Speed Aircraft, NASA Contractor Report 4517, June, 1993.

[8] R.P. Gangloff and E.A. Starke, Jr.; NASA-UVa Light Aerospace Alloy and Structures Technology Program: Supplement on Aluminum Based Materials for High Speed Aircraft, Report No. UVA/528266/MSE97/122, March, 1997.

4.3. Subsonic Aircraft

The vast majority of the metals research performed in support of subsonic aircraft was done in the R&T base program. The most notable exceptions to this were the Aging Aircraft Project and the National Aviation Safety Program. The Aging Aircraft Project (NASA Structural Integrity Program (NASIP)[1]) was led by Langley materials and structures technical experts in conjunction with Langley nondestructive evaluation (NDE)[2] experts. It was initiated in response to the Aloha Airlines Flight 243 accident where a major section of the fuselage separated from the aircraft in flight and miraculously the pilot was still able to land the aircraft (**Figure 4.3-1**). This project will be discussed in detail in a later section. The Aviation Safety Program, also led from Langley, was a national program with the FAA and technical people from the airlines and the aircraft manufactures.

Figure 4.3-1: Forward fuselage after Aloha Airlines accident (1 person killed), April 28, 1988. Fuselage of Aloha Airlines Flight 243 after explosive decompression.

The top-level goal of the national aviation safety initiative,[3] started in 1999, was to reduce the aircraft accident rate fivefold within 10 years and tenfold in 20 years.

"This is an exciting challenge that will have a significant benefit for every man, woman, and child in this country who steps on an airplane," said Dr. Jeremiah F. Creedon, the director of NASA Langley at that time, "Flying already is the safest way to travel. Now it will be even safer."

The Aviation Safety Program was created in response to a report from the White House Commission on Aviation Safety and Security, chaired by Vice President Al Gore. The program also was part of a new "Three Pillars for Success" initiative that spelled out what NASA would do to achieve national priorities in aeronautics and space transportation technology.

NASA worked the safety program in partnership with the FAA, the DoD, and the aviation industry.

Langley was selected to lead the safety program by NASA Headquarters in Washington, D.C. Critical roles in the program, however, were filled by three other agency field installations: Ames Research Center in Mountain View, California; Armstrong Flight Research Center in Edwards, California; and Glenn Research Center in Cleveland, Ohio.

In establishing the safety program, it was noted that although major strides had been made in the last 40 years to make flying the safest of all major modes of transportation. More technological advances were needed to prevent a rise in accidents if air traffic triples as predicted in the next 20 years.

The safety program emphasized not only accident reduction, but also a decrease in injuries when accidents do occur. The safety initiative include research to reduce human-error-caused accidents and incidents, predict and prevent mechanical and software malfunctions, and eliminate accidents involving hazardous weather and controlled flight into terrain.

It also was focused on using information technology to build a safer integrated aviation system to support pilots and air traffic controllers. The FAA helped to define requirements and actions to enact many of the safety standards. The DoD shared in technology development as well as applying safety advances to military aircraft.

NASA, in partnerships with the FAA and private industry, has made significant accomplishments in aviation safety. Some examples include

- providing technology for advanced warning of wind shear;
- designing advanced air-traffic-management equipment and procedures.
- developing ways to ensure older aircraft are as structurally sound as new ones;
- improving engine reliability, systems, and displays;
- developing advanced ice-protection concepts to improve aircraft operations;
- improving the control of general aviation aircraft stall and spin.

Although materials and structures research was not a major focus of this program funding was provided to the aging aircraft team after the formal Aging Aircraft Project was finished.

References

[1] Harris, C.E., Newman, Jr., J.C., Piascik, R.S. and Starnes, Jr., J.H.; "Analytical Methodology for Predicting Widespread Fatigue Damage Onset in Fuselage Structure," Journal of Aircraft, Vol. 35, No. 2, pp. 307-317, March-April 1998.

[2] Harris, C.E. and Heyman, J.S.; "Overview of NASA Research Related to the Aging Commercial Transportation Fleet," Journal of Aircraft, Vol. 30, No. 1, pp. 64-68, Jan-Feb, 1993.

[3] http:/www.nasa.gov/centers/Langley/news/factsheets/AvSP-factsheet.html.

4.4. General Aviation Aircraft

The work done in the R&T Base Research Program was equally applicable to both subsonic transports and general aviation (GA) aircraft. The one notable R&D effort that stood out as a focused effort had to do with improving the survivability of occupants in small aircraft crashes.

In 1974, a cooperative research program was initiated between NASA, the FAA, and the GA aircraft industry to improve the crashworthiness of small aircraft.[1] The objectives of this program were to determine the dynamic responses of the aircraft structure, seats, and occupants during crash events; to determine the effect of flight parameters at impact (flight speed, flight-path angle, pitch angle, roll angle, etc.) on the magnitude and pattern of structural damage; to determine the failure modes of the seats and occupant restraint systems; and to determine the impact loads imposed upon the occupants. The program included extensive analytical work, test data evaluation, and structural concept development that were focused on enhancing the survivability of future GA aircraft with minimal increase in weight and cost. Dynamic structural response data were obtained by conducting full-scale crash tests of GA aircraft under a variety of impact conditions. In all, 33 crash tests were performed during the 10-year period from 1974 through

1983. Most of the test articles (Piper Aztecs and Cherokees) were obtained for scrap aluminum value because the aircraft had been submerged during a flood at the Piper plant in Pennsylvania and they could not be certified, retrofitted, or sold. Later crash tests were performed on Cessna 172 aircraft and larger pressurized Piper Navajos. Some of the test parameters included the impact velocity, the attitude of the airframe at impact, and the impact surface (hard surface and soft soil). Photographs of selected impact tests performed in support of the GA aircraft crash test program were shown earlier in **Figure 2.2-3**.

Since it was not possible to evaluate all potential impact scenarios, most of the tests were performed for impact conditions that represented the more serious but potentially survivable GA airplane crashes. The data obtained during the GA aircraft crash test program was used to define the levels of acceleration typically experienced by the airframe structure and by the occupants during crash events. The occupant data were compared with different human injury prediction criteria to determine injury risk levels during airplane crashes. The structural data from this landmark crash test program was used to establish impact criteria for aircraft seats that are still used as the FAA standard for seat certification testing today. Later, the data were used as the foundation for the Crash Survival Design Guide for GA aircraft.[2]

References

[1] Karen E. Jackson, Richard L. Boitnott, and Edwin L. Fasanella, Lisa E. Jones and Karen H. Lyle; "A History of Full-Scale Aircraft and Rotorcraft Crash Testing and Simulation at NASA Langley Research Center", Jan 01, 2004.

[2] Hurley, T. R. and Vandenburg, J. M., editors; "Small Airplane Crashworthiness Design Guide," AGATE Report Reference No. AGATE-WP3.4-034043-036, Simula Technologies Reference No. TR- 98099, April 2002.

4.5. Rotorcraft

NASA and the Army have had a long standing joint program to develop new technologies to improve the performance and safety of rotorcraft both for military and commercial applications. **Figure 4.5-1** shows an artist's concept of a rotorcraft on the runway, and it shows specific areas where NASA Aeronautics has contributed to rotorcraft.

Figure 4.5-1:NASA Aeronautics Research; Decades of Contributions to Rotorcraft Aviation.

These contributions include the following:

1. Computational Fluid Dynamics: applies to commercial aircraft, general aviation and military aircraft (1970s–2016)
2. NASA Structural Analysis (NASTRAN): applies to commercial aircraft, general aviation and military aircraft (1960s–2016)
3. Composite structures: applies to commercial aircraft, general aviation and military aircraft (1970s–2016) (pointing to the fuselage, the tail, and the blade)
4. Drive train/gearbox (1970s–2016) (pointing to the bottom of the helicopter blades)
5. Propulsion: (1980s–2016) (pointing above the fuselage area)
6. Crashworthiness: applies to commercial aircraft, general aviation and military aircraft (1970s–2016) (pointing below the windows in the fuselage area).
7. Glass cockpit: applies to commercial aircraft, general aviation and military aircraft (1970s–1980s) (pointing to the cockpit).
8. Digital flight control systems: (1970s–1980s) (pointing to the cockpit area)
9. Rotor Research Program: (1950s–1990s).
10. Research aircraft/wind tunnels/simulators: (1970s–2016)
11. Air loads database: (1980s–2016)

The research conducted at Langley Research Center on metallic materials for rotorcraft has been primarily focused on fatigue and fracture testing and analyses and crash dynamics. Most dynamic components in helicopters are designed with a safe-life constant-amplitude testing approach that has not changed in many years. In contrast, the fatigue methodology in other industries has advanced significantly in the last two decades. Recent research[1] at the NASA Langley Research Center and the U.S. Army Aerostructures Directorate at Langley are reviewed relative to fatigue and fracture design methodology for metallic components. Most of the Langley research was directed towards the damage tolerance design approach, but some work was done that is applicable to the safe-life approach. In the areas of testing, damage tolerance concepts are concentrating on the small-crack effect in crack growth and measurement of crack opening stresses. Tests were conducted to determine the effects of a machining scratch on the fatigue life of a high-strength steel. In the area of analysis, work was concentrated on developing a crack closure model that will predict fatigue life under spectrum loading for several different metal alloys including a high-strength steel that is often used in the dynamic components of helicopters. Work is also continuing in developing a three-dimensional, finite-element stress analysis for cracked and uncracked isotropic and anisotropic structures. A numerical technique for solving simultaneous equations, called the multigrid method, is being pursued to enhance the solution schemes in both the finite-element analysis and the boundary element analysis. Finally, a fracture mechanics project involving an elastic-plastic finite element analysis of J-resistance curve is also being pursued.

4.5.1. Crash Testing of the CH-47 Chinook Helicopter[2]

In 1975 and 1976, two full-scale crash tests of the CH-47 “Chinook” helicopter were performed in support of the U.S. Army Aviation Applied Technology Directorate located at Ft. Eustis, VA. The CH-47 helicopter is a heavy lift, troop, and equipment transport helicopter. The objectives of the crash tests were to evaluate the load-limiting performance of the seats, the structural response of the airframe, and the integrity of the cargo restraint systems. A series of photographs showing the sequence of events during the crash test of the CH-47 helicopter is shown in **Figure 4.5-2**. Data acquired from these initial helicopter crash tests were used to correlate with kinematic computer models. Also, results from the tests highlighted several potential structural and post-crash fire hazards.

In 1981, a full-scale crash test of the YAH-63 prototype helicopter was conducted at the Impact Dynamics Research Facility (IDRF).[3] This helicopter was designed and manufactured by Bell Helicopter Textron as its bid in the competition for the Army’s Advanced Attack Helicopter Program. The crash test was performed to evaluate the energy-absorbing and load-limiting features of the airframe, landing gear, and seats. A pretest photograph of the YAH-63 helicopter in the impact position is shown in **Figure 4.5-3**. A photograph of the YAH-63 during the crash test is shown in part 2 of this figure. The Bell airframe did not win the award, which went to the Hughes Helicopter (now Boeing) AH-64 Apache.

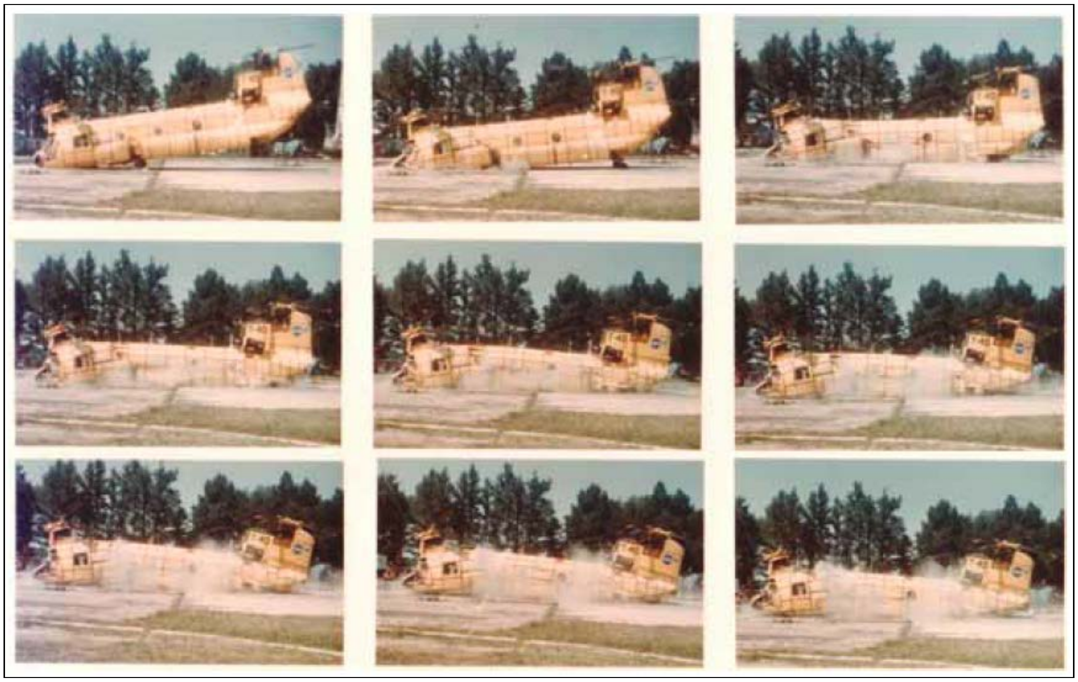


Figure 4.5-2: Series of Photographs Showing the Deformation of the CH-47 Helicopter During Crash Testing.

(a) Pre-test photograph. (b) Photograph during impact.

Figure 4.5-3: Pre- and Post-Test Photographs of the Bell YAH-63 Helicopter.

References

[1] https://ntrl.ntis.gov/NTRL/dashboard/searchResults/titleDetail/N8816633.xhtml.

[2] http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20040191337.pdf

[3] Karen E. Jackson, Richard L. Boitnott, and Edwin L. Fasanella, Lisa E. Jones and Karen H. Lyle, "A History of Full-Scale Aircraft and Rotorcraft Crash Testing and Simulation at NASA Langley Research Center", NASA Document ID 20040191337, 2004.

4.6. Supersonic Aircraft

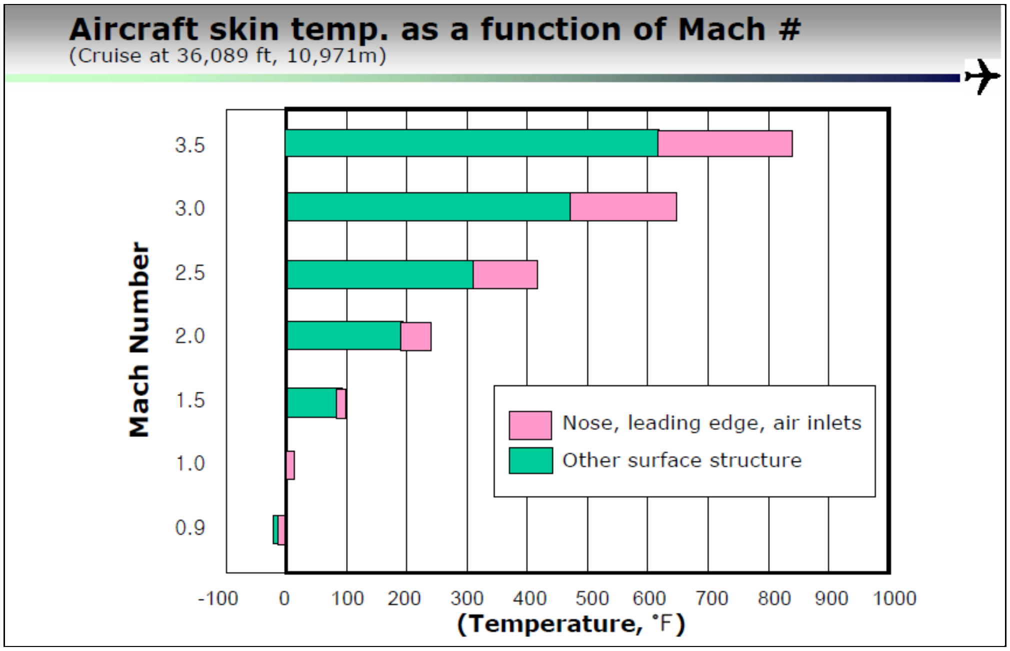


Figure 4.6-1: Skin Temperature as a Function of Mach Number.

Metallic materials and structures has been a key element of every supersonic focused project since the late 1940s. As shown in **Figure 4.2-1**, these projects have included the X-1 through X-5 (1946–1956), the Supersonic Transport (SST) Program (mid-1950s–1971), YF-12 Project (1962–1978), SCAR Project (1970–1977), DoD led SR-71 Blackbird Project (1964–1998), HSR Program (1990–1999), and The Fundamental Aero Supersonic Project (2000–2020). Aerodynamic heating leads to increase in skin temperature of the aircraft, as shown in **Figure 4.6-1**. Materials have included high-temperature Al alloys and Al metal matrix composites (MMC), Titanium alloys and Ti MMC, superalloys, and high-temperature polymer matrix composites. The types of studies conducted by Langley researchers has included

- creep studies of Al alloys;
- thermal aging studies to assess microstructural stability;
- property measurements at room and at projected-use temperatures, alloy development with Al companies to achieve improved elevated temp properties and stable microstructure for long times at elevated temperatures;
- fatigue and fracture at service temperatures;
- time-temp-stress studies where specimens are repeatedly cycled through simulated service conditions;
- fabrication technology to manufacture lightweight panels;
- lightweight structural concepts;
- structural sizing codes with temp dependent material properties;

- superplastic forming and diffusion bonding of Ti panels;
- NDE techniques to inspect multilayer panels designed for the load carrying fuselage structure;
- hot structure testing to validate structural analyses codes.

To fully appreciate the supersonic metallic materials story, a brief look back at the focused projects is included.

4.6.1. Titanium Alloys and Processing for High-Speed Aircraft

Titanium alloys are prime candidate materials for supersonic aircraft at speeds above Mach 2. Each class of titanium alloys has advantages and disadvantages for hot airframe structures. NASA studies different alloys to develop an understanding of the behavior of the alloy and to match particular alloys and processes to the appropriate application to maximize structural and operational efficiency. NASA also studied fabrication practices in an effort to identify practices that did not severely degrade material properties and could be accomplished at reasonable cost. A paper by Brewer, Bird, and Wallace[1] reviews some of the NASA sponsored research to develop titanium alloys and associated fabrication practice for application to airframe structures operating at speeds above Mach 2.0. The emphasis is on significantly improving the mechanical properties of titanium alloys over those of industry standards (Ti-6Al-4V, e.g.) while maintaining acceptable fabricability and long term stability in projected service environments. This study focused on the effects of heat treatment, service temperatures from –54ºC to +177ºC, and selected processing on the mechanical properties of several candidate beta and alpha-beta titanium alloys. Included are beta alloys Timetal 21S, LCB, Beta C, Beta CEZ, and Ti-10-2-3 and alpha-beta alloys Ti-62222, Ti-6242S, Timetal 550, Ti-62S, SP-700, and Corona-X. The emphasis was on properties of rolled sheet product form and on the superplastic properties and processing of the materials.

Another paper[2] by these researchers is typical of the work performed to address critical issues with candidate titanium alloys for supersonic airframe structures. NASA Langley also conducted a sizable effort to the fabrication and mechanical property characterization of titanium metal matrix composites. The typical type of studies conducted is found in the paper by Brewer, Unnam, and Tenney.[3] This study was undertaken to identify the mechanisms of mechanical property degradation in a Borsic (silicon-carbide coated boron) fiber reinforced Ti-3Al-2.5V composite exposed to elevated temperature. Samples containing 0.45 volume fraction of fibers were exposed, in vacuum, to temperatures from 700 K to 1255 K for times up to 240 hours. Room temperature tensile properties of unidirectional material were determined in both the longitudinal and transverse directions, before and after high-temperature exposure. Electron micro-probe analysis, scanning electron microscopy, and X-ray diffraction were used to determine the compounds formed and the extent of interaction between the boron, SiC coating, and matrix materials. In a follow-on to this study Brewer and Unnam[4] studied interface coating to reduce interaction between SiC fibers and the Ti matrix alloy. They observed that silicon titanium reactions in silicon carbide/titanium systems were reduced significantly by introducing aluminum or Ti3AI layers into the SiC/Ti system. The Ti3Al was somewhat more effective in reducing the reactions than pure aluminum. In addition, they found that coating the fiber with a 1 pm thick layer of aluminum improved the as-fabricated strength of a stoichiometric SiC fiber and reduced the fiber degradation during exposure to composite-fabrication conditions. These improvements in fiber properties carried over into improved composite properties. Applying an interfacial barrier by coating the matrix foils instead of the fibers was found to be an effective method for improving composite strength. Composites made with aluminum-coated TiA55 matrix foils had about 50% greater tensile strength than composites made with uncoated foils. They also observed that significant improvements in composite strength were obtained by reducing the fabrication temperature. Strong, well-consolidated composites were fabricated at temperatures well below those customarily used for SiC/Ti composite fabrication.

4.6.2. Breaking the Sound Barrier: Proving the Feasibility of Supersonic Flight

The following section gives a chronology of the development of supersonic flight.[5] NASA's engagement in research related to supersonic structures and materials was driven by the overall efforts in the world to fly faster and further. The United States' decisions to fund research related to supersonic flight was driven first by national defense considerations and having air superiority and secondly by balance of trade considerations. The need to help commercial air carriers compete in the world market and the desire to reduce travel times for long haul aircraft routes were significant factors in securing government funding for high speed research.. Below is a list of significant historical events:

- 1940s: NACA's Langley Aeronautical Laboratory develops experimental supersonic aircraft to understand the transonic region
  - XS-1 (built by Bell Aircraft Company)
  - D-558 (build by Douglas Aircraft Company)
- October 14, 1947: test pilot Chuck Yeager broke the sound barrier by going at Mach 1.06 in the XS-1
- 1951: Whitcomb's transonic area rule allowed for a significant reduction of drag during the transonic regime
- September 1952: two Boeing engineers publish a paper stating commercial SSTs are not feasible because of the increased costs (they recommended the idea be revisited in 30–40 years)
- 1956: Eggers developed the "supersonic wedge principle." By placing the body of the aircraft entirely under the wing the shockwave produced by the body would create pressure on the bottom of the wing adding lift and increasing aerodynamic efficiency at Mach 3 by 20% to 30% (this would make cruising at supersonic speeds possible).
- 1956: the Air Force propulsion laboratory shows that blade cooling techniques could be safely applied to engines improving the supersonic efficiency
- 1956: Boeing starts a company funded project to study the development of a supersonic transport, and England soon follows with its own program.
- October 1956: the Air Force redirects the WS-100 program toward sustained supersonic flight
- November 1956: first flight of ConvairB-58 Hustler (a Mach 2 capable bomber). This aircraft was capable of achieving supersonic flight for only a short duration (minutes)

- 1957: Boeing and North American submit proposals for new supersonic aircraft
- 1957: pressure to fund commercial SST research and development was mounting and a general belief that such a technology would be widely available within 10–15 years was spreading. One problem was that the project would need to be government-funded since U.S. manufacturers were hurting from producing the jet aircraft and did not have the resources for another large scale development project.
- 1960s: After the successful creation of supersonic military jets, the launch of Sputnik, and the burgeoning Cold War (all in the 1950s) the race to create a commercial version of the aircraft was on.
- 1960s: the United Kingdom, Soviet Union, France, and the U.S. all funded SST Programs
  - In their view they were competing for continued balance of trade, technological parity or superiority, and national prestige
  - It was believed that a commercial SST would make the jet aircraft obsolete

  This development was conducted in a setting where increased speed was considered a virtue (good in its own right).
  - Cultural enthusiasm for technology (both pre-and postwar)
  - Faster transport and ways of doing business promised increased profits and a stronger economy
  - In aviation, progress came to be defined as higher speeds and altitudes

4.6.3. NACA, NASA, and the Supersonic-Hypersonic Frontier

4.6.3.1. Early History of NACA Research on High-Speed Flight

Across the history of flight, adversity and seemingly insurmountable challenges have goaded and inspired aerospace scientists and engineers into producing some of aviation's greatest scientific and technical accomplishments. The advent of the supersonic-hypersonic age[6] and the work of the professional staffs of NACA and its successor, NASA, certainly exemplify this. Over the first three decades of NACA, the speed of American operational aircraft rose fourfold to over 550 mph by the end of World War II. By that time, the anticipated speed of the most advanced American aircraft, then under development, the Bell XS-1, was almost double this. Conceived in 1944 and designed and built during 1945, it eventually reached nearly 1000 mph in 1948. (A derivative of this same design, the X-1A, having greater fuel capacity, and thus longer engine-burn time, exceeded 1600 mph in 1954.) Some of the aircraft that made headlines in the 1950s are shown in **Figure 4.6-2**.

Figure 4.6-2: Typical high-speed research aircraft that made headlines in the 1950s. The Bell X-1A (lower left) had much the same configuration as the earlier X-1. Joining the X-1A were (clockwise); the Douglas D558-I Skystreak; Convair XF92-A, Bell X-5 with variable sweepback wings, Douglas D-558-I Skyrocket; Northrop X-4; and (Center) the Douglas X-3.

In 1958, the pioneer era of supersonic flight ended, coincident with the closing of the NACA era, the onset of the NASA era, and the beginning of the Space Age signaled by the launch of Sputnik. That year, the last flying X-1 (the X-1E) retired, the Lockheed F-104 Starfighter (the first operational Mach 2 military aircraft) entered service, and airlines began their first transoceanic intercontinental jet transport operations, with de Havilland's Comet IV, Boeing's 707, and the Douglas DC-8. By this time, planners were conceptualizing operational aircraft at speeds over Mach 3, exemplified by a then-highly classified study effort that would spawn the Lockheed A-12/YF-12A/SR-71 Blackbird. The era of piloted hypersonic flight was dawning as NACA, the U.S. Air Force, the U.S. Navy, North American, and Thiokol put finishing touches on the first of the X-15s, a rocket-powered, air-launched "Round Two" successor to the early "Round One" research airplanes (such as the X-1 and Douglas D-558-2) that had blazed the sonic frontier a decade earlier. Further away, but gestating, were programs for both winged and ballistic orbital vehicles, typified by the "Round Three" study effort leading to the abortive Boeing X-20A Dyna-Soar (an important predecessor to the space shuttle), and the Man-in-Space-Soonest (MISS) studies eventually spawning Project Mercury.

4.6.3.2. From Subsonic to Supersonic

The high-speed breakthrough—from subsonic through transonic and on to supersonic and hypersonic velocities—constituted a singular milestone in the evolution of flight, enabling the achievement of routine rapid global air transport and access to space. The practical difficulties of high-speed flight did not become a significant hindrance to safe aircraft operations until the mid-1930s.

The "Round One" research airplanes contributed significantly to fundamental understanding in aerodynamics, stability and control, propulsion, and structures and thus to future aircraft design practice. The price for this was nine aircraft destroyed, with five aircrew killed (four pilots and one on-board technician) and others injured. Ironically, only one (the X-2 #1, lost in 1956 from inertial coupling at nearly Mach 3.2) came close to “pushing the envelope” at high Mach. Seven were propulsion-related losses. Four rocket-propelled research aircraft (the X-1 #3, X-1A, X-1D, and X-2 #2) exploded on the ground or in the air from frozen leather seals contaminated with tricresylphosphate detonating under the jolt of pressurization. These catastrophes, the cause of which took far too long to identify, claimed two Boeing EB-50 Superfortress launch airplanes as well. The seventh was a D-558-1 #2 that crashed on takeoff due to turbine disintegration that severed its control lines. The X-5 #2 crashed when its pilot inadvertently entered an unrecoverable (and fatal) spin.

By the time of the creation of NASA, the “pioneering days” of supersonic flight had passed, and the “macro” performance boundaries of future transonic and supersonic aircraft—to Mach 0.82+ at over 40,000 feet for commercial air transports, and to Mach 2+ at over 60,000 feet for the most advanced military aircraft—were well established. Generally speaking, a half century later, they remain unchanged. From this point on, emphasis would be upon refining explicit aircraft performance parameters and capabilities within these general boundaries, for example, delaying transonic shock formation by tailored supercritical airfoils; improving supersonic lift-to-drag and cruise efficiencies; refining aerodynamic-structural-propulsion integration; enhancing control efficiencies as evidenced by the fly-by-wire revolution; exploring exploitation of advanced electronic stability and control architectures with relaxed-stability (or even inherently unstable) aircraft configurations made possible by the composite revolution to generate previously unattainable designs, such as optimized low observable (e.g., “stealth” reduced radar cross-section) aircraft, high-aspect-ratio “spanloaders,” and highly agile transonic and supersonic aircraft (exemplified by the X-29 and X-31); enhancing the thrust-to-weight and reliability of the gas turbine power plant itself; searching for cleaner, more efficient high-performance engines; and tailoring supersonic aircraft shapes to reduce sonic boom formation and impingement. This continuing refinement defined NASA’s aeronautics endeavors in the transonic and supersonic field in the post-1958 period, replacing the “epic” search for solutions and basic knowledge that had characterized the work of NACA in the “crisis” days of early transonic and supersonic exploration when the transonic slotted throat tunnel was a thing of the future and the transonic-supersonic research airplane the most reliable (if risky) means of securing “real world” data.

Generally speaking, however, NACA’s and NASA’s work in the difficult years of the transonic and supersonic era was overwhelmingly excellent, as evidenced by the frequent requests by foreign governments and research establishments for reports and familiarization visits. Continuing a trend found in global aeronautics in the late 1930s, both foreign and American companies in the postwar years generally looked to NACA as the recognized global authority (certainly in the West) on aircraft design and research.

4.6.4. SST Program

Supersonic manned flight officially began with Air Force test pilot Capt. Chuck Yeager’s October 14, 1947 flight of the experimental Bell X1 research rocket plane over what is now Edwards AFB, California. Generations of increasingly fast and capable military aircraft followed, culminating in the “supercruise” capabilities of the fifth generation F22 Raptor and F35 Lightning II. Bringing supersonic flight to commercial transport, however, proved far more difficult. Only two aircraft have flown regular commercial schedules the Tupolev Tu144 and the Aérospatiale (now EADS)/BAC (now BAE) Concorde.

The Tu144 first went supersonic on June 5, 1969, and, 10 days later, became the first commercial transport to exceed Mach 2. What had seemed an edge for the Soviet Union turned sour with a crash at the 1973 Paris Air Show. This delayed its introduction into passenger service until November 1977, two years after Concorde. The next May, a Tu144D crashed during delivery, and the passenger fleet was permanently grounded after only 55 scheduled flights.

The first supersonic flight of the Concorde was on October 1, 1969, although it did not begin regular commercial flights until January 1976. The Tupolev's problems significantly reduced airline interest in supersonic transports, however, as did a major spike in fuel costs. And with environmental concerns about sonic booms soon leading to a ban on overland flights, the market essentially vanished. British Airways (BA) and Air France flew flights supersonically across the Atlantic from 1978 to 1980, ending when the plan proved unprofitable. The two announced simultaneous plans to retire the Concorde in 2003—Air France in June and BA in October.

Although, a commercial supersonic transport was never built in the United States, considerable R&D was done by Boeing and Lockheed and by NASA in the late 1960s and early 1970s.

4.6.4.1. NASA Engagement in Supersonic Flight

The research at NASA Langley Research Center in supersonic technology (Error! Reference source not found.) was documented in a book by Joe Chambers[7] entitled "Innovation in Flight." Research on high-speed flight technology began in the mid-1930s and continues through the present time (2016). This research had been started and terminated several times over the years as National Priorities in aviation have changed. In the early days, the focus was on fundamental understanding of the issues associated with supersonic flight ranging from the aerodynamics of basic shapes and aircraft configurations, development of experimental methods and test facilities, structural designs, and the development of long life materials for hot structures. Results of this early research performed by NACA formed the bases for the Department of Defense and U.S. industry in designing fighters and other high-speed aircraft of the 1950s and later.

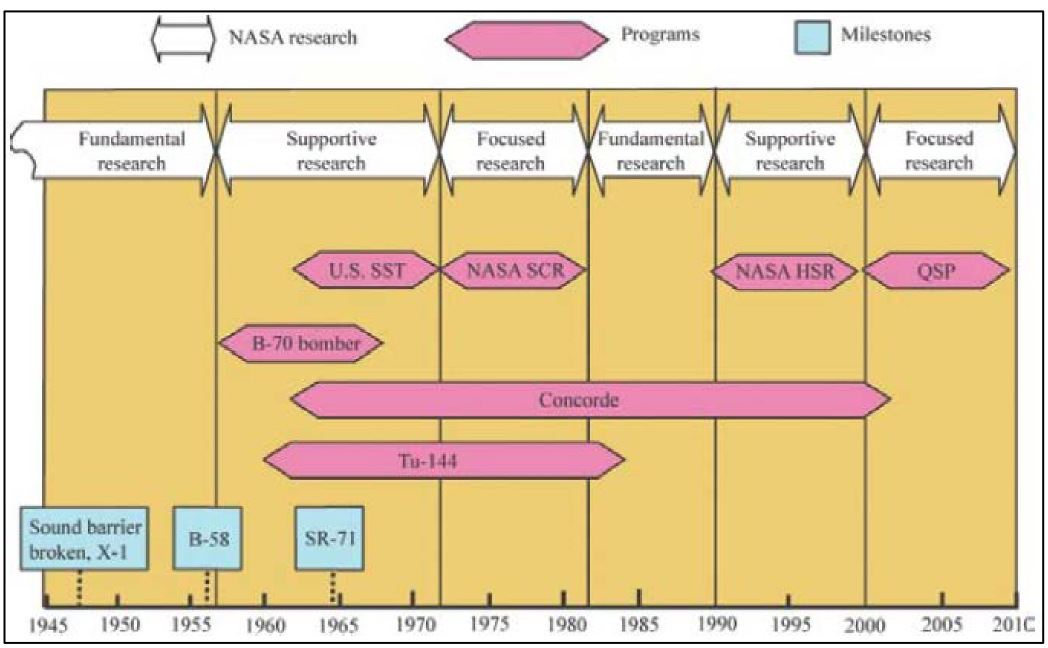


Figure 4.6-3: Chronology of Supersonic Research at NASA Langley Research Center.

After its formation in 1958, the National Aeronautics and Space Administration—in keeping with the reason for its creation—began devoting the lion's share of its growing resources to the Nation's new civilian space programs. Yet, 1958 also marked the start of a new program in the time-honored aviation mission that the new Agency inherited from NACA. This new task was to help foster an advanced passenger plane that would fly at rates at least twice the speed of sound, a concept initially named the Supersonic Commercial Air Transport (SCAT). The strategy for developing SCAT depended heavily on leveraging technologies being developed for another Air Force bomber—one much larger, faster, and more advanced than the B-58. This would be the revolutionary B-70, designed to cruise several thousand miles at speeds of Mach 3. NACA experts had been helping the Air Force plan this giant intercontinental bomber since the mid-1950s (aerodynamicist Alfred Eggers of the Ames Laboratory conceived the innovative design for it to ride partially on compression lift created by its own supersonic shock waves). North American Aviation won the B-70 contract in 1958, but the projected expense of the program and advances in missile technology led President Dwight D. Eisenhower to cancel all but one prototype in 1959. The administration of President John F. Kennedy eventually approved production of two XB-70As. Their main purpose would be to serve as Mach 3 test beds for what was becoming known simply as the SST, for "Supersonic Transport." Even though DoD resources, especially the Air Force's, would be important in supporting SST development, the aerospace industry made it clear that direct Federal funding and assistance would be essential. Thus, research and development (R&D) of the SST became a split responsibility between the Federal Aviation Agency and the National Aeronautics and Space Administration—with NASA conducting and sponsoring the supersonic research and the FAA overseeing the SST's overall development. Much of NASA's SST-related research involved advancing the state of the art in such technologies as propulsion, fuels, materials, and aerodynamics. These research activities began to proliferate under the new pro-SST Kennedy administration in 1961. After the president formally approved development of the supersonic transport in June 1963, sonic boom research really took off. Langley's experts, augmented by NASA contractors and grantees, published 26 papers on sonic booms just three years later, while Ames also conducted related research. An excellent summary of the early sonic boom research a NASA Aeronautics Book entitled "Quieting the BOOM."[8] NASA research encompassed most of the disciplines. In the area of configuration aerodynamics over 30 basic configurations concepts were explored. The four most promising concepts were explored by Boeing and Lockheed under contracts[9] to NASA that began in Feb. 1963 and were completed in Sept. 1963. These studies concluded that derivatives of at least two of the four configurations were technically feasible. These studies demonstrated the desirability of a titanium airframe and the necessity of advanced engines. However, it was indicated that resulting airplanes would be larger and heavier than corresponding subsonic jets, and their economic feasibility was questioned.

4.6.4.1.1.Structures and Materials

The supersonic transport poses many structures and materials problems associated with the long life time and relatively high temperatures to which the structure will be subjected. Studies of different structural concepts for the supersonic transport in the Mach 2.5 to Mach 3 range by both industry and NASA indicate that the lightest weight structures could be achieved through the use of titanium alloys. Titanium favored skin-stringer construction for both wing and fuselage structures. The leading titanium alloy of interest at that time was 8Al-1Mo-1V. NASA initiated a comparative study of several different methods of fabricating skin-stringer panels representative of wing compression cover skins (see results in **Figure 4.6-4)**. In addition to studies of fabrication technology, considerable effort was also devoted to studying the fatigue characteristics at elevated temperatures. Although several promising materials were examined, the bulk of the effort was on Ti-8Al-1Mo-1V and Ti-6Al-4V. An example of the type of research being conducted at that time can be found in an article by L.G. Imig and L.E. Garrett.[10] Key researchers at Langley during this period who were publishing research papers on materials for SST applications included George Heimerl,[11,12] David A. Braski,[13] Bland A. Stein,[14] W. Berry Lisagor,[15] and Dick M. Royster.[16] NASA work on Ti-8Al-1Mo-1V alloy[17] showed that it was very susceptible to hot salt stress corrosion and was dropped from further research efforts by NASA and industry. Extensive research was also performed by NASA Langley Researchers[18] on the effects of longtime environmental exposure on mechanical properties of sheet materials for a supersonic transport.

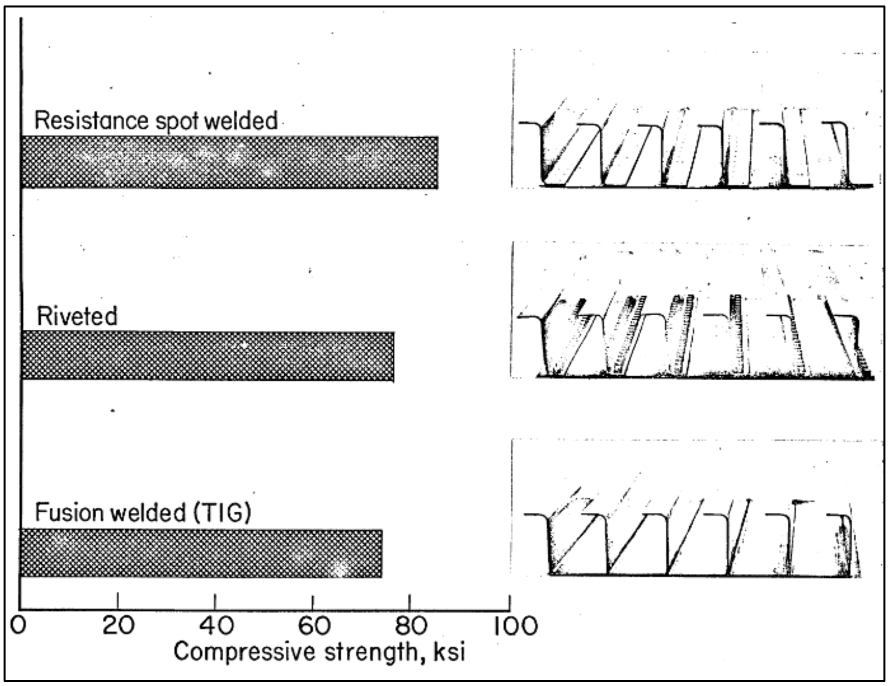


Figure 4.6-4: Compressive Strength of Skin-Stringer Panels fabricated from Ti-8Al-1V Alloy Sheet.

Congress cancelled the U.S. SST Program in March 1971. Cancellation justification was based on both environmental and performance issues. Environmentally, many countries outlawed supersonic flight overland because of the sonic boom, thus severely restricting projected market penetration; atmospheric scientists predicted catastrophic reductions of ozone from engine emissions severely restricting fleet size; aircraft regulators wanted the engines that were designed for supersonic flight to meet subsonic noise certification standards; and health officials were concerned about the effects of high-altitude atmospheric radiation. In addition, performance issues that were cited for the cancellation included the need for more efficient lift-to-drag ratio for both subsonic and supersonic flight; sufficient thrust from propulsion at both supersonic and subsonic speeds with low noise and efficient fuel consumption; airframe structures and materials with greater strength with less weight, and system integration techniques to maximize airplane efficiency. Another unresolved problem in the structures area was related to poor flutter characteristics of the aircraft and high-operating empty-weight fraction which adversely affected the economics of the aircraft.

Following the cancellation of the U. S. National SST Program, NASA was requested in 1972 to initiate a Supersonic Cruise Aircraft Research (SCAR) Program to provide the further data required to make rational decisions in the United States relative to future development of military and civil supersonic cruise aircraft.

4.6.5. Supersonic Cruise Aircraft Research (SCAR) Program

The Supersonic Cruise Aircraft Research Program was initiated in 1972 and the structures and materials subprogram was focused on technology advances needed to achieve major reductions in the airframe structural weight of large, flexible, high-temperature, long-life supersonic aircraft. Primary emphasis was placed on the design and development of advanced structural concepts that would be applicable to high-performance supersonic cruise aircraft and to the development, manufacture, and proof test of advanced titanium and composite components for application in both primary and secondary structures.[19]

The materials contracts initiated under the SCAR Program are shown in **Figure 4.6-5** and **Figure 4.6-6**. The work performed on polymers and polymer matrix composites is covered in a companion document entitled "Structural Framework for Flight: NASA's Role in Development of Advanced Composite Materials for Aircraft and Space Structures,", authored by Tenney and Co-authors and will not be covered in this monograph focused on metals.

NUMBER	TITLE	COMPANY	AWARD COMPLETION	COST $K
NAS2-7331	Synthesis of Perfluorinated Polyesters for Sealant Application	Peninsula Chemical Corporation	Dec 1972 -	91
NAS7-100	Prediction of Service Life of Sealant Materials	Jet Propulsion Lab	-	85
NAS2-7112	Characterization of Polybenzimidole Composite Foams	Whittaker Corporation	-	18
NAS2-7981	Crosslinking and Degradation Mechanisms in Model Sealant Candidates	Ultra Systems, Inc.	-	29
NAS2-8103	Synthesis of Heterocyclic-Block	Stanford Research Institute	-	16
NAS2-7341	Design, Fabrication and Operation of a Fuel Tank Sealant Exposure Apparatus	Boeing Commercial Airplane Company	Nov 1972 -	48
NAS1-12079	Improved Resins for AST Composites	General Electric Research	Jan 1973 Oct 1976	400
NAS3-16799	Development of Polyphenylquinoxaline/ Graphite Composites	Boeing Company	Mar 1973 -	89
NAS3-17770/ NAS3-17824	Development of Autoclavable Polyimides	TRW, Incorporated	Jun 1973 -	193
NAS1-12308	Study of Time - Temperature-Stress Capabilities of Composite Materials for Advanced Supersonic Technology Application	General Dynamics Corporation	Jun 1973 Apr 1976	919
	Miscellaneous Polyimide Resin Support			33

Figure 4.6-5 SCAR Polymer and Composites Contracts and Grants

In the SCAR program research in metals was focused on two major technology areas, fabrication of structural panels and long term durability in simulated flight service environments. An example of the types of research efforts directed at service lives can be found in a key reference by Cooper and Heldenfels[20]. In the area of fatigue Langley researcher L. Imig[21] was a key player[22] and his work was pioneering[23] in nature.

NUMBER	TITLE	COMPANY	AWARD COMPLETION	COST $K
NAS1-13681	Effects of Simulated Service and Flight Service Environments on the Performance of Aluminum Brazed Titanium Honeycomb-Core Sandwich Construction for Supersonic Cruise Aircraft Research	Boeing Commercial Aircraft Company	Nov 1974 Jan 1979	68
NAS1-13897	Flight Service Evaluation on Boeing 737 Aircraft of Two Aluminum Brazed Titanium Spoilers for Supersonic Cruise Aircraft Research	Boeing Commercial Aircraft Company	May 1975 Nov 1978	33
NAS1-11820/ NAS1-13649	Continuation of Real-Time Testing	Lockheed-California Company	Jan 1973 Jun 1976	111
NAS1-12501	Acceleration of Fatigue Tests for Advanced Supersonic Transports	Boeing Company	Jun 1973 -	235
	Miscellaneous Structural Panels			8C
NSG-1228	Fracture of Advanced Composites	George Washington University	Sep 1975	31
NAS1-12675	Fabrication of Graphite/Epoxy Specimens	McDonnell Douglas Aircraft	Oct 1974	190
AF Contract FO 4606-73-C-0013	AST Structural Panel Program	Lockheed-California Company	Oct 1972	934
NAS1-13095	Fabrication of Structural Tests Specimens	DWA Composite Specialties, Inc.	Apr 1974 Sep 1975	15
NAS1-13306	Borsic/Aluminum Panels	United Aircraft Hamilton Standard	Apr 1974 -	12

Figure 4.6-6: SCAR Metals and Metal Matrix Composites Contracts and Grants

At the initiation of the DOT/SST program, Lockheed-California Company in 1965 undertook a study to determine the lives of notched titanium-alloy coupons for both real-time/temperature/stress tests and accelerated fatigue tests. NASA assumed responsibility for the study in January 1972 with the SCAR program under Contract NAS1-11820. The objective of this study is to subject titanium specimens to flight-by-flight loading and heating and to apply approximately 3000 real -time flights per year. Lockheed's tests employed six titanium alloy materials (Ti-8Al-1Mo-1V sheet, mill, duplex, and triplex annealed; Ti-8Al-1Mo-1V mill annealed extrusion; Ti-6Al-4V mill annealed sheet; and Ti-6Al-4V solution treated and aged extrusion) and four test conditions. All of the tests were conducted with flight-by-flight fatigue loading. Real time tests emulated the real-time cyclic heating of wing-skin material for a supersonic transport. The other three test conditions (accelerated tests) neglected the real-time aspect of the supersonic transport service environment and were conducted with rapid cyclic temperature, constant elevated temperature, and constant room temperature.

Fatigue lives for real-time tests were within the range of lives for the three kinds of accelerated tests (except for the Ti-6Al-4V sheet which had longer lives than any accelerated test). Fatigue lives for real-time tests of all materials were longer than the lives from accelerated tests with constant elevated temperature. For most of the materials, the accelerated tests at room temperature and the accelerated tests with cyclic temperature yielded fatigue lives which more closely represented the real-time fatigue lives than the fatigue lives from the constant elevated temperatures. In order to investigate the influence of thermal stresses on fatigue life of structural elements and to establish test methods to shorten and simplify fatigue testing, a contract (NAS1-12501) was awarded to The Boeing Company in 1974. The structural element utilized in the test program consisted of a flat sheet with a hat-section stringer attached with rivets. Thermal stresses were developed through non-uniform heating to simulate supersonic transport aerodynamic heating environments. The fatigue life and failure locations were established in the tests. Rapid thermal cycling and load cycles were employed in the tests. The results of the contract are empirical stress/number-of-cycles, (S-N) curves for the titanium structural elements and analysis that accounts for thermal soak effects. For information on related work performed at the Langley Research Center on real-time and accelerated fatigue tests, see papers by Imig.[10,24] The fatigue lives from the Boeing accelerated tests of Ti-6Al-4V annealed specimens with cyclic temperature were about the same as those obtained in the Lockheed real-time tests.

Fabrication Technology

A key reference for the biography of SCAR is found on the NTRS.NASA.gov web site.[25] An excellent paper[26] authored by Bales and coworkers entitled “Fabrication and Evaluation of Brazed Titanium-Clad Borsic@/Aluminum Skin-Stringer Panels” summaries some of the pioneering work done at Langley in support of supersonic flight. This paper summarizes much on the work performed at Langley to build and perform validation testing of a metal matrix composite structural panel. An example of the excellent research done during this period can be found in a paper by Bales, Wiant, and Royster.[27] In this study, a fluxless brazing process was developed at the Langley Research Center that minimizes degradation of the mechanical properties of Borsic/aluminum composites. The process, which employs 718 aluminum alloy braze, is being used to fabricate full-scale Borsic/aluminum-titanium honeycomb-core panels for Mach 3 flight testing on the NASA YF-12 aircraft and ground testing in support of the SCAR Program. The manufacturing development and results of shear tests on full-scale panels are presented in this report. The location of the test panels on the YF-12 Aircraft are shown in **Figure 4.6-7**. Structural element testing was conducted at Langley and verified the adequacy of the BSC/Al-Ti honeycomb-core panel design to fulfill the design requirements of the YF-12 panels.

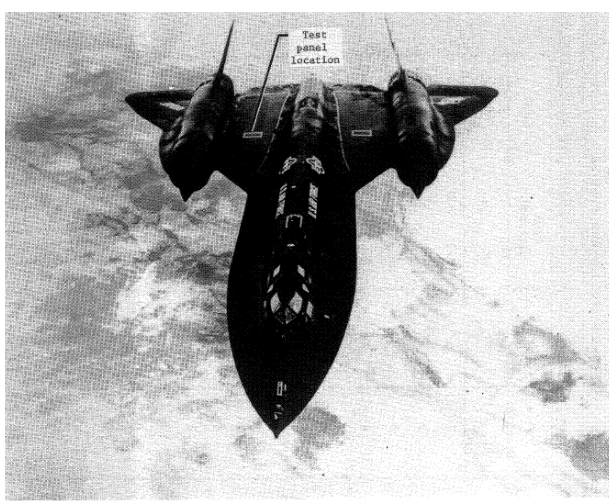


Figure 4.6-7: Test Panel Location on YF-12 Aircraft.
http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19830019827_1983019827.pdf.

Although, metal matric composites were studied during this period of time the major fabrication technology focus was on titanium alloys. Selected examples of the scope of manufacturing technology developed under the SCAR Program are illustrated in the following figures. **Figure 4.6-8** shows an example of the superplastic forming / diffusion bonding (SPF/DB) work performed by Bales[28,29] and coworkers[30,31,32] at NASA Langley Research Center.

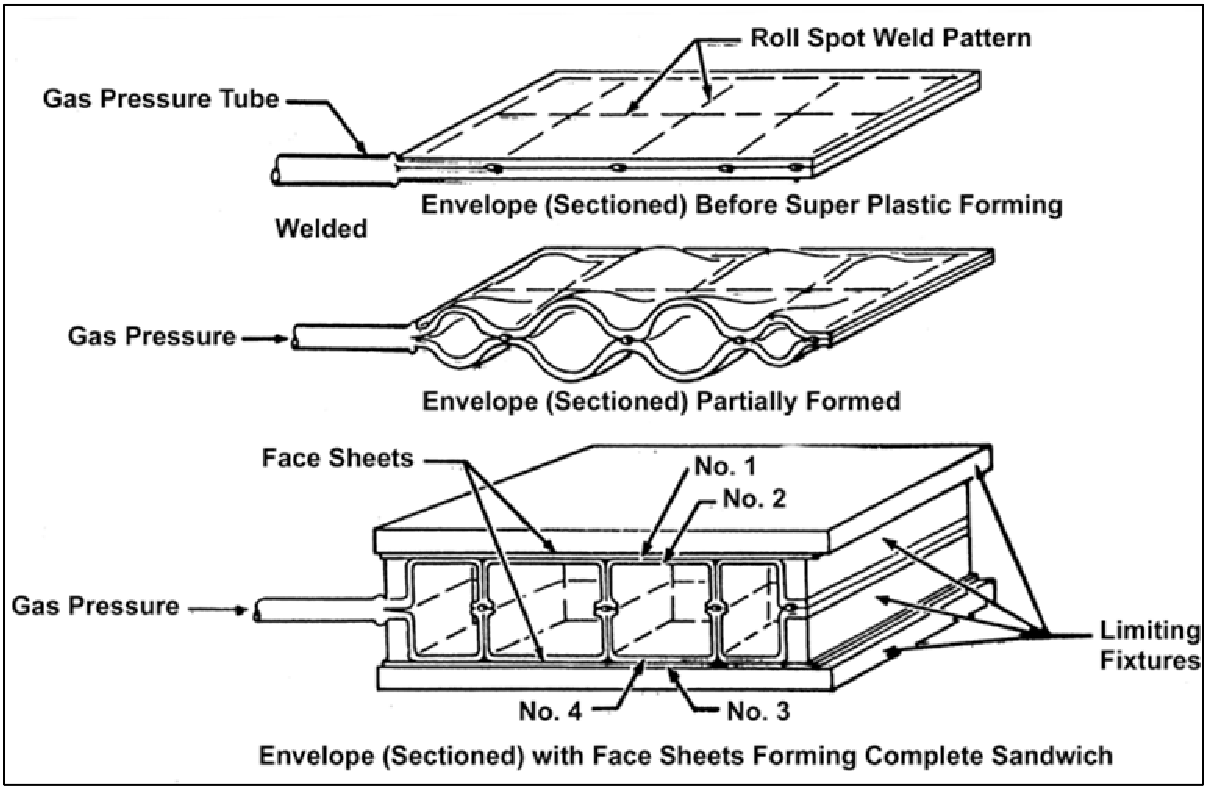


Figure 4.6-8: SPF/DB Titanium 4 Sheet Sandwich Fabrication.

Additional examples of the excellent fabrication technology research performed by Bales and coworkers are illustrated in the following two figures. **Figure 4.6-9** shows the forming stages of forming a two-sheet Ti panel by superplastic forming. **Figure 4.6-10** shows an example of a weld-bonded SPF beaded web truss core sandwich panel.

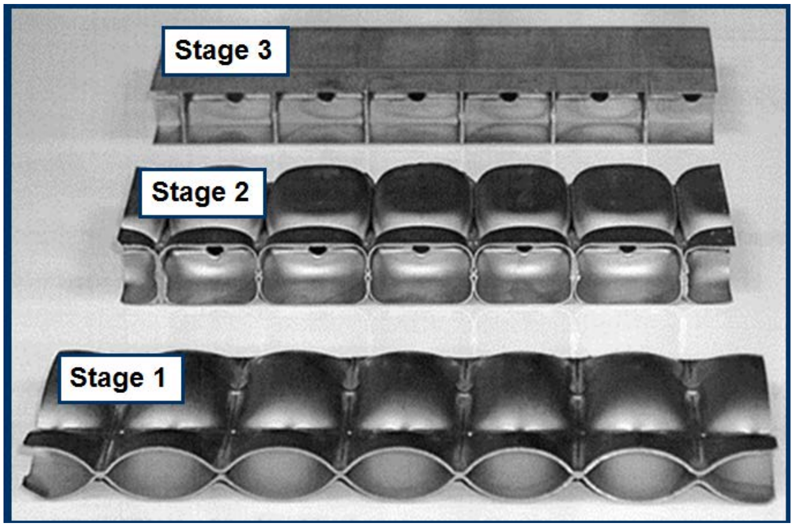


Figure 4.6-9: Three Stages of SPF Two Sheet Ti Core.

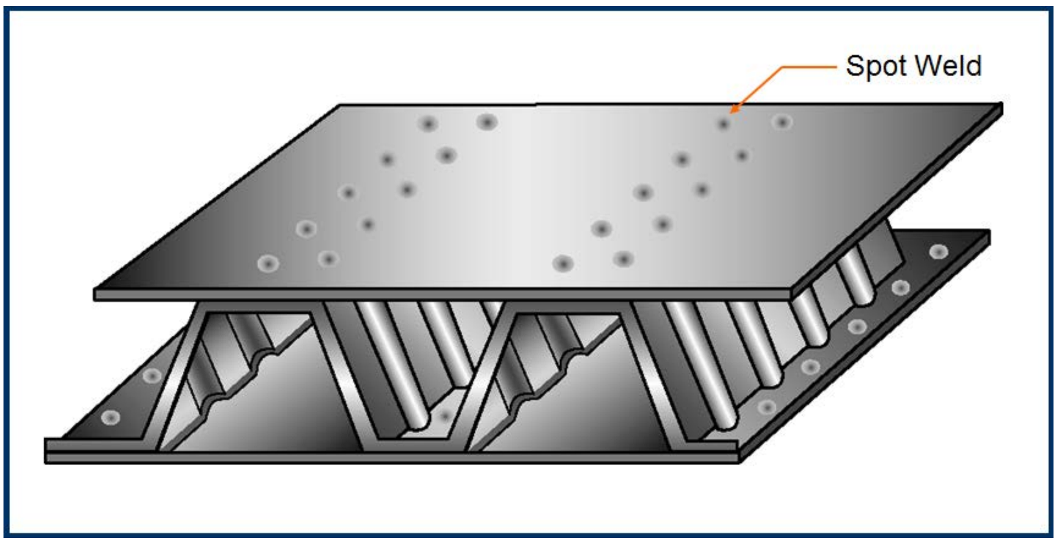


Figure 4.6-10: Weld-Bonded SPF Beaded Web Truss Core Sandwich.

4.6.6. High-Speed Research (HSR) Program

In 1997, NASA developed an aeronautics and space transportation technology strategic roadmap called the "Three Pillars for Success." As the name suggests, this plan mapped out NASA's future efforts and goals through the year 2020. Three categories (or Pillars) were described. The Pillar One focus was on Global Civil Aviation. Goals in Pillar One concentrate on increased civilian safety, reduced subsonic exhaust and noise emissions, and increased affordability. Pillar Two, Revolutionary Technology Leaps, is the location of the High-Speed Civil Transport Program. Also included in Pillar Two were programs to develop innovative design and manufacturing tools and technology. To maintain the nation's aeronautical leadership, NASA was to work in concert with the aircraft industry to develop enabling technologies for a HSCT. The enabling technology goals to be reached within 20 years were (1) reduce overseas travel time by 50 percent, (2) reduce exhaust emissions to well below today's subsonic engines, (3) decrease noise levels slightly below present engines, and (4) achieve this with, at most, a 15%

increase in today's subsonic fares. The focused program chartered to turn these goals into reality was embodied in the High-Speed Research (HSR) Program. Research efforts were targeted for a 300 passenger aircraft that would fly at supersonic speeds of Mach 2.4 and be capable of taking-off and landing at conventional airports. Many enabling technologies were required to meet this target configuration and the most critical were addressed in the HSR Program.

Finally, Pillar Three concentrated on access to space. Included in Pillar Three were efforts to reduce costs of spaceflight by developing reusable launch vehicles (RLV) and advancing propulsion technologies. To achieve all of the goals listed for each Pillar by the year 2020 strong partnerships between NASA, industry, and academia were undertaken.

Beginning in 1989, NASA and industry investigated the potential of a HSCT, the airplane specifications, and required technologies. The existing Mach 2 European Concorde and Russian Tu-144 airplanes are not environmentally acceptable or economically viable. The original U.S. SST design was planned for Mach 2.7, but its titanium structure was too heavy. In 1989, the National AeroSpace Plane Program was investing in Mach 25 technology for both Earth-to-Orbit transport and "Orient Express" civil transport applications. At these speeds, the required hydrogen fuel would dictate extreme changes in existing airport infrastructure, and the airplane efficiency would be limited because it would rarely see cruising speed with long acceleration and deceleration times required for passenger comfort. The studies concluded that an airplane launched in the early 21st century should be compatible with current airports, use jet fuel, and be within a 10- to 15-year technology reach. Both Boeing and McDonnell Douglas converged on a Mach 2.4, 300-passenger, and 5000 nautical mile airplane as a focus for technology development.

Based on the market and technology projections of a HSCT, NASA started the two phase HSR Technology Program in 1990 with the civil transport industry—Boeing, McDonnell Douglas, General Electric, and Pratt and Whitney. The $280 million Phase I Program focused on the development of technology concepts for environmental compatibility. With the successful completion of Phase I, the $1400 million Phase II Program started in 1993. This Phase was to demonstrate the environmental technologies and define and demonstrate selected high-risk technologies for economic viability. However, because of global economics and the U.S. industry focus on keeping their subsonic market viable, the HSR Program was cancelled in 1999. At this point in the program, the technology selections were made for final full and large-scale demonstrations based on medium-scale ground tests and flight tests.

The challenge associated with meeting the objectives of the HSCT concept vehicle is shown in **Figure 4.6-11**. Structures and materials was a major focus of NASA HSR Program. Although the HSR Project was focused toward a Mach 2.4 aircraft, work was also sponsored on materials for a Mach 1.8 to 20 aircraft. For these lower Mach numbers, high-temperature Al alloys were a viable and considerable research was performed with the University of Virginia, the Al companies, and Boeing and McDonald Douglas to develop improved high-temperature Al alloys. Research papers on this work are available in the open literature, and selected highlights of this work are discussed in section 5.4, "High-Temperature Al Alloy Development for Supersonic Aircraft." After the HSR Project was cancelled, work on these alloys was picked up by the DoD, and variants of the alloy chemistries studied have been used in DoD armor applications and for commercial aircraft wheels which experience rapid heating during landing.

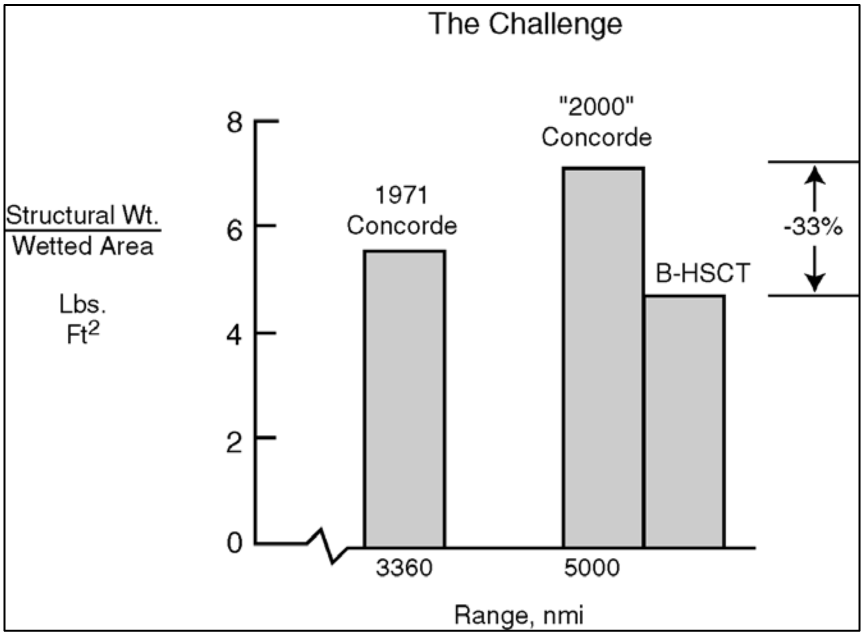


Figure 4.6-11: Weight Reduction Required to Meet Objectives of the Boeing HSCT Concept Vehicle.

The fraction of the operating empty weight for airframe structure is much smaller for a supersonic transport than for conventional subsonic commercial vehicles. This requires the use of innovative structural concepts and advanced materials to satisfy this stringent weight requirement. The operating environment is also more severe because of the high temperatures associated with the aerodynamic friction heating caused by supersonic cruise speeds.

The Mach 2.4 economically viable HSCT drives the materials and structures technology development with 60,000 hour durability at a cycled 350°F skin temperature and a 30-percent reduction in weight relative to the Concorde. Conventional airplane materials such as aluminum and thermoset composites such as bismaleimides do not have the temperature capability, and titanium alloys are too heavy for the entire airframe. Over 140 different materials were analyzed to down select to a handful of materials for the enhancement of mechanical properties and fabrication processes.

Titanium was a prime candidate for the main wing box which required high-strength for the high-temperature-stagnation regions of the aerodynamic surface leading edges. Advanced titanium alloys were developed with a goal of 20-percent improvement in mechanical properties. Major technology challenges included the effects of thermomechanical processing on optimum alloy compositions and the manufacturing processes for reducing costs and risks.

To reduce weight of the fuselage, outboard wing, strake and empennage, polyimide carbon fiber matrix composites (PMC) were developed. A NASA-patented polyimide resin called PETI-5, when combined with a vendor-produced IM7 fiber, demonstrated mechanical properties greater than bismaleimides at 350°F. A “wet” prepreg was developed for laboratory hand layup structures that required long cure times at high pressure in autoclaves to remove the volatiles and was demonstrated in the fabrication of large scale panels.

At the end of the program, dry prepreg was being developed that potentially had more affordable manufacturing processes such as resin film infusion and insitu robotic layup. Durability isothermal tests after 55,000 hours of a PMC showed no degradation, and PETI-5 had over 15,000 hours. Because of the criticality of the durability data, the thermal mechanical fatigue tests were continued after the end of the program.

NASA's High-Speed Research Program was on track to meet all of the environmental and economic goals established for the program. Technology was demonstrated in medium scale ground tests and flight tests. However, the program was cancelled in 1999 before the large scale demonstration test articles were developed and tested. The reasons given for the cancellation were primarily related to issues associated with environmental issues such as sonic boom during overland flights and a week business case for the aircraft to be profitable to operate.

4.6.7. Fundamental Aeronautics Supersonic Aircraft Project

The Commercial Supersonic Technology (CST) Project within the NASA Advanced Air Vehicles Program addresses development of tools, technologies, and knowledge that will help eliminate technical barriers to practical commercial supersonic flight. The challenges being worked in supersonics are sonic boom mitigation, take-off and landing noise, high-altitude emissions, lightweight durable structures and materials for engines, and aeroelasticity for long, slender SSTs. The two primary efforts to address those are N+2 and N+3. N+2 is a 2025 TRL capability for a small supersonic airliner in the transatlantic range, meeting environmental goals that will enable it to operate without any impact larger than current subsonic aircraft. N+3 is a generation beyond that—a 2035 technology availability date and a larger airliner, in the 100–200 passenger class, with transpacific range, again meeting all environmental restraints in place at that time. That obviously requires more technology.

N+2 system validation activity is working on technologies such as shaping the aircraft to reduce sonic booms, nozzle concepts for low take-off and landing noise, and 3-D modeling and design methodology that would allow researchers to simulate boom reduction and efficiency enhancement. The goal is a design optimization study focused primarily at creating a shaped sonic boom ground signature with a perceived loudness of less than 80 PNdB, which is judged to be the threshold for supersonic overland flight. Artist drawings of potential future supersonic concept vehicles are shown in **Figure 4.6-12** and **Figure** 4.6-13. An artist concept of a Boeing concept aircraft recently shown by NASA headquarters[33] is shown in **Figure 4.6-14**.

Figure 4.6-12: Artist Drawing of Future Supersonic Concept Vehicle. https://www.nasa.gov/press-release/nasa-invests-in-future-of-aviation-with-supersonic-research-projects.

Figure 4.6-13: Future Aircraft Design for Supersonic Flight Over Land. Concept is an "Inverted-V" engine under wing Configuration.

Figure 4.6-14: Rendering of Boeing's concept aircraft. Courtesy NASA.

Structures and materials for the airframe is not a current focus of NASA's supersonic aircraft project. However, if the goals for the sonic boom ground levels can be successfully demonstrated, future additional research on advanced materials to address long term durability and weight reduction will become key priorities.

References

[1] Brewer, W. D., Bird, R. K., Wallace, T. A.; "Titanium Alloys and Processing for High Speed Aircraft", NASA Technical Report, NAS1-20220, Jan. 01, 1996, http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20040110434_2004115408.pdf.

[2] Bird, R.K., Wallace, T.A., and Brewer, W.D.; "Effects of Heat Treatment on Microstructure, Strength, and Toughness of Timetal 21S", Proceedings of the 125th TMS Annual Meeting, 1996.

[3] Brewer, W. D., Unnam, J., and Tenney, D. R.; "Mechanical property degradation and chemical interactions in Borsic/titanium composite", Conference Proceedings (See A79-43228 18-23), The enigma of the eighties: Environment, Economics, Energy; Twenty-fourth National Symposium and Exhibition; Society Advanced Materials and Engineering, c. 1979, pp. 1288-1298, Publication date Jan. 01, 1979.

[4] Brewer, W. D. and Unnam, J.; "Interface Control and Mechanical Property Improvements in Silicon Carbide/Titanium Composites", NASA Technical Paper 2066, Aug. 1982.

[5] Supersonic Transport: Kieran Downes, Spencer Lewis, Alex Mozdzanowsk http://ocw.mit.edu/courses/engineering-systems-division/esd-85j-integrating-doctoral-seminar-on-emerging-technologies-fall-2005/lecture-notes/lec9_sst.pdf

[6] https://www.nasa.gov/pdf/607087main_NASAsFirst50YearsHistoricalPerspectives-ebook.pdf.

[7] Chambers, Joseph R.; “Innovation in Flight”, NASA SP-2005-4539.

[8] https://www.nasa.gov/sites/default/files/files/QuietingtheBoom-ebook.pdf.

[9] Alford, William J. and Driver, Cornelius; “Recent Supersonic Transport Research”, http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19660005992.

[10] Imig, L. A.; and Garrett, L. 5; “An Investigation of Fatigue Test Acceleration for Conditions of Mach-3 Fight Using Flight-by-Flight Loading”. NASA TN D-7380, December 1973.

[11] Heimerl, George J.; Baucom, Robert M.; Manning, Charles R., Jr.; and Braski, David N.; “Stability of Four Titanium-Alloy and Four Stainless-Steel Sheet Materials After Exposures up to 22 000 Hours at 550' F(561o K)”. NASA TN D-2607, 1965

[12] Heimerl, G. J.; Braski, D. N.; Royster, D. M.; and Dexter, H. B.: “Salt Stress Corrosion of Ti-8Al-1Mo-1V Alloy Sheet at Elevated Temperatures. Stress-Corrosion Cracking of Titanium”, Spec. Tech. Publ. No. 397, Am. SOC.Testing Mater., c.1966, pp. 194-214.

[13] Braski, David N.; and Heimerl, George J.: “The Relative Susceptibility of Four Commercial Titanium Alloys to Salt Stress Corrosion at 550^{o} F”. NASA TN D-2011, 1963.

[14] Stein, Bland A.; Dexter, H. Benson; and Royster, Dick M.; “Coatings and Surface Treatments for Longtime Protection of Ti-8Al-1Mo-1V Alloy Sheet From Hot-Salt Stress Corrosion”. NASA TN D-4319, 1968.

[15] Lisagor, W. Berry, Manning, Charles R. Bales, Thomas T.; “Stress Corrosion Cracking of Ti-6Al-4V Titanium Alloy in Nitrogen Tetroxide”, NASA TN D-4289, 1968.

[16] Royster, Dick M.; and Lisagor, W. Barry; “Effect of High-Temperature Creep and Oxidation on Residual Room-Temperature Properties for Several Thin-Sheet Superalloys”. NASA TN D-6893, 1973.

[17] Heimerl, George J.; Baucom, Robert M.; Manning, Charles R., Jr.; and Braski, David N.; “Stability of Four Titanium-Alloy and Four Stainless-Steel Sheet Materials After Exposures up to 22 000 Hours at 550' F(561 K)”. NASA TN D-2607, 1965.

[18] Pride, Richard A., Royster, Dick M., Stein, Bland A., and Gardner, James E.; “Effects of longtime Environmental Exposure on Mechanical Properties of Sheet Materials for a Supersonic Transport”, NASA TN D-4318, 1968.

[19] Cooper, P.A. and Heldenfels, R.R.; “NASA Research on Structures and Materials for Supersonic Cruise Aircraft”, NASA TM X-72790, Jan. 1976.

[20] Cooper, P.A. and Heldenfels, R.R ; “NASA Research on Structures and Materials for Supersonic Cruise Aircraft”, NASA TM X-72790, Jan. 1976.

[21] Imig, L. A.; “Effect of Initial Loads and of Moderately Elevated Temperature on the Room-Temperature Fatigue Life of Ti-8Al-1Mo-1V Titanium-Alloy Sheet”. NASA TN D-4061, August 1967.

[22] Imig, L. A.; and Illg, W.; “Fatigue of Notched Ti-8Al-1Mo-1V Titanium Alloy at Room Temperature and 550°F(560OK) With Flight-by-Flight Loading Representative of a Supersonic Transport.” NASA TN D-5294, July 1969.

[23] Imig,L.A.and Garrett, L.E.; “An Investigation of Fatigue Test Acceleration for Conditions of Mach-3 Flight Using Flight-by-Flight Loading”, NASA TN D-7380, December 1973.

[24] Imig, L. A.: "Crack Growth in Ti-8Al-1Mo-1V with Real Time and Accelerated Flight-by-Flight Loading". NASA TM X-72754, July 1975.
[25] http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19780004952_1978004952.pdf
[26] Thomas T. Bales, Dick M. Royster and Robert R. McWithey; "Fabrication and Evaluation of Brazed Titanium-Clad Borsic@/Aluminum Skin-Stringer Panels", NASA Technical Paper 1674, July 1980.
[27] Bales, Thomas T., Wiant, H. Ross, Royster, Dick M.; "Brazed Borsic/Aluminun Structural Panels", NASA TM X-3432.
[28] Royster, Dick M.; Davis, Randall C.; Shinn, Joseph M. Jr; Bales, Thomas T.; Wiant,H. Ross; "Fabrication and Evaluation of Superplastically Formed/Weld-Brazed Corrugated Compression Panels With Beaded Webs". NASA Technical Paper 2512.
[29] Bales, Thomas T.; ed.: "SPF/DB Titanium Technology". NASA CP-2160, 1980.
[30] Royster, Dick M.; and Bales, Thomas T.; "Elevated Temperature Behavior of Superplastically Formed/Weld-Brazed Titanium Compression Panels Having Advanced Shaped Stiffeners". NASA TP-2123, 1983.
[31] Royster, Dick M.; Bales, Thomas T.; and Wiant, H. Ross; "Superplastic Forming/Weld-Brazing of Titanium Skin-Stiffened Compression Panels. Materials Overview for 1982", Volume 27 of National SAMPE Symposium an Exhibition, Soc. Advance. Mater. & Process Eng., 1982, pp. 569-582.
[32] Royster, Dick M.; Bales, Thomas T.; Davis, Randall C.; and Wiant, H. Ross; "Fabrication and Evaluation of Cold-Formed/Weld-Brazed Beta-Titanium Ski Stiffened Compression Panels". NASA TP-2201, 1983.
[33] https://www.flightglobal.com/news/articles/nasa-proposes-x-plane-revival-with-supersonic-subso-421736/.

4.7. Hypersonic Flight Vehicles

The Hypersonic Research Projects worked by NASA have included (**Figure 4.2-1**) the X-20 Dyna-Soar Project (1957–1963), the X-15 Project (1959–1969), HL-10 and HL-20 Lifting Body Studies (mid-1960–2010), DC-X and DC-XA (1991–1996), X-30 NASP (1990–1993), X-33 and X-34(1996–2001), X-37 (1999–2011), HYPER X-43A (2001–2004), and hypersonic research in the Fundamental Aero Program (2004–2012).

4.7.1. Early Beginning: Historical Background

An excellent history of hypersonics research in the U.S. can be found in a NASA History Series publication entitled "Facing the Heat Barrier: A History of Hypersonics" by T. A. Heppenheimer.[1] This publication covers the early work in Germany on the V-2 rocket in the 1940s, the development of all of the Mach 3 and higher aircraft such as the SR-71, all of the aircraft noted above, as well as the technology development during the NASP Program, and the flight of NASA's X-43A. With this publication as a backdrop, comments in this section will be focused on some of the general materials considerations.

4.7.1.1. Airframe Structure and Aerodynamic Heating

If drag rise was the great challenge of transonic flight, and stability and control challenged supersonic flight, heating posed and poses still the great challenge to practical hypersonic flight. At hypersonic speeds aerodynamic heating gives rise to serious structural problems. One of the most critical is the combination of aerodynamic heating and thermodynamic effects, or "aerothermodynamics," leading to expansion and distortion of structures and greatly complicating the challenge facing structural designers. Understanding and accommodating such heating was a particular challenge on the Lockheed Blackbird flight development program, and it is a remarkable tribute to Clarence "Kelly" Johnson, Ben Rich, and the rest of the Lockheed "Skunk Works" design team associated with this remarkable aircraft that they were able, at a time of very little knowledge, to conceive, produce, and place in service an aircraft facing as daunting and unknown a flight environment as the X-1 had in the 1940s. High-supersonic aerodynamic heating studies constituted one of the key research "targets" for NASA researchers when they had the opportunity to use two early Blackbirds for a decade of concentrated supersonic cruise research beginning in the late 1960s.

In 1954 a team headed by John V. Becker of the NACA Langley Memorial Aeronautical Laboratory (now the NASA Langley Research Center) derived the basic X-15 configuration, stipulating a nickel-alloy Inconel structure, relatively conventional wing configuration, a rocketlike four-surface tail, and "off the shelf" rocket engines, in this case from the Hermes rocket (a V-2 program derivative). This influential study triggered development of the transatmospheric X-15, which first flew in 1959 (**Figure 4.7-1**). Powered by a 57,000-pound thrust throttleable rocket engine, the X-15 extended piloted flight through Mach 3 and 4 on to 5 and 6, and beyond, completing 199 flights by 12 pilots and reaching an altitude of 67 miles in 1963; it reached Mach 6.70 in 1967. Heating problems, challenging enough with the Blackbird, became acute with the hypersonic Mach 6+ North American X-15. On one flight, it experienced heating severe enough to shatter a cockpit panel. On another flight, in October 1967, heating nearly led to loss of the X-15 #2 when unexpected localized heating effects seriously damaged its structure, causing a dummy scramjet test article to separate from the craft; they also damaged its fuel jettison system, forcing a "heavyweight" landing that might have had—but fortunately did not—disastrous results.

X-15 researchers pursued aerodynamic and structural heating investigations through 1963, following these by using the X-15 to carry experiments into the upper atmosphere or to above Mach 5; many of these supported the Apollo effort. On October 3, 1967, Major William J. "Pete" Knight took a modified X-15, the X-15A-2, to Mach 6.70 (4520 mph), carrying a dummy supersonic-combustion (scramjet) engine shape. Unanticipated heating, caused by turbulent flows and inadequate dissipation, led to multiple structural failures and the melting of the dummy scramjet from the aircraft; it also damaged its fuel jettison system. Fortunately, Knight landed successfully. Shortly thereafter, Major Michael Adams, U.S. Air Force, was killed when the third X-15 broke up[2] following a combination of instrumentation and control systems failures aggravated by the pilot's own unusually susceptible vertiginous tendencies. Loss of this aircraft forced NASA to abandon ambitious plans to modify one of the X-15s as a scramjet-powered slender delta, a decision that, in retrospect, was unfortunate. Overall, the X-15 contributed greatly to the understanding of the requirements for practical hypersonic vehicles; the program generated 700 technical reports and demonstrated the value of undertaking repeated flight research missions as opposed to a few "technology demonstrations."

Figure 4.7-1: North American X-15 Mach 6+ Hypersonic Trans-Atmospheric Research Aircraft. NASA Image E-7411.

The development of low-density materials with higher strength and stiffness and more efficient engine and airframe structures is still considered enabling technology for reusable hypersonic vehicles. Advanced structural concepts are required for minimum weight hot structures that will be fully reusable. Key design drivers are maximum heating rate, duration of heating, total heat load, flight envelope and type of propulsion system, mission life requirements, and containment of liquid hydrogen. For hot structures applications in the range from 600–1800°F, advanced alloys of titanium, titanium and nickel aluminides, and metal matrix composites are leading candidates because of their high specific properties. For temperatures in excess of 2000°F carbon-carbon and ceramic-matrix composites are the most structurally efficient materials. An excellent overview paper by Tenney[3] and coauthors published in 1988 addressed the technology issues for lightweight hot structures, and gave a brief assessment of the state of the art at that time. Areas requiring additional development were also identified.

The period from the late 1980s through the end of the HYPER X project in 2004 was a very active time for research on high-temperature materials for hypersonic applications. During this time, NASA sponsored research on Ti alloys, Ti-MMC, TiAl, Ti_3Al, TiAl-MMC, and superalloys for the vehicle structure. Techniques were developed for the design and fabrication of lightweight structures from these materials and experimental testing was performed to assess the capabilities of the materials and structural subcomponents to withstand repeated and prolonged exposure to the severe aerodynamic heating encountered in hypersonic flight. As for all aerospace structures, the minimization of weight was a critical design driver. In addition, the hostile thermal environment and the unique requirements of cryogenic hydrogen tankage introduce additional structural design problems and constraints and added new dimensions to the problems of reliability, maintenance, and life. From a programmatic point of view the many starts and stops in hypersonic research has been disruptive to the development of high-temperature materials for hot structure applications. However, even with the disruptions many significant developments have come from each of the projects and several spinoffs to other applications can be traced to the work performed in these projects.

4.7.2. National Aero-Space Plane Program (NASP)

The shuttle inspired global emulation, most notably with the Soviet Buran, French Hermes, and Japanese Hope, and helped generate a climate conducive to hypersonic studies of a variety of inhabited and uninhabited systems. In America, post-shuttle interest ultimately spawned the most ambitious and complex attempt to develop a hypersonic orbital aircraft since the shuttle: the National Aero-Space Plane Program (NASP), the X-30 (**Figure 4.7-2)**. Though primarily an Air

Force development effort, the NASP involved significant NASA participation from its inception through cancellation. Begun in the mid-1980s and “baselined” in 1991, the single-stage-to-orbit (SSTO) X-30 replicated and/or encountered many of the same problems encountered three decades previously with a similar large air-breathing SSTO Program, the Air Force’s discredited Aerospace plane of the early 1960s. At the time of its demise in the early 1990s, its development team had achieved some impressive technical successes involving materials, fuels, and propulsion; but even so, the X-30 remained controversial, having grown in size and complexity, and with an unresolved velocity deficit of approximately 3000 feet per second that would have prevented it from actually reaching orbit as a single-stage vehicle. This program considered technologies ranging from air-breathing scramjet engines to advanced materials including various MMCs, titanium-based alloys, and titanium matrix composites (TMC) skin structures for thermal protection.

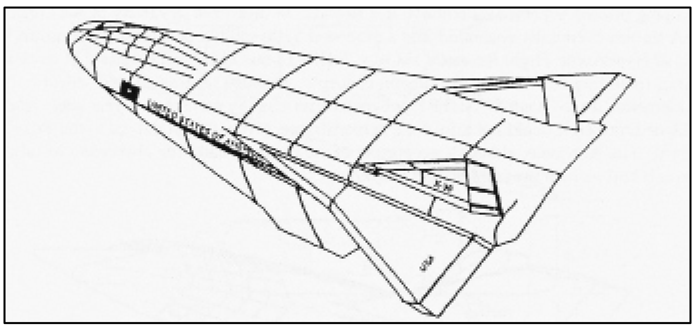


Figure 4.7-2: Final General Design Configuration of the X-30 National Aero-Space Plane. Air Force SAB.

An example of the type of fuselage structure that was fabricated for NASP is shown in **Figure 4.7-3**.

Figure 4.7-3: Fuselage Section of National Aerospace Plane (NASP), SiC/Ti Stiffeners, Spot-Welded to 4' × 4' Panels.

Following a pattern traditional for the hypersonic field, the aftermath of the NASP was one of contraction, frustration, and delayed expectation. Ironically, even as American hypersonics slowed, mastery of the field and foreign interest continued to grow. For NASA, faced with the challenges of maintaining the shuttle, completing the International Space Station (ISS), and meeting many other ambitious exploration goals, hypersonics was just one of many areas of research interest. Other agencies and organizations, faced with many competing interests, had the same challenge. Accordingly, while many possible hypersonic programs and starts beckoned—some, such as the Affordable Rapid Response Missile Demonstrator (ARRMD), X-33, X-34, X-38, and Hyper-X (subsequently designated the X-43), showing real promise—only a handful went ahead, with just one actually flying, the X-43. The X-33 was initiated in 1996, the X-34 also started in 1996 and both were terminated in 2001. The X-37 began in 1999 but was also later canceled. NASA's X-43A made aviation history with its first success flight of a scramjet powered airplane at hypersonic speeds in March 2004.[4] The research vehicle broke its own record in mid-November 2004, flying at nearly Mach 9.8, demonstrating the present and immediate future of hypersonic flight, with its accompanying need for advanced lightweight material systems.

4.7.2.1. Materials Development for NASP

Metallic materials are of interest for hot structures because of the large experience base in designing metallic structures for aircraft applications. However, the unique materials issues to be addressed for metallic hot structures are the high-temperature material systems themselves, the processing of these systems into useful product forms, and the fabrication of these product forms into practical structures. A material system that has shown significant promise for high-temperature use is TiAl, also known as gamma titanium aluminide. This material has undergone significant improvements over the last 10 years and is now being produced in ingot form with room temperature elongation properties that are approaching values needed for practical structures (~1.5%). The properties of monolithic TiAl of interest at high temperature are strength and creep resistance.

Because of the low-room-temperature ductility of TiAl, the commonly used ingot metallurgy processes become difficult and require numerous processing steps. The thin gauges extensively used in aircraft skins can be formed with these ingot metallurgy processes, however, exploration of alternate approaches, having fewer processing steps and potentially better properties, are being actively explored. A new approach for the efficient manufacture of TiAl foil with improved ductility was developed by Steve Hales[5] and coworkers. Such foil can be used in the manufacture of metallic thermal protection system (TPS) or in the manufacture of metal matrix composites. The process utilizes the plasma spray deposition of pre-alloyed powders, followed by consolidation via vacuum hot pressing and heat treatment to produce TiAl foil in relatively few processing steps. It also eliminates the "canning" requirements of ingot rolling processes. The objective was to produce a very clean material (low interstitial content) with a highly refined, homogeneous microstructure placed in a fully lamellar condition.

High-temperature MMCs were extensively investigated during the NASP Program. These tasks and subsequent investigation of these material systems focused on advanced Ti and intermetallic MMCs for 1200°F–1500°F applications. The goal then and now is to develop lightweight high-temperature MMCs for robust low-cost metallic hot airframe structure, as illustrated in **Figure 4.7-4**. Efficient joining and attachment processes for MMCs are critical to their successful application in future extreme environment applications. Affordability permeates throughout the development from manufacture of the basic raw material stock, the development of various forming processes for the fabrication of complex shapes required in airframe applications, and even modeling of the basic material itself. Modeling includes micromechanical models, interface models between the micro-level models and structural design models, and models of the thermal structural behavior of these hot structures.

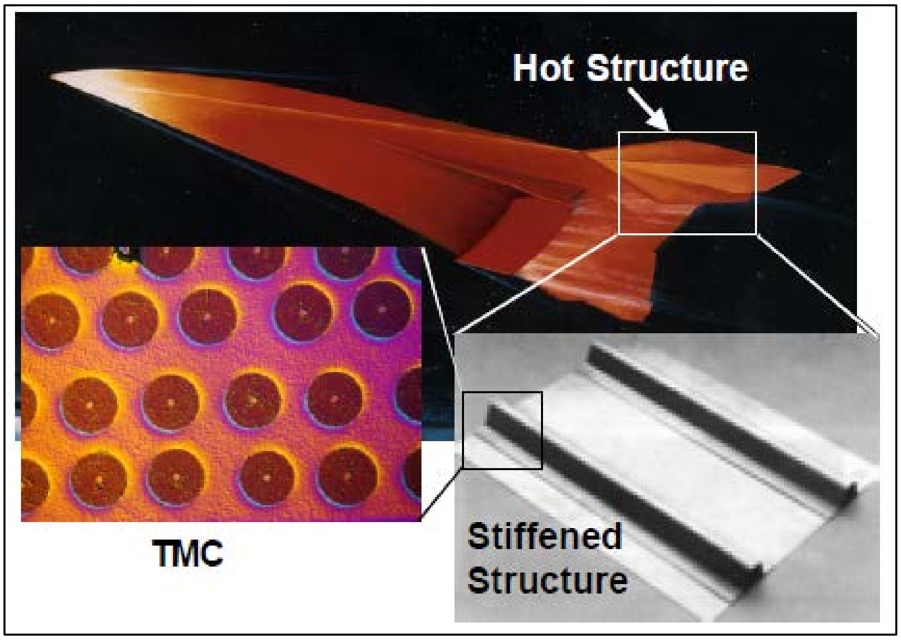


Figure 4.7-4: Stiffened TMC Panel.

A key paper by Tenney, Lisagor, and Dixon entitled "Materials and Structures for Hypersonic Vehicles,"[6,7] gave a good assessment of the state of material development in the NASP Program in 1988 which was close to the peak of the NASA research performed for NASP. Stein et al.[8] also published a report on airframe materials for hypersonic vehicles in that same time frame. More recent overview paper on materials and structures for reusable launch vehicles have been published by Steve Scotti, David Glass, et al.. [9]

4.7.2.2. Ordered Alloys and Metal-Matrix Composites.

Long-range-ordered alloys are a unique new class of high-temperature structural alloys. The relatively slow atomic mobility and unique dislocation dynamics in ordered lattices result in these alloys having unusual properties such as the yield strength increasing rather than decreasing with increasing temperature. The creep and fatigue strengths of these alloys at elevated temperatures are generally superior to similar disordered alloys. However, these alloys tend to be brittle at room temperature. Alloy development work performed at Oak Ridge National Laboratory produced a number of long-range-ordered alloys, $(Fe,Ni)_3V$, $(Fe,Co,Ni)_3V$, and $(Fe,Co)_3V$, which have good ductility.

Although Fe, Ni, and Co-base intermetallics looked very attractive for many high-temperature applications, they were generally considered to be too heavy for weight-critical hypersonic vehicles like NASP. The NASP materials program focused on the development of titanium aluminides and titanium aluminide composites because they offered the greatest potential for meeting mission requirements. Representative properties of some aluminide materials are compared with those of conventional titanium and nickel-based alloys in **Table 4.7-1**: Properties of high-temperature alloys.. Titanium aluminide has a density approximately half that of superalloys with a stiffness 50-percent greater than that of titanium alloys. The modulus of conventional titanium alloys drops rapidly with temperature to a value of approximately 10 Msi at 1000°F, whereas TiAl has a higher modulus at 1832°F than titanium does at room temperature. The creep strength of the aluminides is very good as is the oxidation resistance, particularly TiAl, which is an alumina former. The most significant limitation on the aluminides is their low ductility at room temperature.

Table 4.7-1: Properties of high-temperature alloys.

	Ti Base	Ti_3Al	TiAl	Superalloys
Density (lb/in^3)	.163	.150 -.170	.136	.300
Young's Modulus (Msi)	16 -14	21-16	25	30
Max. Temp. - Creep (°F)	1000	1500	1900	2000
Max. Temp. - Oxidation (°F)	1100	1200	1900	2000
Ductility - R.T. (%)	~20	2-5	1-2	3-5
Ductility - Operating (%)	High	5-8	7-12	10-20

For programs such as NASP where the ultimate in performance is demanded from the materials, fiber reinforcement of titanium aluminide alloys is a key materials development activity. Projected rule of mixture properties of conceptually possible titanium aluminide metal-matrix composites is shown in **Table 4.7-2**.

Table 4.7-2: Specific Strength and Stiffness Properties Calculated From Rule of Mixtures.

MATERIALS	E, MSI	ULT,KSI	ρ, #/IN³	E/ρ, IN.	ULT/ρ, IN.
Rene' 41	31.6	170	.298	106 x 10⁶	570 x 10³
Ti_3Al	20	180	.180	111	1000
$P100/Ti_3Al$(1)	57.5	240	.130	442	1850
$IM6/Ti_3Al$(1)	32	440	.128	250	3440
SiC/Ti_3Al(1)	41	315	.141	291	2230
$TiB_2/TiAl$(1)	37.5	295	.159	236	1860
TiB_2/Ti_3Al(1)	35	315	.180	194	1750
TiC/TiAl(1)	44.5	295	.166	268	1780
TiC/Ti_3Al(1)	42	315	.187	225	1680

(1) • Room temperature, elastic, unidirectional
- Rule of mixtures for strength and stiffness
- Maximum fiber strain for strength
- 5% weight penalty for fiber coating
- 50% fiber volume

There is a significant increase in specific strength in going from Rene'41 to Ti_3Al; however, there are much larger benefits in specific strength and specific stiffness when comparing isotropic materials to the metal-matrix composite lamina. Additional data is presented in the paper by Tenney et al.,[7] and the reader is referred to the article for additional details.

4.7.3. The Next Generation Launch Vehicles

The United States has made several attempts to develop reusable launch vehicles that are lightweight and robust, and designed for little maintenance and low-cost operations. The NASA Advanced Space Transportation Technology Program hoped to speed the commercialization of space and improve U.S. economic competitiveness by making access to space as routine and reliable as today's airline industry, while reducing costs and enhancing safety and reliability.

Scale models of the X-33 and X-34 RLVs underwent extensive testing in NASA Langley's many wind tunnels. Models of various sizes and materials underwent testing for ground effects, dynamic stability, and aerodynamic and aerothermodynamic properties. The wind tunnel tests provided information about how each vehicle's design performed aerodynamically over a range of speeds from takeoff to 15 times the speed of sound (Mach 15).

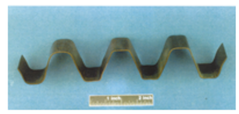
Candidate structures and materials for the X-33 and X-34 were also tested at Langley using loads that simulated the conditions the RLVs were expected to experience during launch. The primary material system of interest was gamma titanium aluminide (TiAl), which had been identified as a high-priority material for future RLVs due to its low density and good properties at temperatures as high as 1600°F. Advanced oxide-dispersion-strengthened (ODS) superalloys that have service temperature up to 2200°F were also investigated. A small effort was invested in high-risk gamma TiAl metal matrix composites due to their potentially high payoff in terms of low density and excellent high-temperature mechanical properties. The task had three primary areas of research: fabrication development, service environment compatibility, and materials development. The fabrication development activity included development of techniques for producing required product forms. These product forms included foil, sheet, plate, extrusions, and near-net-shape parts. Powder metallurgy and plasma spray were two technologies that were specifically addressed. Joining techniques were developed to incorporate the candidate alloys into structural concepts. Fabrication processes were evaluated by producing simple structural web elements with face sheets brazed to them. The web cores were fabricated with conventional ingot metallurgy and machining processes and compared to novel near-net-shape powder metallurgy processes. Highlights of a portion of that research are shown in **Figure 4.7-5**. Much of that research was carried out by Stephen Hales[10] and colleagues.

Established Feasibility of Low-cost Gamma TiAl Processing For Built-up Structures

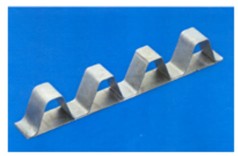
Gamma TiAl Processing

Conventional		Low-cost Process*
Ingot	**Powder**	
Melt	Melt	Melt
Cast Ingot	Atomize	Cast to slab
Hip Compact	Encapsulate Powder	
Cut Ingot	HIP Compact	
Homogenize	Remove Can	
Condition Surface		
Upset forge to pancake		
Cut to rectangle		
Condition surface	Condition surface	Condition surface
Encapsulate	Encapsulate	Encapsulate
Hot roll	Hot roll	Hot Roll

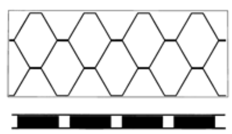
* Cast by Howmet, USA
Rolled by Plansee, Austria

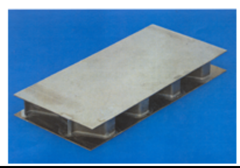


Established hot die Forming parameters for TiAl sheet



Optimized joining Parameters for brazing and diffusion bonding.





Fabricated truss-core & honeycomb core sub-elements

Figure 4.7-5: Material Advancements made at Langley in the Hypersonic R&D Program.

The service environment compatibility activity involved determination of the service limits of the candidate alloys and developing coatings to protect the alloys from the service environment and to provide thermal control. Terryl Wallace, Keith Bird, and Sankra Sankaran[11] performed most of the work on oxidation protection coatings for gamma titanium aluminide alloys. The coating system of primary focus was an ultrathin sol-gel based multilayered coating. Each layer of the coating is designed to provide one of the multiple functions necessary for a successful coating. The coating was scaled up using spray techniques to coat large components combined with curing by radiant heat lamp arrays that cover large areas.

The materials development activity focused on the correlation and refinement of microstructures, properties, and processing routes for the candidate alloys. In addition, a small effort was investigated for silicon carbide fiber-reinforced gamma TiAl metal matrix composite development. Due to thermal expansion coefficient mismatch between the fibers and matrix alloy, only very low fiber volume fraction composites were successfully made. Small diameter (0.0004 in) alumina fibers were also investigated, but their small size made it difficult to achieve reasonable fiber loadings. Dr. W. Steven Johnson[12] worked on gamma TiAl under a NASA grant to Langley.

In a review paper by David Glass[13] selected highlights of Langley work on titanium aluminide was presented in the context of many of the airframe technologies being developed at NASA for the next generation launch vehicle (**Figure 4.7-6** and **Figure** 4.7-7). The Metallic Materials for Airframe Hot Structures Task was focused on development of critical technologies for high-temperature metallic materials and incorporating them into generic RLV hot structures. These hot structures include acreage airframe structure, control surfaces, and thermal protection systems. In addition, coatings to protect these materials from the service environments and to control heat input into the structures were developed and evaluated.

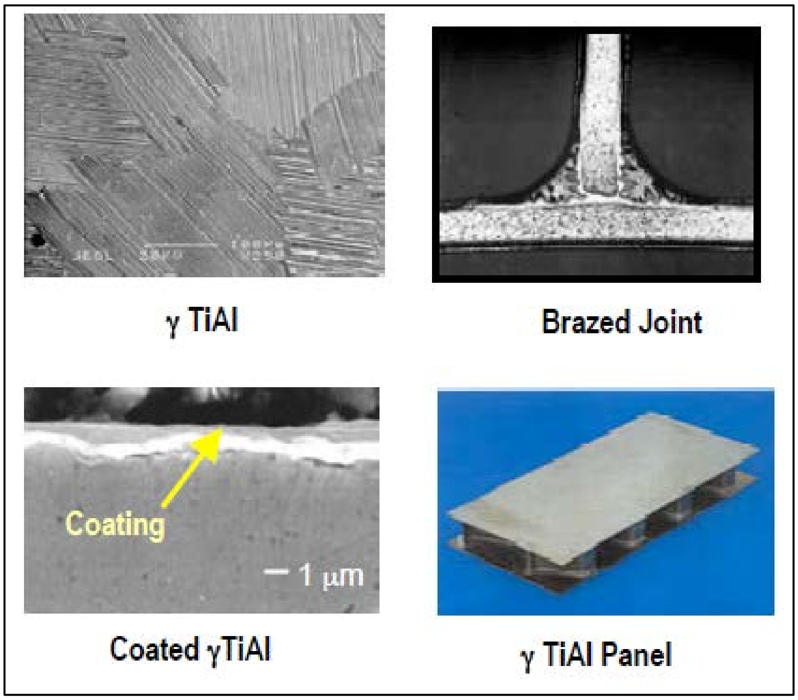


Figure 4.7-6: NASA Langley research on Gamma Titanium Aluminide.

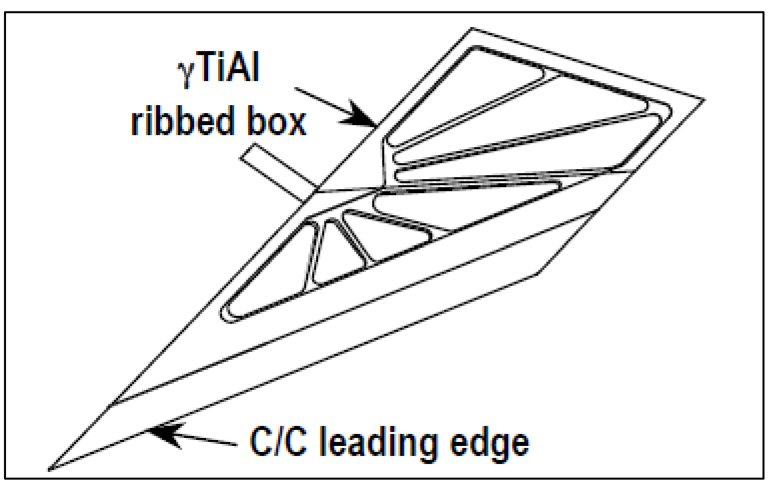


Figure 4.7-7: Structural Concept for Use of Titanium Aluminide for Hot Structure.

4.7.4. X-43A HYPER–X

The Hyper-X Program sponsored by NASA's Aeronautics Research Mission Directorate was a joint venture between Langley Research Center, Hampton, Virginia and NASA Armstong Research Center located in Edwards, California. Langley was the lead NASA center with responsibility for hypersonic technology development. Armstrong Flight Research Center was responsible for flight research and testing. Hyper-X, was a seven-year, approximately $230 million ground and flight test program that explored alternatives to rocket power for space-access vehicles.

NASA's scramjet-powered X-43 (**Figure 4.7-8**) achieved the first demonstration of in-flight hypersonic scramjet ignition and operation with an airplane like configuration. Its flight-test success followed an innovative in-flight hypersonic combustion experiment by a team of Australian researchers from the University of Queensland's Centre for Hypersonics. On July 30, 2002, a team of researchers from the University of Queensland's Centre for Hypersonics launched HyShot over Australia's Woomera test range; it was a small combustor test article lofted by a two-stage booster into the upper atmosphere. HyShot demonstrated 5 seconds of hypersonic combustion at Mach 7.6 as it plunged toward Earth. The stage was now set for a comprehensive demonstration of a true scramjet, the X-43.

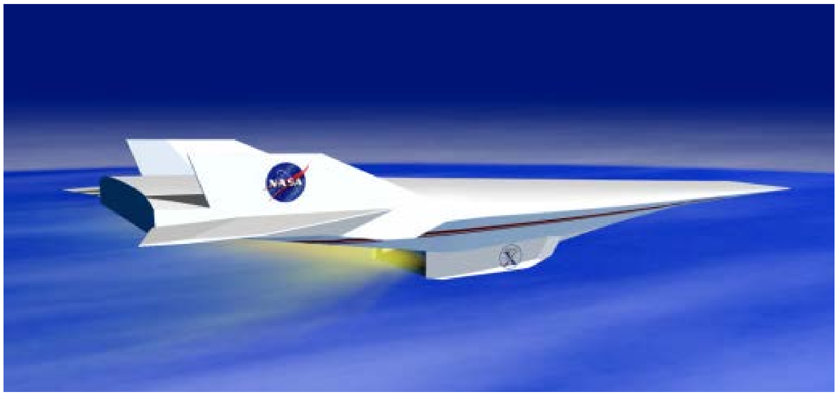


Figure 4.7-8: An Artist's depiction of a Hyper-X Research Vehicle Under Scramjet Power in Free-Flight.

The X-43 joined a sophisticated scramjet engine module developed by the General Applied Sciences Laboratory (GASL) to a surfboard–like, 100-inch-long, 60-inch-span slender lifting body, lofted to hypersonic velocity by an Orbital Sciences solid-fuel winged Pegasus booster air-launched from a Boeing NB-52B Stratofortress (**Figure 4.7-9**) (incidentally, the same launch aircraft that had dropped the X-15, M2-F2/3, HL-10, and X-24A/B lifting bodies). Developers began the Hyper-X Program in 1995, drawing upon a Boeing study effort for a Mach 10 global reconnaissance cruiser and space-access vehicle for its overall configuration. In October 1996, they completed its preliminary design, and Orbital Sciences subsequently received a development contract for the modified Pegasus booster (the HXLV) in February 1997. The Hyper-X vehicle fabrication contract (the HXRV) went to Microcraft, Inc., of Tullahoma, Tennessee, partnered with the GASL for the engine, Boeing, and Accurate Automation Corporation. The engine underwent comprehensive ignition and combustion stabilization hypersonic testing in Langley Research Center's 8-foot High-Temperature Tunnel (HTT).

Figure 4.7-9:Hyper-X Vehicle and Booster on B-52

A picture of the test model in shown in **Figure 4.7-10** and testing in the 8-Foot High-Temperature Tunnel at Langley is shown in **Figure 4.7-11**. The 8 ft HTT simulates true enthalpy at hypersonic flight conditions for testing advanced, large-scale, flight-weight aerothermal, structural, and propulsion concepts. The facility provides combustion-heated hypersonic blowdown-to-atmosphere simulation for Mach numbers of 4, 5, and 7 through a range of altitude from 50,000 to 120,000 feet.

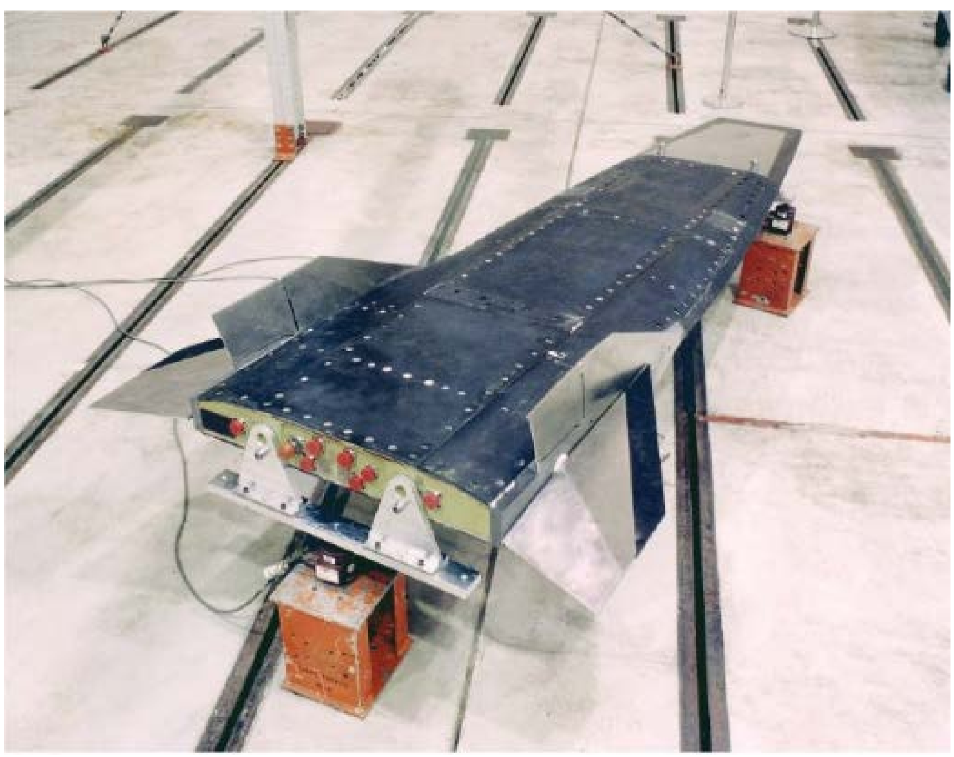


Figure 4.7-10: Hyper-X Flight Hardware.

The test section accommodates very large models, air-breathing hypersonic propulsion systems, and structural and thermal protection system components. Stable test conditions can be provided for roughly 60 seconds. Additional simulation capabilities for ascent or entry-heating profiles are provided by a radiant-heater system. The combustion products of air and methane burned in a pressurized combustion chamber provide the high-energy test medium. Oxygen is added for air-breathing propulsion tests.

Figure 4.7-11: Wind tunnel tests were a necessary step before the first flight attempt, as in this Mach 7 test of a full-scale model with spare flight engine in Langley's 8-Foot High-Temperature Tunnel.

TPS and aerothermal-loads definition tests can be conducted by installing a model into a HTT-supplied panel holder. A sting attaches this panel holder to the curved strut-pitch system mounted on the model elevator, thus exposing the test article to the desired heating profile. Propellant fuels, such as gaseous hydrogen or liquid hydrocarbon and purge gases, are supplied to the test article by the facility.

After the ground test program was complete Microcraft delivered three X-43A flight-test vehicles to DFRC for launch over the Naval Air Warfare Center's Weapons Division Sea Range. The first flight attempt in June 2001 failed after the Pegasus booster shed a control fin just after launch, forcing its destruction by the Range Safety Officer. Thereafter, NASA undertook a painstaking review before clearing the program for a second flight attempt. This reached Mach 6.8 on 27 March 2004 (**Figure 4.7-12**).

Figure 4.7-12: Hyper-X during Pegasus Boost.

Although the Agency briefly considered terminating the program following this demonstration, pressure from hypersonic partisans led to a third flight attempt, this reaching Mach 9.7 (around 6500 mph) at 110,000 feet on November 16, 2004 (**Figure 4.7-13)**. The third vehicle experienced a thermodynamic environment more than 1000°F harsher than that faced by the second, experiencing airframe temperatures of 3600°F. The flight was a great success and NASA has been officially recognized for setting the speed record for a jet-powered aircraft by Guinness World Records.

Figure 4.7-13: The third X-43A accelerates to Mach 9.7 Prior to release from its Pegasus Booster, 16 November 2004, following air-launch over the Pacific Ocean from its Boeing NB-52B mother ship. NASA Image EC04-0325-37.

Though a planned follow-on, the hydrocarbon-fueled X-43C, was canceled, NASA research on hypersonics continued with the support of the Air Force's X-51, a hydrocarbon scramjet test bed designed in 2005 for Mach 5 flight at an altitude of 70,000 feet. It completed its first powered hypersonic flight on May 26, 2010. After two unsuccessful test flights, the X-51 completed a flight of over six minutes and reached speeds of over Mach 5 for 210 seconds on May 1, 2013 for the longest duration hypersonic flight. Practical hypersonic flight applications in the future may include missiles, reconnaissance, transport, and possible first stage for a space launch vehicle.

4.7.4.1. World Speed Records

NASA set the record in November 2004 during the third and final flight of the experimental X-43A scramjet (supersonic-combustion ramjet) project. The X-43A demonstrated that an advanced form of air-breathing jet engine could power an aircraft nearly 10 times the speed of sound. Data from the unpiloted, 12-foot-long research vehicle show its revolutionary engine worked successfully at Mach 9.6 (approximately 7000 mph), as it flew over the Pacific Ocean west of California.

The flight was the culmination of NASA’s Hyper-X Program.

This was the second world speed record earned by the Hyper-X Program. The first followed a Mach 6.8 (approximately 5000 mph) flight in March 2004. Both records were featured in the 2006 edition of the Guinness World Records book published in September 2005. The fastest air-breathing, manned vehicle, the SR-71, achieved slightly more than Mach 3.2. The X-43A more than tripled the top speed of the jet-powered SR-71.

The Guinness World Record certificate states, “On 16 November, 2004, NASA’s unmanned Hyper-X (X-43A) aircraft reached Mach 9.6. The X-43A was boosted to an altitude of 33,223 meters (109,000 feet) by a Pegasus rocket launched from beneath a B52-B jet aircraft. The revolutionary ‘scramjet’ aircraft then burned its engine for around 10 seconds during its flight over the Pacific Ocean.”

The previous record for an air-breathing vehicle, but not an airplane, was held by a ramjet-powered missile, which achieved slightly more than Mach 5. The highest speed attained by a rocket-powered airplane, NASA’s X-15, was Mach 6.7.

4.7.4.2. Integrated Design and Engineering Analyses (IDEA) Environment

A significant contributor to the success of the Hyper-X Program was the excellent work done by the Vehicle Analysis Branch at NASA Langley Research Center. To achieve efficient designs of aircraft and space launch vehicles a multidisciplinary design approach must be used. This is particularly true for hypersonic vehicles where systems are dominated by strong non-linear interactions between disciplines. Furthermore, increased analytical fidelity at the conceptual design phase is highly desirable, as many of the non-linearities are not captured by lower fidelity tools.

The design of hypersonic airbreathing vehicles, like NASA’s X-43 vehicle shown above in **Figure 4.7-8,** is dominated by strong non-linear interactions. For instance, the forebody and aftbody surfaces on the underside of the vehicle provide the majority of the vehicle’s total aerodynamic lift, but also act as the inlet and nozzle for the scramjet engine. As such, both the aerodynamic and propulsion disciplines are greatly affected by their design, which is often determined through a multi-disciplinary optimization performed at the vehicle level. Such trade-offs and multi-disciplinary analyses are common for this class of vehicle and, in fact, are required for the design to achieve its full performance potential.

The Vehicle Analysis Branch at NASA Langley Research Center developed the Integrated Design & Engineering Analysis (IDEA) Environment.[14] IDEA is a collaborative environment for parametrically modeling conceptual and preliminary designs for launch vehicle and high-speed atmospheric flight configurations using the Adaptive Modeling Language as the underlying framework. The environment integrates geometry, packaging, propulsion, trajectory, aerodynamics, aerothermodynamics, engine and airframe subsystem design, thermal and structural analysis, and vehicle closure into a generative, parametric, unified computational model where data is shared seamlessly between the different disciplines. Plans are also in place to incorporate life cycle analysis tools into the environment that will estimate vehicle operability, reliability, and cost.

Figure 4.7-14 shows the combination of analytical disciplines typically involved in the design, analysis, and optimization of hypersonic airbreathing vehicles.

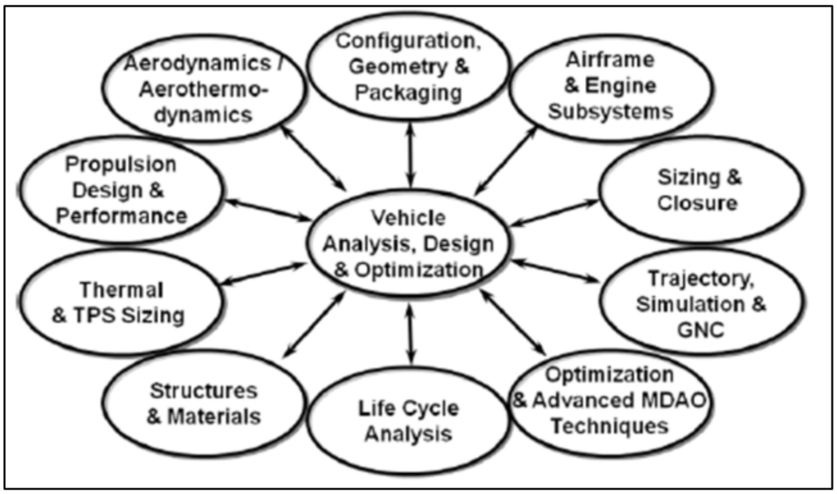


Figure 4.7-14: Analytical Disciplines involved in Hypersonic Systems Analysis and Design.

Among these ten analytical disciplines, "Life Cycle Analysis" encompasses an additional set of disciplines that help to provide estimates of system cost, reliability, and operability. Classic Multidisciplinary Design, Analysis and Optimization (MDAO) methods (response surface fitting techniques, multi-objective / multi-attribute optimization, numerical smoothing, uncertainty quantification / uncertainty propagation, etc.) are captured under "Optimization & Advanced MDAO Techniques." The remaining eight discipline areas are those that are traditionally included in determining the overall performance of the system.

Table 4.7-3 shows the analytical fidelity definitions for the structures and materials discipline. Separate efforts are being undertaken to support Level 1 and Level 2 modeling. To support both efforts, a load case generation module has been developed. This module allows the user to parametrically identify critical load cases experienced by the vehicle for a given trajectory. Typical load cases include maximum and minimum (or maximum negative) normal acceleration and maximum axial acceleration. The user can set the module up to automatically identify these cases and to extract necessary information required for structural analysis, such as vehicle and propellant mass, accelerations, and applied forces. Flight condition information will also be extracted and supplied to an aerodynamic analysis code so that distributed aerodynamic forces or pressures can be obtained. All of this information will then be compiled and used to develop load cases for structural analysis. Additionally, the user can specify non-trajectory-based load cases, often used for modeling a runway bump or landing load. Here, the user is allowed to supply a flight condition for aerodynamic analysis, if desired, as well as accelerations to be applied.

Table 4.7-3: Fidelity Level Definitions for the Structures and Materials Discipline.

Level 0	Level 1	Level 2	Level3	Level 4
Parametric or historical equations adjusted to level 1 or higher for similar technology and vehicle configuration	1D bending loads analysis based on structural theory of beams, shell, etc… with non-optimums based on level 2 or higher results	Limited 3-D FEA (<20,000 nodes) for all major load cases, structure sized to allowables, non-optimums determined empirically or analytically	3-D FEA (>20,000 nodes) for all major load cases, structure sized to allowables, non-optimums determined empirically or analytically. Thermal effects included. Dynamic frequencies estimated.	3-D FEA (>100,000 nodes) for all load cases, structure sized to allowables, non-optimums determined empirically or analytically. Thermal effects included. Dynamic frequencies estimated.

For Level 1 analysis, 1-D beam and shell theory is used to estimate structural component masses. Here, 3-D aerodynamic forces will be mapped to a 1-D line model, thrust and point loads applied, and a 1-D mass distribution developed. Once section loads have been generated, a structural concept and a material system need to be defined in order to estimate structure weights. For example, a stiffened-skin wing structure consists of skins, ribs, and spars. A stiffened-skin fuselage would have skin, stringer, frame, and bulkhead structural elements. Section properties are used to distribute section loads to cross-section structural elements. For instance, the longitudinal stringers at a fuselage cross-section would be sized to resist axial force and bending moment. The skin would carry shear and would transmit pressure loads to the stringers and frames. From this point, shear and moment diagrams can be created, and mass estimates for each section generated.

For Level 2 structural analysis, structural elements such as ribs, spars, bulkheads, floors, and stringers can be created as part of the packaging system. This allows these elements to be conformal with the vehicle IML. Knowledge of the other packaging elements also allows automated cutouts in the shape of each element to be made in the structure to accommodate them. Once the structure has been laid out, the individual elements are sewn together and passed to Patran© or a similar code to be meshed. Once the mesh is ready, it is combined with load case information generated from the trajectory and passed to Nastran© to generate structural deflections. Nastran output will then be passed to Hypersizer©, a commercial structural sizing program from Collier Research Corporation, in order to generate masses for each of the structural components. Several iterations of this loop are required to generate a final set of structural element masses, which guarantees that all bending and deformation constraints have been satisfied. Once this sizing system is in place, it can easily be extended to allow structural dynamics analyses, as well as analyses of hot structures.

These types of efforts are critical for achieving an optimum vehicle design that satisfies all requirements. Advancements in metallic materials and processing technologies can best be achieved by having the material engineer be an integral member of this type of design activity. A detailed understanding of property requirements, required geometric shapes, fabrication technology needed to produce the desired structural concepts, and environmental effects are essential to guiding new material development. Meaningful advancements in metallic materials can only be achieved by having materials as an integral element in system level design efforts.

References

[1] Heppenheimer, T. A.; “Facing The Heat Barrier: A History of Hypersonics”, history.nasa.gov/sp4232-part1.pdf.

[2] http://history.nasa.gov/hyperrev-x15/ch-6.html.

[3] Tenney, D.R., Lisagor, W.B., Dixon, S.C. ; “Materials and Structures for Hypersonic Vehicles”, NASA –TM-101501, Oct. 1988.

[4] NASA Hyper-X Program Demonstrates Scram-Jet Technlogies: X-43A Flight Makes Aviation History. October 2004. FS-2004-10-98-LaRC.

[5] Hales, S.J.; Saqib, M.; and Alexa, J.A.; “An innovative method for manufacturing g-TiAl foil”. Gamma Titanium Aluminides 2003, edited by Kim, Y.-W., Clemens, H. and Rosenberger, A.H., TMS, Warrendale, PA, 2003.

[6] Tenney, Darrel R., Lisagor, W. Barry, Dixon, Sid C.; “Materials and Structures for Hypersonic Vehicles”, NASA Technical Memorandum 101501, Oct. 1988.

[7] Tenney, Darrel R., Lisagor, W. Barry, and Dixon, Sidney C.; “Materials and Structures for Hypersonic Vehicles”, Journal of Aircraft, Vol. 26, No.11 (1989), pp. 953–970.

[8] Stein, Bland A.; Maahs, Howard G.; and Brewer, William D; “Airframe Materials for Hypersonic Vehicles”. NASA CP 2482, Metal-Matrix, Carbon, and Ceramic Matrix Composites, Edited by J. D. Buckley, 1987, pp. 1–28.

[9] Scotti, Stephen J., Clay, Christopher, and Razin, Marc; “Structures and Materials Technologies for Extreme Environments Applied to Reusable Launch Vehicles”, AIAA-2003-2697, AIAA/ICAS International Symposium and Exposition, 14-17 July 2003/ Dayton, OH, USA.

[10] Hales, Stephen J., Saqib, Mohammad, and Alexa, Joel A.; “An innovative Method for Manufacturing γ-TiAl Foil”, Gamma Titanium Aluminides 2003, Edited by Kim,Clemens,Rosenberger, TMS (The Minerals, Metals & Materials Society, 2003.

[11] Wallace, T. A., Bird, R. K., and Sankaran, S. N.; “Development of Oxidation Protection Coatings for Gamma Titanium Aluminide Alloys”, JANNAF 39th Combustion Meeting; Colorado Springs, CO; 1–5 Dec. 2003.

[12] Johnson, W. Steven, Weeks, Carrell; “Evaluation of Gamma Titanium Aluminide for Hypersonic Structural Applications”, FINAL REPORT NASA Grant Number: NAG-1-02018 Georgia Tech Project Number: E-18-A22.

[13] Glass, David E.; “Airframe Technology Development for Next Generation Launch Vehicles”, 55th International Astronautical Congress; Vancouver; 4-8 Oct. 2004; Canada.

[14] Jeffrey S. Robinson; “An Overview of NASA's Integrated Design and Engineering Analysis (IDEA) Environment”, NASA Document ID:20110010978, 2011. http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20110010978_2011009621.pdf

4.8. Space Shuttle

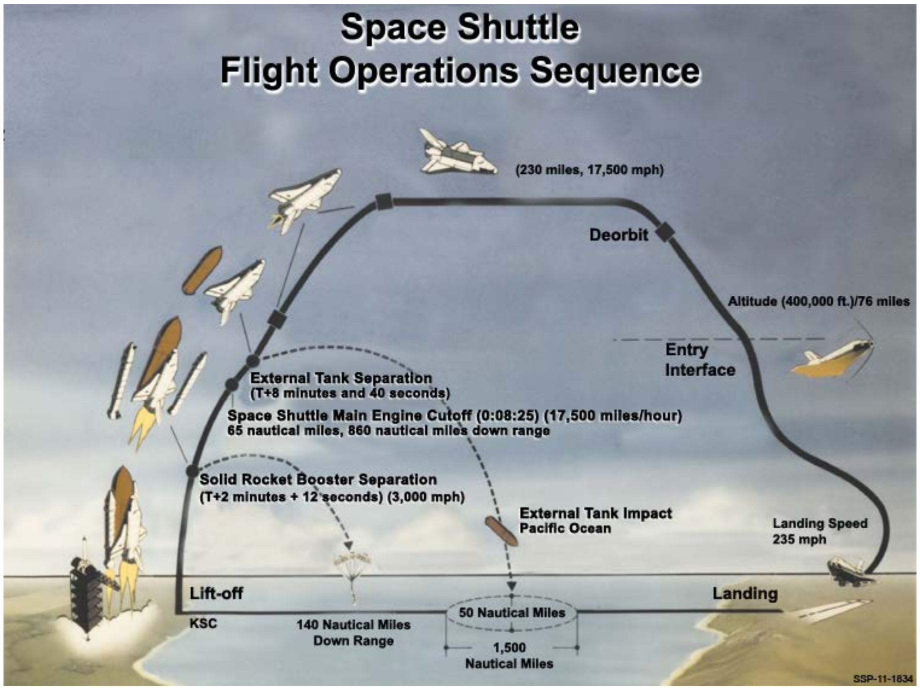


Figure 4.8-1: Shuttle Launch Sequence.

4.8.1. Background

As the Apollo Program began winding down in the late 1960s, NASA began looking ahead to the next step beyond lunar exploration. A crewed space station and alternatives to expendable rockets were considered and the concept of a reusable space shuttle (**Figure 4.8-1**) was particularly appealing as a vehicle to ferry people and supplies to and from orbit. In the late 1960s, conceptual trade studies defined the general characteristics of the shuttle. Findings of two design studies determined the spacecraft would be a two-stage, fully reusable craft capable of performing for 100 missions; it would feature high-performance hydrogen/oxygen engines with throttle capability to power the vehicle; it would take off vertically and land horizontally; and the orbiter's cargo bay was to be 60 feet long and 15 feet in diameter. Many other questions about how the shuttle would be built and how it would operate remained and would be answered before the first shuttle lifted off on its first mission in 1981.

The shuttle required a heavier structure than the expendable launch vehicles and a recovery system (wings, thermal protection system, wheels, etc.) that reduce payload capacity. The shuttle additionally carried a crew whose weight, supplies, and life support systems further decrease payload capacity. The shuttle orbiter was a major national asset, and its high cost (far more than a single expendable launch vehicle) and presence of a crew required stringent "man rated" flight safety precautions that increased launch and payload costs. Only five orbiters were built, and the unexpected loss of two (*Challenger* and *Columbia*) significantly impacted the capacity and viability of the Shuttle Program. Each loss also resulted in an extended hiatus in shuttle flights compared to those following most expendable launch failures, each of which impacted only that model of launch. The shuttle was originally intended to replace expendable launchers in the launching of satellites, but after the loss of *Challenger*, the shuttle was reserved for previously planned missions and those requiring a crew.

Spacecraft launched by the shuttle included several Tracking and Data Relay Satellite Systems (TDRSS) communications relays heavily used by the Shuttle Program itself, a series of commercial communication satellites, and the interplanetary probes Magellan, Galileo, and Ulysses. Several classified military payloads were also carried.

The first launch of the space shuttle was on April 12, 1981. The Shuttle Program spanned 30 years of missions. Starting with *Columbia* and continuing with *Challenger*, *Discovery*, *Atlantis*, and *Endeavour*, the spacecraft carried astronauts into orbit repeatedly, launched, recovered and repaired satellites, conducted cutting-edge research, and built the largest structure in space, the International Space Station. The final space shuttle mission (**Figure 4.8-2**), STS-135, ended July 21, 2011 when *Atlantis* rolled to a stop at its homeport, NASA's Kennedy Space Center in Florida.

Figure 4.8-2: Final Launch of Space Shuttle on July 8, 2011 (first launch was on April 12, 1981).

4.8.2. STS-135: The Final Mission

Wrapping up 30 years of unmatched achievements and blazing a trail for the next era of U.S. human spaceflight, NASA's storied Space Shuttle Program came to a "wheels stop" July 21, 2011, when Space Shuttle *Atlantis* completed the 135th mission. During the 12-day mission, which launched July 8, 2011, astronauts delivered more than 9,400 lbs of spare parts, spare equipment and other supplies in the Raffaello multi-purpose logistics module, managed by engineers at the Marshall Center. These supplies will sustain space station operations for the next year. The 21-foot-long, 15-foot-diameter Raffaello brought back nearly 5700 lbs of unneeded materials from the space station. The STS-135 crew consisted of Commander Chris Ferguson, Pilot Doug Hurley, and Mission Specialists Sandra Magnus and Rex Walheim. "This final shuttle flight marks the end of an era, but today, we recommit ourselves to continuing human spaceflight and taking the necessary and difficult steps to ensure America's leadership in human spaceflight for years to come," said NASA Administrator Charles Bolden.

4.8.3. Langley's Materials and Structures R&D for the Shuttle Program

During the 1960s and early 1970s, NASA sponsored research on high-temperature superalloys for supersonic and hypersonic transport structure, shuttle metallic thermal protection systems, and aircraft turbine applications. The bulk of NASA Langley's research was focused in two major areas: (1) airframe materials and structures with an emphasis on hot structure and (2) metallic thermal protection system concepts, candidate high-temperature alloys, and simulated service life performance. An overview paper by Kelly, Rummler and Jackson,[1] published in 1979, provides a review of some of the advances made during the period from late 1960s to the late 1970s in structures and materials that have application to future space transportation systems. The paper concentrates on metallic thermal protection systems and structures which could provide the structural efficiency, reliability, and durability dictated by future space utilization requirements.

Much of the structures and materials research conducted at Langley during this period was on heat shield designs and ablation materials. NASA engineers had solved the reentry problem for the Mercury, Gemini, and Apollo capsules by using ablative materials that heated up and burned off as the capsule encountered the upper atmosphere upon reentry. However, these capsules were not designed to suffer the rigors of multiple flights and reentries and were thus retired after use. Each shuttle orbiter was designed to experience up to 100 launches and returns. Its thermal protection system had to be robust enough to stand repeated heating loads and the structural rigors of reentry. The system had to be relatively light to keep the orbiter's overall weight acceptably low. In addition, it had to be relatively cheap to refurbish between flights.

Between 1963 and 1973, NASA studied a wide variety of technologies to protect the orbiters' bottom and side surfaces. It investigated

- "hot structures," in which the entire structure took the heat load;
- heat shields separated from a lightweight orbiter structure by insulation;
- ablative heat shields over a lightweight structure;
- low-density ceramic heat shields (tiles) bonded to a lightweight structure.

The "hot structures" would have required developing exotic and expensive titanium or other alloys that could dissipate reentry heating and simultaneously withstand the mechanical loads from aerodynamic pressure. The heat-resistant panels separated by insulation would transfer the mechanical load while shielding the underlying structure from atmospheric heating. This concept suffered from excessive weight and difficulties in designing the shielding to avoid buckling or excessive deflection. NASA's estimates showed that the ablative heat shields would require costly refurbishment. NASA chose the fourth option after extensive testing, in part because the agency decided that using tiles would lead to the lowest overall cost. A ceramic heat shield also allowed NASA engineers to use aluminum for the shuttle orbiter's structure a material with which they had considerable experience.

4.8.4. High-Temperature Alloys for Airframe Structure

Two key technology areas worked by Langley during the Shuttle Technology Development Program were development of advanced processing to fabricate efficient light-weight metallic structures for high-temperature applications and generation of residual mechanica1 property data on candidate alloys after exposure to the environmental conditions imposed by the flight requirements to establish the upper temperature use limits of the materials. Work on the superalloy sheet materials focused on oxidation and creep, elevated temperature properties, high-temperature fatigue of titanium alloys, and fabrication of structural panels for various thermal protection system concepts.

Fabrication technology to produce honeycomb panels using foil-gage materials was a key focus of the Shuttle Materials Development Program.[16] Liquid interface diffusion bonding (LID) bonded honeycomb panels were fabricated and characterization tests were performed to determine the effect of the LID bonding process on the material properties. The results of the tests showed that the LID bonding process had several adverse effects including reduced static strength and elongation at –50°F and RT, lower RT fatigue strength, higher fatigue crack growth rates especially in the thinner gages, and welds through the LID-treated material developed delayed weld cracking without loads being applied. This work illustrates that joining of foil gage materials requires that procedures and processes must be optimized for the alloys, section thicknesses and use temperatures.

4.8.5. Metallic Thermal Protection System (TPS)

Metallic thermal protection systems was a major focus of much of the shuttle-related work performed at Langley from the early 1960s through the mid-1970s in both hot structures and high-temperature alloys. Bob Jackson, Sid Dixon, and others in the structures division were key leaders in developing and testing new heat shield structural concepts. Tom Bales and colleagues were engaged in developing new and emerging fabrication technology to produce these new structural concepts, and a host of researchers including Lisagor,[2] Rummler,[3] Stein,[4,5] Royster,[6] Tenney,[7] Clark, and others were active in studying the performance of candidate high-temperature alloys in simulated shuttle reentry environments. In the early 1960s, Langley was also engaged in assisting with the development of new and emerging high-temperature alloys. Manning[8] and coworkers investigated a new nickel alloy strengthened by dispersed Thoria which became known as TD-NiCr. Extensive research was conducted on this family of alloys to evaluate the oxidation resistance in a hypersonic flowing air environment formulated to simulate shuttle reentry conditions.

Elevated temperature oxidation resistance, creep resistance, and strength are significant properties for heat shield design.[9] The metallic TPS materials studied at Langley are shown in Table 4.8-1. The nickel- and cobalt-based superalloys studied included Hastelloy X, Inconel 718, L605, and René 41. Dispersion-strengthened NiCr alloys (TD-NiCr) were also studied. Testing for performance under simulated reentry conditions were in the Hypersonic Materials Environmental Test System (HYMETS) facility at Langley by Tenney[10–11] and coworkers. These publications contain an excellent overview of the state of the technology in metallic TPS systems including structural concepts, aerothermal loads, materials performance in Arc-Jet tests where shuttle reentry conditions were simulated, structural heat transfer analyses, and high-temperature test techniques.

Table 4.8-1: Metallic TPS Materials.

MATERIAL	APPROX MAX-USE TEMP, °C	APPROX ORBITER AREA BELOW MAX-USE TEMP, %
TITANIUM	480	25-50
SUPERALLOYS	1000	65-90
DISP STR NiCr	1150	85-95
COATED COLUMBIUM	1300	90-98
COATED TANTALUM	1500	95-98

For a given reentry environment, the surface temperature is governed primarily by the emittance and catalytic activity of the surface. An example of the research conducted at Langley[12] in an effort to lower the catalytic activity of superalloys for heat shield applications is shown in **Figure 4.8-3**. Data for Inconel 617 and a dispersion strengthened iron base superalloy MA-956 are shown.

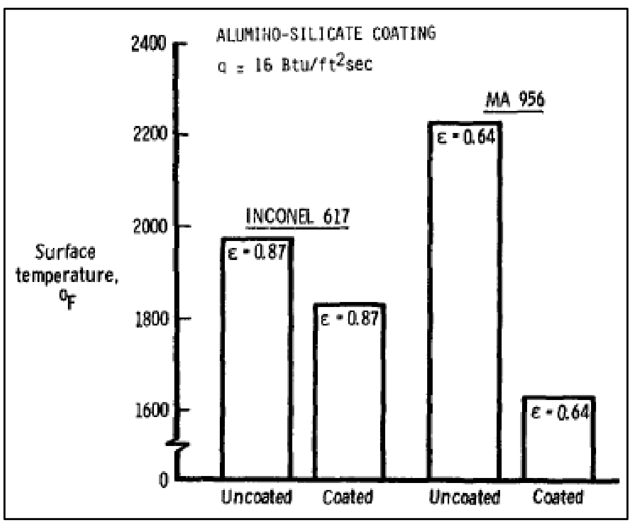


Figure 4.8-3: Effects of Coatings on Catalysis of Superalloys.

The borosilicate coatings applied to the surface in a thickness of a few hundred angstroms resulted in a dramatic reduction in the catalytic activity of the MA-956 surface resulting in a 600°F decrease in the equilibrium surface temperature for the particular exposure conditions selected for this test. Similar research was also conducted at Langley on other candidate alloys including TD-NiCr[13] and several other high-temperature superalloys. Ronald K. Clark published several key papers[14–15] on this subject.

An example of the type of residual property data[16] required to establish the upper temperature use limits of thin-sheet superalloy for metallic TPS is shown in Figure 4.8-4. Results are shown for 100 hours cumulative exposure at 1800°F on 0.020 in thick oxidation specimens subjected to continuous and half-hour cyclic exposures. The effect of sheet thickness on creep resistance of selected superalloys at 1400°F is shown in Figure 4.8-5. For both René 41 and Haynes 188 alloys at 1400°F the 0.010 in sheet had a markedly lower creep resistance than the 0.020 in sheet. For the René 41 alloy the difference was an order of magnitude. These results are particularly important because they illustrate that data generated on sheet material may not be very useful for predicting the lifetimes of foil gage alloys which are being considered for some of the new metallic TPS concepts such as multiwall.

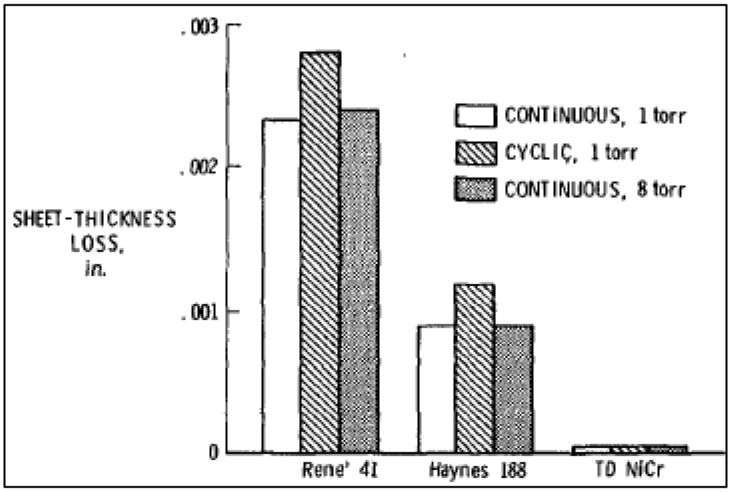


Figure 4.8-4: Results of 100-Hour Cumulative Exposure at 1800°F on 0.020 in Thick Oxidation Specimens Subjected to Continuous and Half-Hour Exposures.

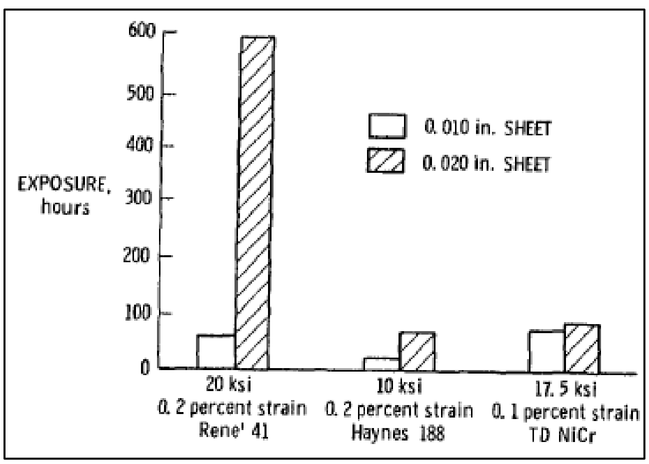


Figure 4.8-5: Effect of Sheet Thickness on Creep Resistance of Selected Superalloys at 1400°F.

4.8.6. Super Lightweight Tank

Langley made major contributions to the development of the super lightweight external tank (SLWT) for the shuttle. Details of this work are included in section 2.7, "Success Stories and NASA LaRC's Role."

References

[1] Kelly,H. N., Rummler, D. R. and Jackson, L. R.; “Research in structures and materials for future space transportation systems - An overview”, AIAA Paper 79-0859, Conference Proceedings, Jan. 01, 1979.(Journal of Spacecraft and Rockets, Jan.-Feb. 1983, pp.89

[2] Lisagor, W. Berry and Stein, Bland A. ; “A Study of Several Oxidation-Resistant Coatings on Cb-10Ti-5Zr Alloy Sheet at 2000^o F,2400^{o}F, and 2700^{o}F (1365 K, 1590 K and 1755 K)”, NASA TN D-3275.

[3] Rummler, Donald R.; Stein, Bland A.; and Pride, Richard A.; “A Study of Several Oxidation-Resistant Coatings on Mo-O.5Ti Alloy Sheet at 2500°F”. NASA TN D-2040, 1964.

[4] Stein, Bland A.; and Lisagor, W. Barry; “Diffusion Studies of Several Oxidation Resistant Coatings on Mo-O.5Ti Molybdenum Alloy at 2500°F”. NASA TN D-2039, 1964.

[5] Wichorek, Gregory R.; and Stein, Bland A.; “Experimental Investigation of Insulating Refractory-Metal Heat-Shield Panels”. NASA TN D-1861, 1964.

[6] Royster, Dick M. and Lisagor, W. Barry; “Effect of High-Temperature Creep and Oxidation on Residual Room-Temperature Properties for Several Thin-Sheet Superalloys”, NASA TD-6893, 1972.

[7] Young, C. T., Tenney, D. R. and Herring, H. W.; “Dynamic Oxidation Behavior of TD-NiCr Alloy with Different Surface Treatments”, Matallurgical Transactions A –Physical Metallurgy and Materials Science; 6A; Dec. 01, 1975.

[8] Manning, Charles R., Jr.; Royster, Dick M.; and Braski, David N.; “An Investigation of a New Nickel Alloy Strengthened by Dispersed Thoria”. NASA TN D-1944, 1963.

[9] Stein, Bland A.; Illg, Walter; and Buckley, John D.; “Structural Materials for Hypersonic Aircraft”. Conference on Hypersonic Aircraft Technology, NASA SP-148, 1967, pp. 485–499.

[10] Tenney, D.R., Lisagor, W.B., and Dixon, S.C.; “Materials and Structures for Hypersonic Vehicles”, Journal of Aircraft, Vol. 26, No. 11 (1989), pp. 953–970.

[11] Young, C.T., Tenney, D.R., and Herring, H.W.; “Dynamic Oxidation Behavior of TD-NiCr Alloy with Different Surface Pretreatments”. Metallurgical Transactions A, Vol. 6A, Dec. 1975, pp. 2253–2265.

[12] Clark, Ronald K.; Cunnington, George R.; and Robinson, John C.; “Vapor Deposited Emittance/Catalysis Coatings for Superalloys in Heat Shield Applications”. AIAA 23rd Aerospace Sciences Meeting, Reno, Nevada, Jan. 14-17, 1985. AIAA Paper No. 85-0403.

[13] Clark, Ronald K., Dicus, Dennis L., and Lisagor, W. Barry; “Emittance of TD-NiCr after Simulated Reentry Heating”, NASA Technical Memorandum 78784, 1978.

[14] Weidemann, Karl E., Clark, Ronald K., and Unnam, Jalaiah; “Oxidation and Emittance of Superalloys in Heat Shield Applications”, NASA Technical Paper 2578, 1986.

[15] Wallace, Terryl A.;Clark, Ronald K.; Sankaran, Sankara N.; Wiedemann, Karl E.; “Oxidation characteristics of Ti-25Al-10Nb-3V-1Mo intermetallic alloy”, NASA-TP-3044, 1990.

[16] Royster, Dick M. and Lisagor, W. Barry; “Effect of High-Temperature Creep and Oxidation on Residual Room-Temperature Properties for Several Thin-Sheet Superalloys”, NASA TN D-6893, 1972.

4.9. Space Rockets R&D

4.9.1. Early Years

Many orbital expendable launchers are derivatives of 1950s-era ballistic missiles. The vehicles used for orbital human spaceflights are shown in Table 4.9-1. This list includes vehicles developed in the U.S., Soviet Union, and China.

Table 4.9-1: Orbital Human Spaceflights.

Orbital Human Spaceflight		
Name	Debut	Launches
Vostok	1961	6
Mercury (1959 through 1963)	1962	4
Voskhad	1964	2
Gemini	1965	10
Soyuz	1967	110
Apollo	1968	15
Shuttle	1981	135
Shenzhou	2003	3

4.9.1.1. Mercury

Project Mercury was the first human spaceflight program of the United States. It ran from 1959 through 1963 with the goal of putting a human in orbit around the Earth. The Mercury-Atlas 6 flight on February 20, 1962 was the first American flight to achieve this goal.[1]

The program included 20 unmanned launches, followed by two suborbital and four orbital flights with astronaut pilots. Early planning and research were carried out by NACA, but the program was officially conducted by its successor organization, NASA. Mercury laid the groundwork for Project Gemini and the following Apollo Moon-landing program.

On June 24, 1952, the NACA Committee on Aerodynamics recommended that NACA increase its research efforts on the problem of manned and unmanned flight at altitudes between 12 and 50 miles and at speeds of Mach 4–10. As a result of this recommendation, the Langley Aeronautical Laboratory began preliminary studies on this project and immediately identified several problem areas. Two of these areas were aerodynamic heating and the achievement of stability and control at very high altitudes and speeds. Of the two, Langley considered aerodynamic heating to be the more serious, and, until this problem was resolved, the design of practical spacecraft was not possible. During that same year, the NACA Langley Aeronautical Laboratory Pilotless Aircraft Research Division started the development of multistage, hypersonic-speed, solid-fuel rocket vehicles. These vehicles were used primarily in aerodynamic heating tests at first and were then directed toward a reentry physics research program. On August 20, 1953, the first Redstone missile was test-fired by the Army at Cape Canaveral, Florida. The Redstone, on which research and development had begun in 1950, was later used as a launch vehicle in the manned suborbital flights and in other development flights in Project Mercury.

During 1955–1956 the NACA Langley and Ames Aeronautical Laboratories developed high-temperature jets, wind tunnels, and other facilities for use in materials and structures research at hypersonic speeds. These facilities provided, among other things, data proving that ablation was an efficient heat-protection method for reentry vehicles.

On October 4, 1957, the Union of Soviet Socialist Republics launched Sputnik I, the first artificial Earth satellite. This event galvanized interest and action on the part of the American public to support an active role in space research, technology, and exploration.

On October 14, 1957, the American Rocket Society presented President Eisenhower with a suggested program for outer space exploration. They proposed the establishment of an Astronautical Research and Development Agency similar to NACA and the Atomic Energy Commission. This agency would have responsibility for all space projects except those directly related to the military services. A list of proposed projects was presented at an estimated cost of $100 million per annum.

On October 15–21, 1957, a "Round 3" conference involving studies for follow-on to the X-15 Program, which subsequently led to the X-20 Dyna Soar, was held at the Ames Aeronautical Laboratory.

On November 21, 1957, NACA established a Special Committee on Space Technology to study and delineate problem areas that must be solved to make spaceflight a practical reality and to consider and recommend means for attacking these problems.

On July 16, 1958, Congress passed the National Aeronautics and Space Act of 1958 which was signed into law by President Eisenhower on July 18, 1958. In August 1958, President Eisenhower assigned the responsibility for the development and execution of a crewed spaceflight program to the National Aeronautics and Space Administration. However, NASA did not become operational until October 1, 1958.

4.9.1.2. Gemini

After the existing Apollo Program was chartered by President John F. Kennedy on May 25, 1961 to land men on the Moon, it became evident to NASA officials that follow-on to the Mercury Program was required to develop certain spaceflight capabilities in support of Apollo. Originally introduced on December 7 as Mercury Mark II, it was re-christened Project Gemini on January 3, 1962, from the fact that the spacecraft would hold two crewmen, seated abreast, as Gemini in Latin means "twins" or "side-by-side."

There were 12 Gemini flights (**Figure 4.9-1**) including two unmanned flight tests. All were launched by Titan II rockets. The first unmanned mission was in 1964, and the last mission was in 1966. The first spacewalk or extravehicular activity by an American was made by Edward White in June 1965. Later that same year, the first week-long flight was made with the first use of fuel cells for electrical power. At the end of the year, the first space rendezvous was accomplished with Gemini 6 and 7. In the first half of 1966, the first docking between Gemini 8 and an unmanned vehicle was accomplished, too. The highest altitude of the missions was reached by Gemini 11 at 1190 km (740 mi). It was reached by using the Agena propulsion system after docking.

Figure 4.9-1: Gemini–Titan Launches 1964–1966.

4.9.1.3. Apollo

The Apollo Program was the spaceflight effort that landed the first humans on Earth's Moon. With the Apollo 11 mission, astronauts Neil Armstrong and Buzz Aldrin landed their lunar module on the Moon on July 20, 1969 and walked on its surface while Michael Collins remained in lunar orbit in the command spacecraft, and all three landed safely on Earth on July 24. Five subsequent Apollo missions also landed astronauts on the Moon, the last in December 1972. In these six spaceflights, 12 men walked on the Moon. The Apollo 15 command/service module in lunar orbit is shown in **Figure 4.9-2**. These are the only times humans have landed on another celestial body.

The Saturn family[2] of American rocket boosters was developed by a team of mostly German rocket scientists led by Wernher von Braun to launch heavy payloads to Earth orbit and beyond. A picture of Saturn V rocket launch of Apollo 11 in 1969 is shown in **Figure 4.9-3**. Originally proposed as a military satellite launcher, the Satern V rockets were adopted as the launch vehicles for the Apollo Moon Program. The two most important members of the family were the Saturn IB and the Saturn V.

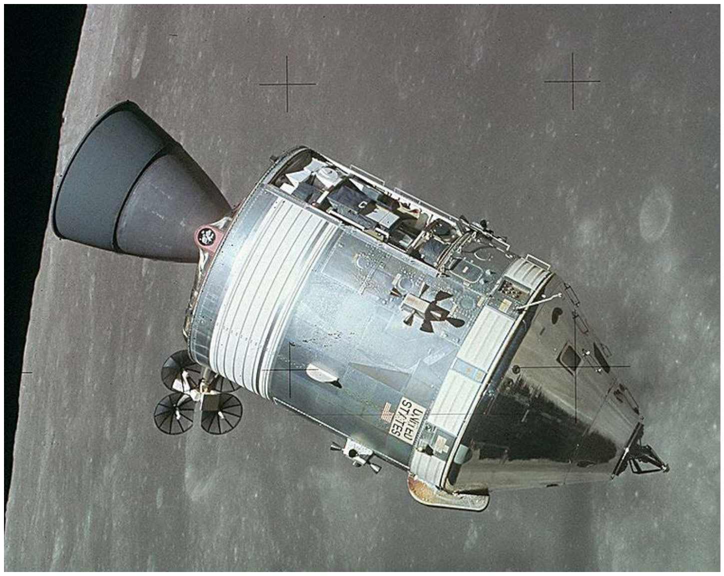


Figure 4.9-2: *Apollo 15* Command/Service Module in Lunar Orbit.

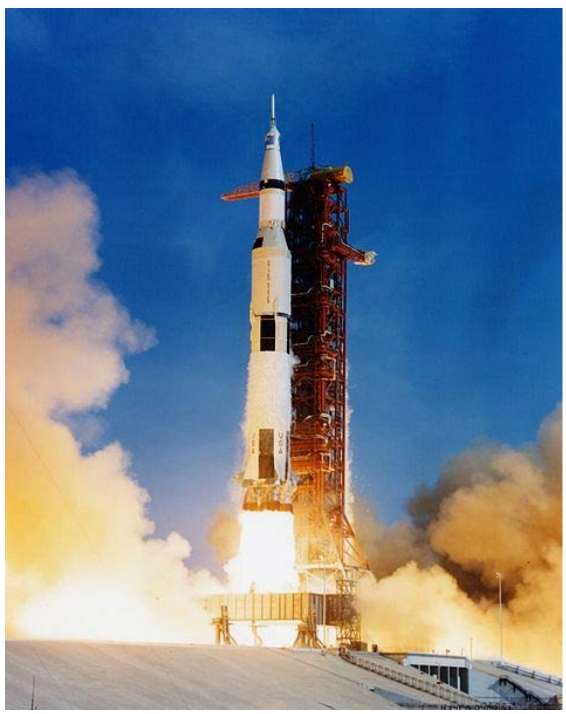


Figure 4.9-3: Saturn V Rocket Launches *Apollo 11* in 1969.

Stress-corrosion cracking was the most common cause of structural-material failures in the Apollo Program. The frequency of stress-corrosion cracking was high, and the magnitude of the problem, in terms of hardware lost and time and money expended, was significant. In a report by Robert E. Johnson, entitled “Apollo Experience Report: the Problem of Stress-Corrosion Cracking,” published in 1973, Johnson makes the observation that the environments and alloys used in the Apollo Program in which failures occurred were generally the same as those encountered in past aircraft and missile failures. The one exception unique to the Apollo

Program was the finding of methanol-titanium and nitrogen tetroxide-titanium incompatibility. He concluded that part of the problem was the lack of communication between designers and fabrication personnel who were not fully aware of the stress-corrosion problems of some of the alloys used in the Apollo Program. At that time, there was also a general lack of understanding of the importance of certain heat treatments on the susceptibility of certain alloys to stress corrosion cracking. The Johnson report identified stress corrosion cracking failures in 7075-T6 aluminum tube, 7079-T652 machined longeron, and Ti-6Al-4V nitrogen tetroxide pressure vessels. Key conclusions from his report are listed here:

1. Available information on stress corrosion cracking was not applied correctly during design, fabrication, and test phases.
2. Design changes for weight reduction can seriously affect the stress-corrosion sensitivity of the vehicle hardware by changing fabrication techniques, raw-material mill forms, and stress levels and by eliminating corrosion-protection systems.
3. Specific alloys and alloys subjected to certain heat-treatment procedures are very susceptible to stress corrosion cracking and should be avoided.
4. New environment/alloy combinations must be examined experimentally before they are used in hardware programs. The use of material forms, heat treatments, stresses, potential stress concentrations, and environments must be simulated if meaningful service data are to be obtained and program problems are to be avoided.

It should be noted that studies of the stress-corrosion behavior of candidate aerospace alloys for aircraft and spacecraft applications were a significant focus of the materials R&D program at Langley Research Center during the early years of NASA space programs. It is also important to remember that the technology base that enabled the development of space launch vehicles was largely derived from NASA's aeronautics programs combined with that developed by the DoD and industry.

4.9.2. Aluminum Technology for Aerospace Vehicles

The metallic materials research programs at Langley have supported the development of both aircraft and advanced launch systems, as is illustrated in **Figure 4.9-4**. Vehicle projects supported include the ALS/NLS Advanced Launch Vehicle Projects; the Low Cost Commercial Launch Vehicle Project; Super Lightweight Tank Development for the Shuttle; RLV Core Technology; Next Generation Launch Technology; and Integrated Airframe Structures for Aeronautics, and launch vehicle structures. The primary thrusts in each of these projects are shown in **Figure 4.9-4**.

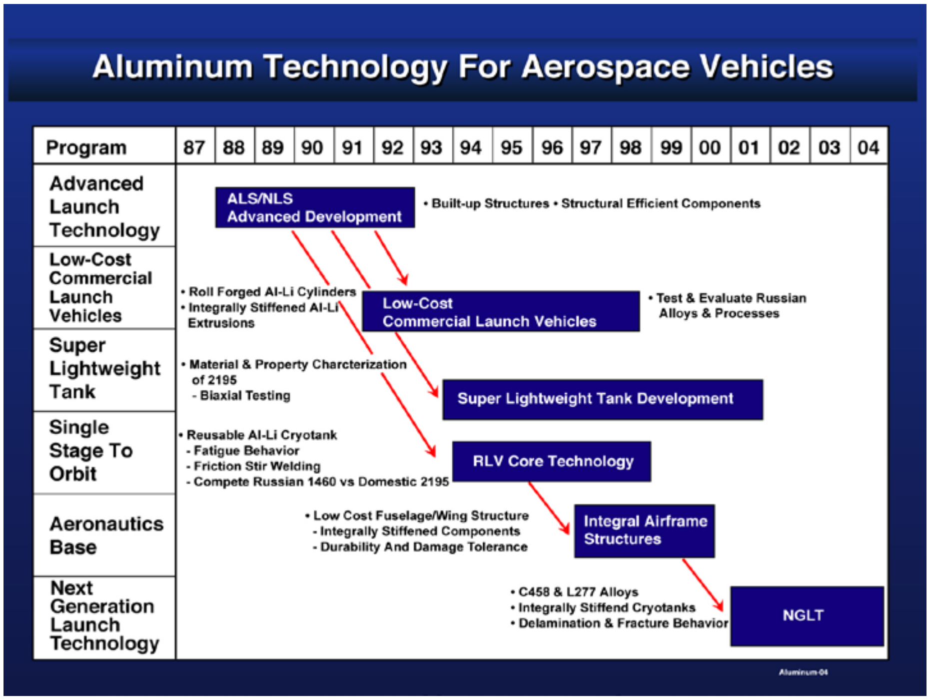


Figure 4.9-4: Aluminum Technology Developed at Langley for Aerospace Vehicles.

The leading candidate Al alloys studied for advanced space transportation systems and the fabrication technologies developed to make structural components are shown in **Figure 4.9-5**.

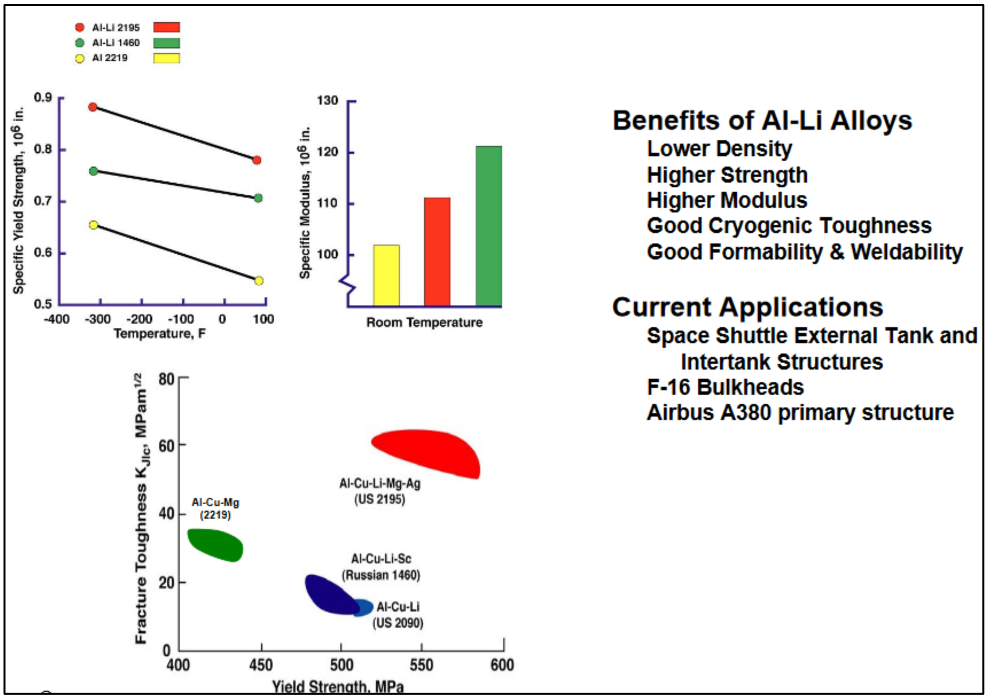


Figure 4.9-5: Advanced Aluminum Alloys for Space Transportation Systems.

Property data shown for Al alloys 2219, 2014, 2195, 2090, and 1460 includes specific yield strength,[3] specific modulus, and fracture toughness. Integrally stiffened extrusions, shear formed cylinders and roll forging of large ring structures were demonstrated. Applications included cryotank barrel sections, adapter rings, cryotank domes, intertank, and other dry bay structures. Examples of near-net-shape manufacturing processes researched at Langley are shown in **Figure 4.9-6**.

Figure 4.9-6: Near-Net-Shape Manufacturing of Al & Al-Li Alloys For Launch Vehicle Structures.

The research conducted in each of the space-vehicle-focused projects, shown in **Figure 4.9-4**, will be discussed in the following sections.

4.9.3. Advanced Launch System (ALS)

The Advanced Launch System (ALS) was a joint USAF and NASA study from 1987–1990 that emerged in the post-*Challenger* period. Colonel John R. Wormington (Brig. Gen., USAF, Ret.) was assigned as Program Director of the Joint DoD and NASA Advanced Launch System Program Office located at Los Angeles AFB, CA with LtCol Michael C. Mushala (Maj. Gen., USAF, Ret.) as his Deputy Program Director. The program considered requirements and launch vehicles for two primary goals. First, the USAF was tasked to deploy the space-based elements of the Strategic Defense Initiative (SDI) Program. Second, because the SDI was initially projected to require many thousands of tons of payload to low-Earth orbit, ALS was intended to reduce the cost of space transportation by an order of magnitude, from about $10,000 per kilogram to less than $1000 per kilogram.

By 1989, the Bush administration inherited a plan for development of the Advanced Launch System that called for the Defense Acquisition Board to approve advanced development of the system in early 1990, leading to a first flight in 1998 and a full operational capability in 2000. This effort would lead to the development of a modular family of launch vehicles, with a payload capacity to low-Earth orbit ranging from 5000 kilograms to 200,000 kilograms, that would replace existing expendable launch vehicles in the 2000–2005 time frame.[4]

However, by late 1989, it was decided that the initial phase of SDI would be deployed using existing Titan IV and Atlas II rockets, and the launch requirements for subsequent phases of SDI deployment were too vague to require immediate development of ALS. The requirements for the ALS Program largely disappeared. By the end of 1990, the ALS Program, once the centerpiece of space planning, had been reduced to a $150 million per year propulsion development effort.[5]

In undertaking the ALS,[6] the Air Force sought to develop a reliable, heavy-lift launch vehicle able to achieve high launch rates at low cost. ALS managers were tasked to achieve a factor of ten reduction over current costs per pound of payload orbited. The design of the ALS was also supposed to allow growth to meet changing mission requirements. The development and operations cost estimates for the ALS compared to other options considered at the time are shown in Table 4.9-2. Other cost estimating approaches were used, and the OTA report on this work contains several different tables of cost estimates. However, in all cases, the ALS was presented as a viable low-cost alternative launch system. It should be noted that the study team received inputs from several NASA experts including Ivan Beckey, Darrell Branscome, Dale Myers, and Robert Rosen.

Table 4.9-2: Cost Estimating Relationships in ALS Study Report

Table A-l.– Nominal Cost-Estimating Relationships

Costs in Fiscal Year 1988 Dollars

Fleet	Dev.	Fac.	Limit	Prod.	Operations[a] per year	Operations[a] per launch
Shuttle	0	x	16/yr	0	$1,336M	$53M
Improved Shuttle	$0.6B	x	16/yr	0	$1,336M	$43M
Shuttle 11	$12B	$1B + X	16/yr	3 X $1,500M	$59M	$33M
Shuttle-C	$1.2B	X	16 - STS	0	0	$236M - C
MLV	0	N/A	12 +/yr	0	0	$35M
Titan IV	0	x	12/yr	0	$200M	$100M
Improved Titan IV	$0.4B	x	12/yr	0	$200M	$95M
Titan V	$1.2B	$0.5B + X	12/yr	0	$267M	$157M
Transition Vehicle	$3.9B	x	0	3 x $11OM	$228M	$54M
ALS	$9.5B	x	0	4 X $425M	$241M	$33M

Dev.: development cost.
Fac,: launch facility conversion or construction cost.
Limit: maximum annual launch rate attainable without new facilities.
Prod.: cost of producing reusable elements.
X: $0.15B per unit increase in annual launch rate limit.
C: SSME credit: $80M if both SSMEs have flown on Shuttles until fully depreciated; pro-rated otherwise. A new SSME is assumed to cost $40M; its allowed lifetime on the Shuttle is assumed to be 10 flights until 1989, 20 flights from 1989 to1995, and 40 flights thereafter.
[a]Includes cost of producing expendable elements.

In July 1987, seven contractors were each awarded $5 million, 1-year contracts by the Air Force to define conceptual designs. The Air Force asked them to include consideration of ground operations in the system designs and cost estimates and to prepare technology development plans and industrial preparedness plans. The contractors' initial concepts considered both expendable and partially reusable vehicles (some with flyback boosters or recoverable propulsion/avionics modules), with capabilities varying from 100,000 to 200,000 lbs to low-Earth orbit (LEO). The Air Force had stated that such a lift capability would primarily be required to launch elements of a ballistic missile defense system and to alleviate payload design weight constraints. The Air Force estimated that the ALS would be capable of 20 to 30 flights per year after 1998.

4.9.3.1. Materials and Structures

ALS was expected to capitalize on advanced materials and manufacturing and launch processing technologies to cut costs. For example, aluminum-lithium alloys could be used in tanks and other primary structures, which could result in 20-percent-lower cost and a 10-percent increase in strength over common steel and aluminum alloys, once manufacturing and supply development was achieved. Filament-wound composite motor casings, shrouds, and adapters likewise were also examined for cost advantages to the ALS by increasing strength and performance while reducing weight. Automation would cut the present high cost of fabricating composite structures, and robotics might be applied to plasma arc welding and other processes effectively, even in relatively low rate production. ALS managers explored a variety of launch operations concepts, including horizontal processing, new launch complexes and improved manufacturing, systems integration, and checkout procedures.

4.9.3.2. Langley's Leadership Role

Langley personnel played key roles in the ALS Program. Charles H. Eldred, Thomas T. Bales, and Allan H. Taylor supported the program by assisting in the evaluation of technical proposals and providing expert advice and consultation to the ALS project office. A NASA metals initiative was added to the program as a direct result of a briefing that Tom Bales made to Col. John Wormington on the merits of exploring SPF Al hat configurations projected to offer increased structural efficiency as a process for fabricating high-performance panels for the vehicle structure (**Figure 4.9-7**). **Figure 4.9-8** shows that the potential benefits of using Al-Li Weldalite 049 (early version of Al-Li alloy 2195) could lead to much larger cost savings compared with an integrally machined 2219 cryogenic tank. The types of SPF stiffened panels, barrel segment, and sub-scale barrel sections fabricated and tested in the ALS Program are shown in **Figure 4.9-9**.

A key factor in Thomas T. Bales securing a 15 min time slot with Col. Worthington was likely because they had spent 2–3 weeks in the Program Office on the west coast reviewing proposals for the ALS Program. This in-depth review provided Bales with insight into the key technical requirements and needs of the vehicle cryogenic tank structure. In a way you might say Bales earned the 15 min time slot with Col. Worthington. Tom did his preparation (few key charts and "touch and feel" SPF beaded web stiffeners resistance spot welded to a simulated cryotank skin that Tom carried out there with him) combined with his technical expertise that quickly convinced Col. Worthington to not only include a NASA Langley metals effort in the R&D program but to ask Tom to lead the entire structures and materials program for ALS.

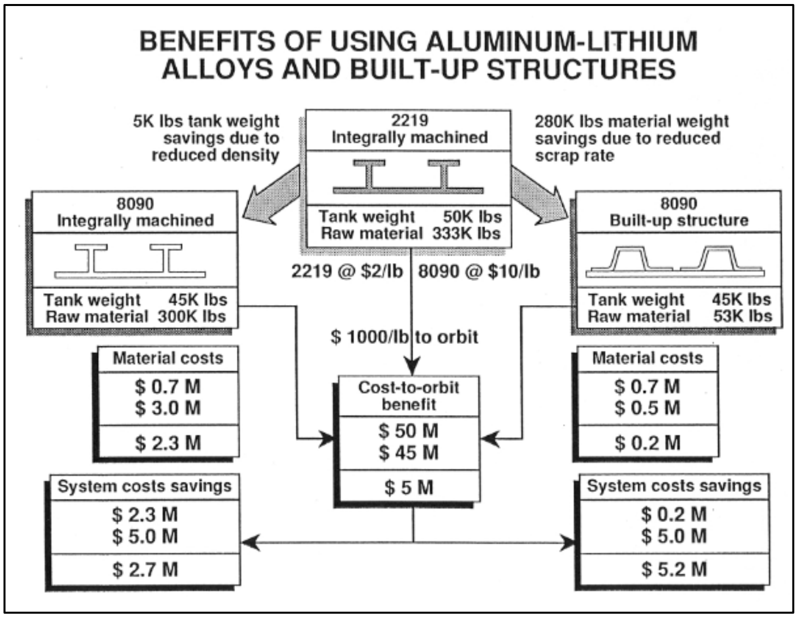


Figure 4.9-7: Potential Benefits of Using Al-Li Alloys and Built-up Structural Concepts.

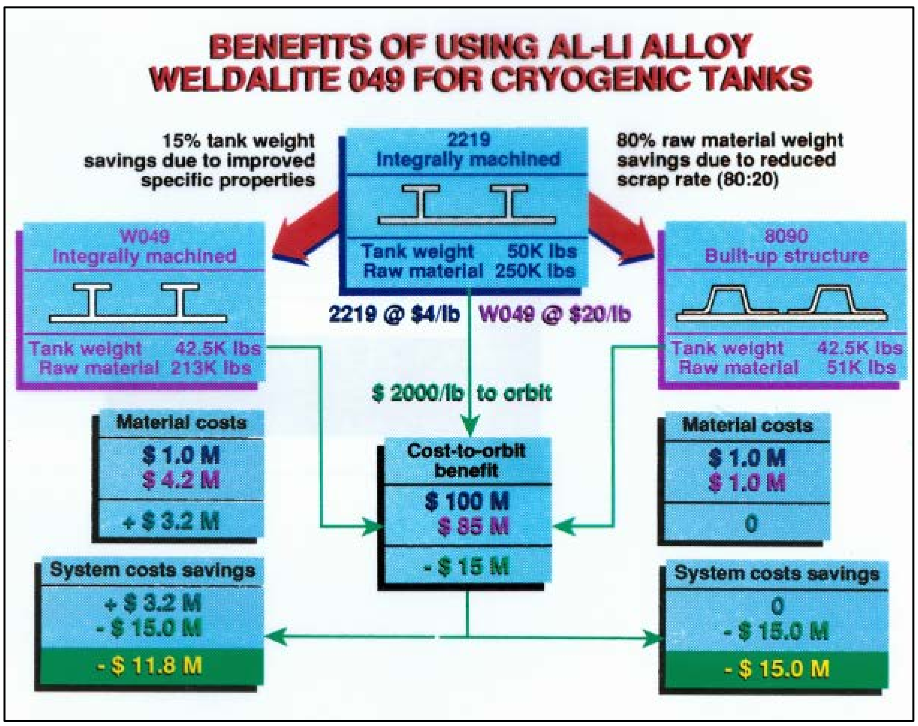


Figure 4.9-8: Potential Benefits of Using Al-Li alloy Weldalite 049 for Cryogenic Tanks.

Later in the program, a budget cut threated to terminate funding for the Al-Li alloy development effort. Tom Bales was able to get this decision reversed by providing a compelling story to the Program Office on the merits of keeping an Al-Li option in the program. At that time ALS was the only source of funding for the work on Al-Li, and loss of the ALS funding would have stopped the whole Al-Li R&D development thrust including the data base development work ongoing at Martin Marietta on Weldalite. This database was critical to the subsequent development of alloy 2195 which was selected for the Super Lightweight Tank Program.

Figure 4.9-9: Fabrication and Testing of SPF Stiffened Aluminum Cryotanks.

Tom Bales led the multi-center NASA and Air Force structures and materials technology development R&D of ALS for the next 2–3 years until the ALS was changed to the National Launch Vehicle (NLS) Program in 1991, which had a different set of goals and objectives.

It is interesting to note that in 1993, a Space Transportation Materials and Structures Technology Workshop was conducted by NASA. The Vehicle Systems Panel addressed materials and structures technology issues related to launch and space vehicle systems not directly associated with the propulsion or entry systems. The Vehicle Systems Panel was comprised of two subpanels: Expendable Launch Vehicles & Cryotanks and Reusable Vehicles. Tom Bales, LaRC, and Tom Modlin, JSC, chaired the expendable and reusable vehicles subpanels, respectively, and co-chaired the Vehicle Systems Panel. Papers were presented by Don Bolstad entitled "Net Section Components for Weldalite™ Cryogenic Tanks" and by Barry Lisagor entitled "Built-up Structures for Cryogenic Tanks and Dry Bay Structural Applications." (The super lightweight tank, which used aluminum-lithium alloy (Al 2195) for a large part of the tank structure, flew in 1998 on STS-91). Much of the material presented illustrated specific components that were created for the Advanced Launch System. The ALS Program pursued advances in the following:

- Net-shape development
- Weld processing
- Efficient manufacturing

- Weld sensor development
- Tank fabrication and testing

Tank fabrication activities were primarily focused on reducing manufacturing and materials costs. Al-Li materials have lower weight (potential reduction of 15% or more) and density, and higher strength and modulus of elasticity than conventional aluminum alloys. To decrease machining scrap in the fabrication process, companies explored methods to extrude large sections in near-net shapes from Al-Li. Several extruded components were demonstrated by the ALS Program. Laboratories also explored methods of creating built-up structures from Al-Li. Initially, much of the work in built-up Al-Li structures focused on cryogenic tank applications (**Figure 4.9-10**) and then expanded to examining application to dry-bay structures.

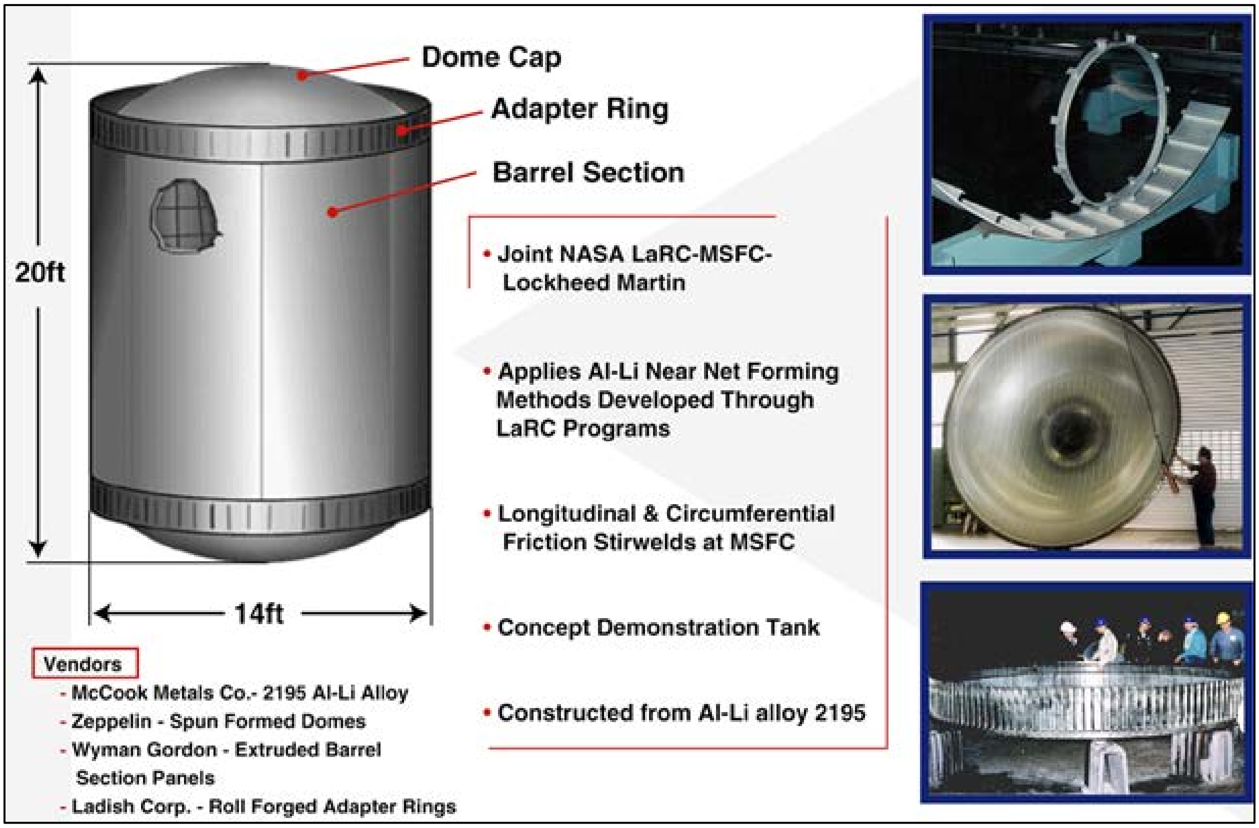


Figure 4.9-10: Cryogenic Tank Technology Development Metals Research.

The cryogenic tank development[7] was a joint NASA-LaRC, NASA-MSFC, and Lockheed Martin program. The material vendors included McCook Metals Co.—2195 Al-Li alloy; Zeppelin spin-formed domes; Wyman Gordon extruded barrel section panels; and Ladish Corp. Roll forged adapter rings. Inspection of a partially formed tank dome is shown in **Figure 4.9-11**. John Wagner the principal researcher responsible for this effort is shown in this figure in the blue shirt on the left. This picture is included to illustrate that Langley worked with industry to scale-up manufacturing processes as well as characterizing properties and microstructure[8] formed in large scale components.

Figure 4.9-11: John Wagner and Eric Hoffman at Inspection of Partially Formed Dome.

The payoffs for advancing technology in this area resulted in lowering vehicle dry weight and lowering system costs due to reduced machining requirements. Examples of built-up Al-Li structures manufactured for the ALS were provided. One of the conclusions reached at this workshop was that continued work was required in built-up Al-Li structures. Fracture and fatigue characteristics of Al-Li built-up structure was also identified as an area requiring additional work.

4.9.4. National Launch System (NLS)

The National Launch System (or New Launch System) was a study[9] authorized in 1991 by President George H. W. Bush to outline alternatives to the space shuttle for access to Earth orbit. Shortly thereafter, NASA asked Lockheed Missiles and Space, McDonnell Douglas, and TRW, to perform a ten-month study. A series of launch vehicles was proposed, based around the space transportation main engine (STME) liquid-fuel rocket engine, a proposed simplified, expendable version of the space shuttle main engine (SSME). The largest of three proposed vehicles was designated NLS-1 and used for its core stage, a modified space shuttle external tank which would feed liquid oxygen and liquid hydrogen to four STMEs attached to the bottom of the tank. A payload or second stage would fit atop the core stage, and two detachable shuttle solid rocket boosters would be mounted on the sides of the core stage as on the shuttle. Drawings such as those illustrated in **Figure 4.9-12** suggest that much larger rockets than NLS-1 were contemplated, using multiples of the NLS-1 core stage.

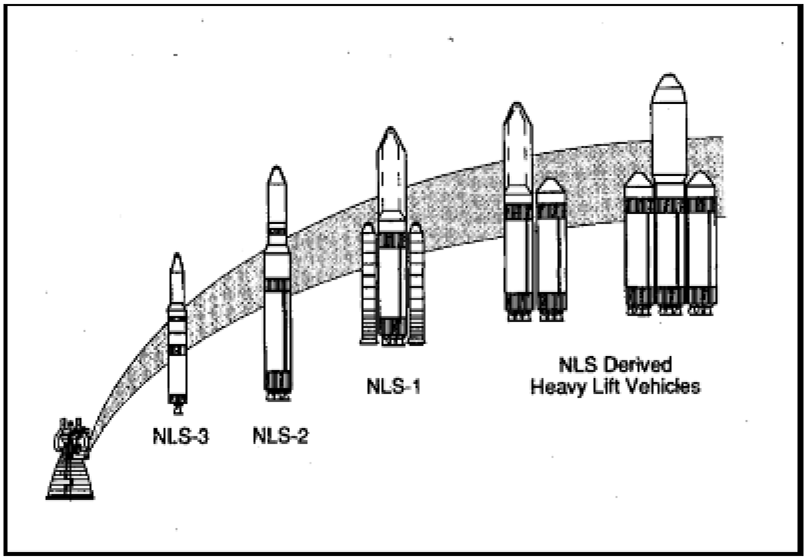


Figure 4.9-12: Proposed NLS Family of Launch Vehicles.

The NLS Program did not venture beyond the planning stages and did not survive the ascendancy of the Clinton administration in 1993. A NASA history from 1998 offers that reusable single-stage-to-orbit rockets and space planes such as the DC-X and X-33 seemed attainable and represented smaller, simpler alternatives to the sprawling Shuttle Program. NLS, by contrast, was more of a continuation of the shuttle legacy. Whether it was ever explicitly stated, by the beginning of the Clinton administration, the expensive space shuttle and planned Space Station Freedom programs had enough momentum to continue, and the SSTO projects showed enough promise to fund. There was no budget left for another big program, the National Launch System.

4.9.5. ARES I and II Launch Vehicles

Langley was a significant participant in the ARES I and ARES II Launch Vehicle Program. In the metallic materials area, the work of John Wagner, Marcia Domack, and Eric Hoffman on near-net-shape (NNS) fabrication of Al-Li alloy 2195 for launch vehicles was particularly noteworthy. Their biggest contributions were in advancing the process to fabricate the ARES I adapter rings by roll forging. AERS I configuration is shown in **Figure 4.9-13**. They also developed the process to produce one-piece domes for the cryogenic tanks by spin-forming.

Langley supported Marshall Space Flight Center in development of the ARES-I y-ring and dome manufacturing. The ARES-I Cryogenic Tank Single-Piece y-ring Adapter Manufactuing Plan is shown in **Figure 4.9-14**. The dome and barrel welded to the top and bottom, respectively, of the y-ring. The traditional approach to forming the tank dome is to form the dome gore panels by stretching a trianglular-shaped flat plate over a mandrel to get the desired curved shape. These gore panels are welded together to form the tank dome (**Figure 4.9-15**). However, a much improved approach was championed by John Wagner, Marcia Domack, and Eric Hoffman at Langley where two flat plates were friction stir welded to give a large plate trimed to a circular shape for subsequent processing. This circular plane was then spun-formed in the final shape of the dome in one operation.

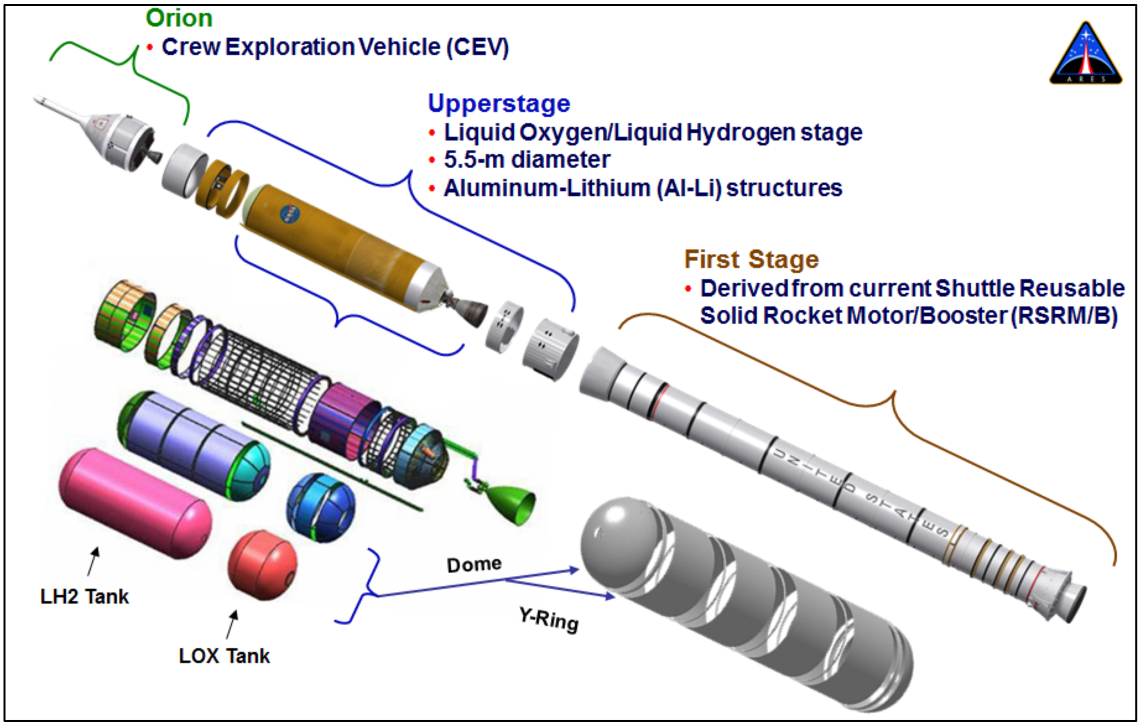


Figure 4.9-13: ARES I Configuration Showing Domes and Y-Rings Worked by Langley.

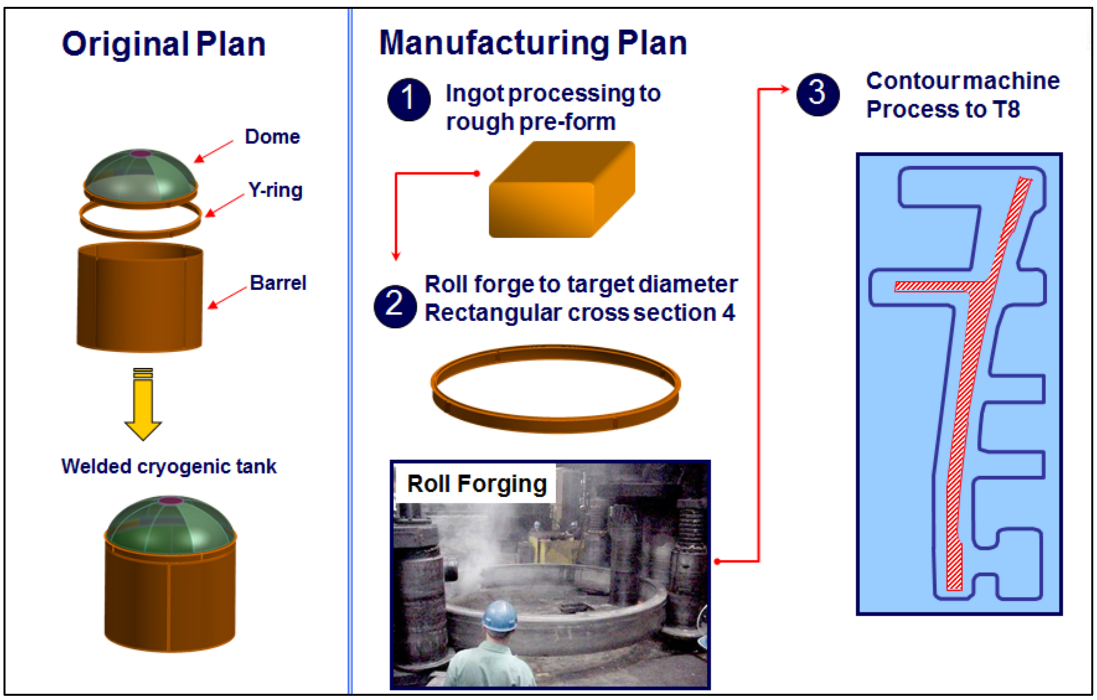


Figure 4.9-14: Manufacturing Plan for the ARES I Cryogenic Tank Single-Piece Y-Ring Adapter.

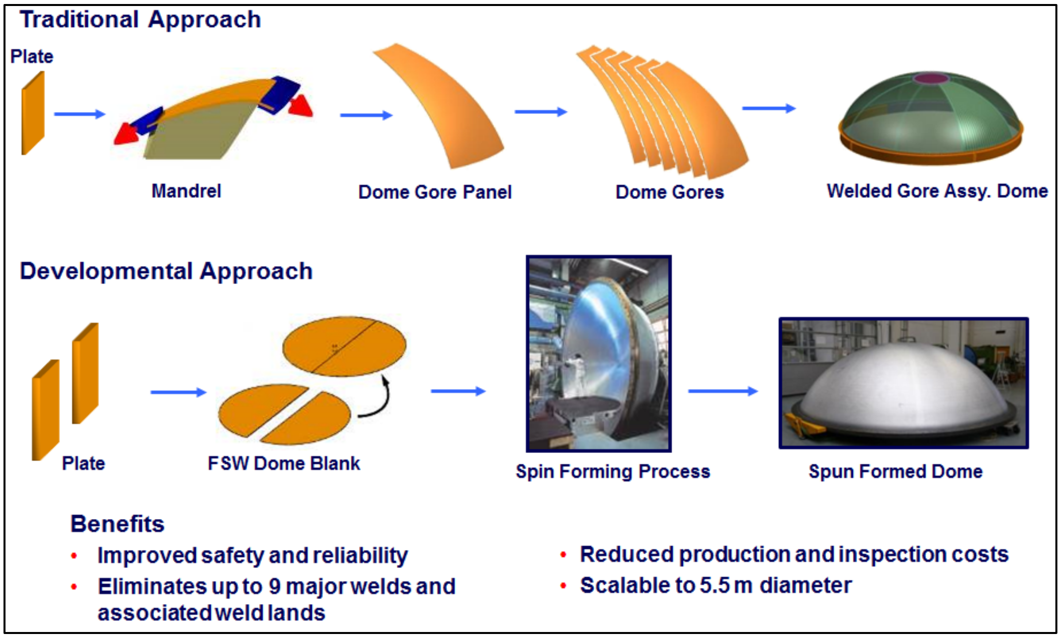
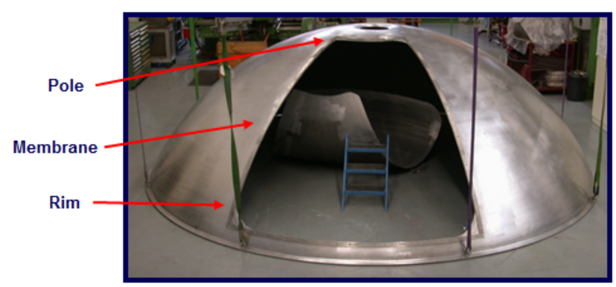


Figure 4.9-15: Cryogenic Tank Dome Manufacturing: Multi-Piece Welded Gore Construction vs. Spin Forming (Alloy 2195).

The tensile properties of the dome at three different locations are shown in **Figure 4.9-16**. All of the properties shaded in green met or exceeded the material property specifications for this alloy. The ones in pink were slightly below the desired values. John Wagner and Eric Hoffman are shown above in **Figure 4.9-11** at an inspection of a partially formed dome. The size of this one-piece dome is impressive.

2195 Base Metal

Longitudinal			
Dome Location	UTS (ksi)	YS (ksi)	e(tot) (%)
Pole	84.56	74.25	9.36
Membrane	79.76	69.12	10.08
Rim	No material available		
Transverse			
Dome Location	UTS (ksi)	YS (ksi)	e(tot) (%)
Pole	85.54	78.35	10.03
Membrane	80.79	70.80	11.15
Rim	81.26	68.23	12.35
45°			
Dome Location	UTS (ksi)	YS (ksi)	e(tot) (%)
Pole	77.82	69.44	13.38
Membrane	75.88	67.65	12.97
Rim	72.07	60.23	14.16



Full-scale (5 meter) dome

Goal Material Properties

Grain Direction	UTS Min (ksi)	YS Min (ksi)	e(tot) Min (%)
Longitudinal	78	73	4
Transverse	78	73	6
45°	73	66	6

= meets 11A1-4 Material Property Specifications
= fails to meet 11A1-4 Material Property Specifications

Figure 4.9-16: Full-Scale 2195 Dome Tensile Properties.

4.9.6. New Space Launch System (SLS)

The proposed next-generation human spaceflight transportation system is known as the space launch system (SLS) (**Figure 4.9-17**) and the multi-purpose crew vehicle (MPCV) (**Figure 4.9-18**). The next-generation human spaceflight system, the SLS and MPCV will be capable of transporting astronauts to multiple destinations beyond LEO. The capabilities provided by these two vehicle systems are necessary for all activities beyond LEO. While NASA's plan calls for the initial destination for human flight beyond LEO to target an asteroid by 2025, other destinations could include cis-lunar space such as the Earth-Moon Lagrange points, the lunar surface, and eventually Mars in the mid-2030s and its moons. The SLS and MPCV are the first important core elements of an evolutionary exploration approach to accomplishing a broad spectrum of missions. The Orion Crew Exploration Vehicle is NASA's new MPCV and the current Orion contract with Lockheed Martin Corporation is being used through at least the development phase of the vehicle.

Figure 4.9-17: Artist Concept of SLS Launch.

In January 2011, NASA announced that it had chosen a Reference Vehicle Design for the SLS derived from Ares and space shuttle hardware. That concept vehicle utilized a LOX/LH2 core, five-segment solid rocket boosters, and a J-2X-based upper stage as the 130-metric-ton (mT) version of the vehicle evolvable from the 70–100 mT versions. As envisioned, this Reference Vehicle Design would allow for use of existing shuttle and Ares hardware assets in the near term, with the opportunity for later upgrades and/or competition for eventual upgrades in designs needed for affordable production. However, NASA is continuing to study other alternative architectures as part of its due diligence.[10]

The U.S. SLS will provide an entirely new capability for human exploration beyond Earth orbit. It also will back up commercial and international partner transportation services to the International Space Station. Designed to be flexible for crew or cargo missions, the SLS will be safe, affordable, and sustainable, to continue America's journey of discovery from the unique vantage point of space. The SLS will be the Nation's first exploration-class, heavy-lift launch vehicle since the Saturn V and will serve as the critical next step beyond the space shuttle. The SLS is to be initially capable of lifting 70–100mT to LEO, while ultimately being evolvable to a lifting capacity of 130 mT or more.

4.9.6.1. Multi-Purpose Crew Vehicle (MPCV)

The MPCV (**Figure 4.9-18**) will provide all services necessary to support a crew of up to four for up to 21-day missions (for very long beyond-LEO missions, such as exploration of near-Earth asteroids or other planetary bodies, additional elements—a space habitation module—will be included to provide long-duration deep space habitation capability). Mounted on top of the SLS for launch and ascent, the MPCV will be capable of performing abort maneuvers to safely separate from the launch vehicle and return the crew to the Earth's surface. The MPCV will also be capable of performing in-space aborts if conditions require the immediate safe return of the crew. MPCV will include the necessary propulsive acceleration capability to rendezvous with other mission elements and return the flight crew from the destination to the Earth's surface. In-space operations, such as rendezvous and docking and extravehicular activities, will be performed with the MPCV in conjunction with other mission elements.

Figure 4.9-18: Multi-Purpose Crew Vehicle.

While the MPCV could be called upon to service the ISS—a backup requirement established by the NASA Authorization Act of 2010—it is well understood that utilizing the MPCV for routine ISS transportation would be a very inefficient and costly use of the MPCV deep-space capability.

Langley has played a key role in developing the technology base required to fabricate and certify the MPCV structure. Marcia Domack,[11,12] Eric K. Hoffman,[13] and coworkers have recently published an extensive report on the results of a study performed under the leadership of Langley on the development of a spin-forming fabrication process for manufacture of the Orion crew module (CM) aft pressure vessel bulkhead. The spin-forming process would create a single-piece aluminum alloy 2219 aft bulkhead (**Figure 4.9-19**)**,** resulting in the elimination of the current multiple-piece welded construction, simplify CM fabrication, and lead to an enhanced design.

Langley has continued to advance manufacturing technologies aimed at producing single-piece, near-net-shape components to replace multi-piece, welded construction wherever possible in launch vehicle structures. They developed the concept, shown in **Figure 4.9-20**, and successfully demonstrated the feasibility of spin forming the forward pressure vessel bulkhead (FPVBH) of the Orion crew module as a single-piece structure, as shown in **Figure 4.9-21**.

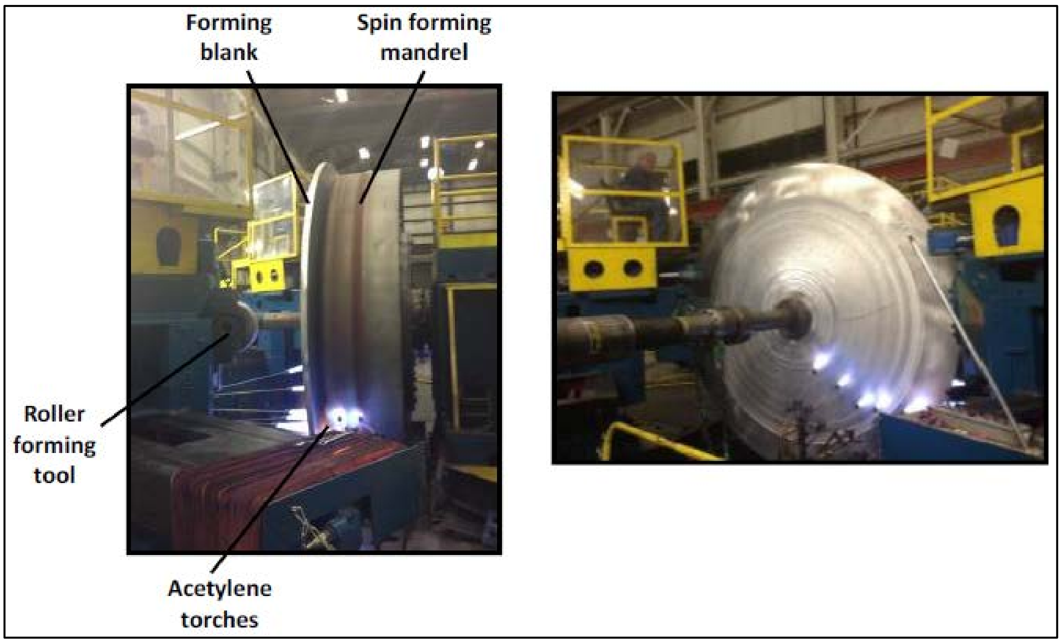


Figure 4.9-19: Convex Spin Forming of the Aft Bulkhead.

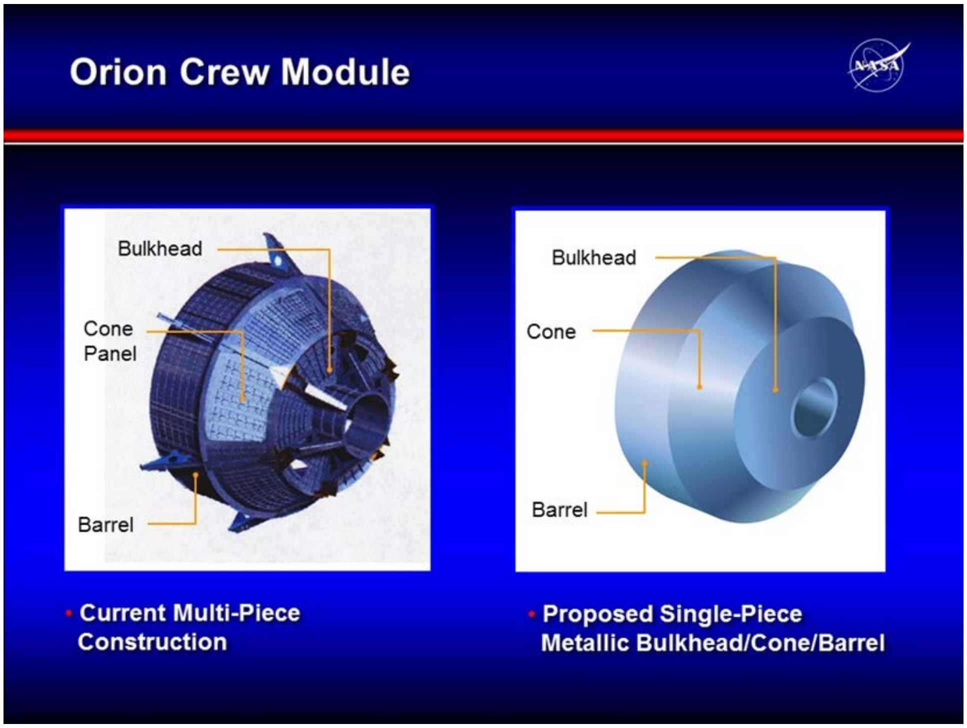


Figure 4.9-20: Concept for a Single-Piece Spin-Formed Single-Piece MPCV Forward Pressure Vessel Bulkhead.

Figure 4.9-21: Spin Forming The Single-Piece MPCV Forward Pressure Vessel Bulkhead.

Structural analysis and materials characterization studies found no insurmountable technical issues with the spin-formed approach. The spin-formed bulkhead was 8% lighter that the multi-piece welded equivalent and had a more uniform load distribution because of the absence of welds. Mechanical properties were comparable to other 2219-T6 wrought products. Boeing adopted spin forming for manufacture of the CST100 crew capsule.

It should be noted that the SLS Program has been and continues to be an advocate for the near-net-shape metals manufacturing research being conducted at NASA Langley by John Wagner, Marcia Domack, and coworkers. They have also co-invested in the near-net-shape technology development at Langley.

References

[1] http://en.wikipedia.org/wiki/Project_Mercury
[2] http://en.wikipedia.org/wiki/Saturn_rocket
[3] Troeger, L.P.; Domack, M.S.; and Wagner, J.A.; "Microstructural and Mechanical Property Characterization of Shear Formed Aerospace Aluminum". NASA/TM-2000-210540, October 2000.
[4] Branscome, D.R.; "United States Space Transportation Survey, "Proceedings of the 2nd European Aerospace Conference on Progress in Space Transportation", (European Space Agency, ESA SP-293, August 1989), pp. 39–44.
[5] Finnegan, Philip; "U.S. Air Force, NASA Restructure Advanced Launch System Program", Defense News, 15 January 1990, page 1, 25.
[6] Launch Options for the Future; "A Buyer's Guide, July 1988, NTIS order #PB89-114268", http://www.fas.org/ota/reports/8826.pdf
[7] Shah, S.; Wells, D.; Wagner, J.A.; Lambert, D.; and Bynum, J.; "Evaluation of Aluminum-Lithium Alloys for Reusable Cryotank Applications". Published in the proceedings of the 2003 JANNAF Conference, Paper No. 2003-0390HK, Colorado Springs, CO, December 1–5, 2003.
[8] Troeger, L.P. and Wagner, J.A.; "Microstructural and Mechanical Property Characterization of Shear Formed Al-Li Alloy 2195 for Launch Vehicle Applications". Journal of Materials Processing and Manufacturing Science, Vol. 9, pp. 205–222, January 2001.
[9] http://en.wikipedia.org/wiki/National_Launch_System
[10] http://www.nasa.gov/pdf/569239main_Bolden_2011_0712_HSSTfinalx.pdf
[11] Hoffman, Eric K.; Domack, Marcia S.; Torres, Pablo D.; McGill, Preston B.; Tayon, Wesley A.; Bennett, Jay E.; Murphy, Joseph T.; "Spin Forming Aluminum Crew Module (CM) Metallic Aft Pressure Vessel Bulkhead (APVBH) - Phase II", NASA TP-2015-218674.
[12] Domack, M. S., Hoffman, E. K., Raju, I. S., Piascik, R. S.; "Spin Forming Aluminum Alloy Crew Module (CM) Metallic Forward Pressure Vessel Bulkhead (FPVBH) – Phase I". February 2014. NASA/TM-2014-218163; NESC-RP-12-00776.
[13] Domack, Marcia S., Hoffman, E. K.; "Supplemental Report - Spin Forming Aluminum Crew Module (CM) Metallic Aft Pressure Vessel Bulkhead (APVBH)", NASA-TM-2015-218797.

5. MATERIALS DEVELOPMENT

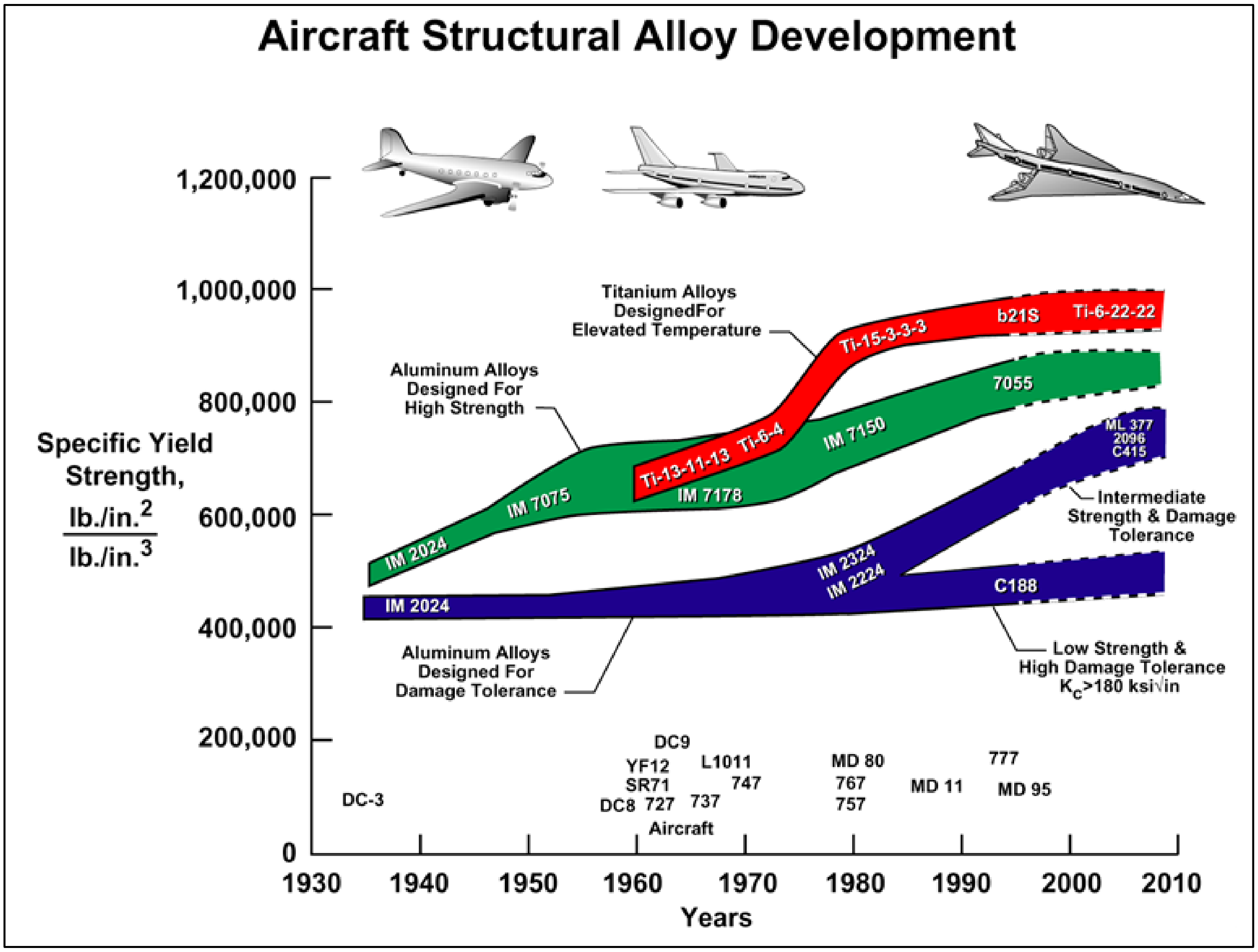
There have always been tensions between the various material camps in aerostructure design since the supply and expertise in production and processing of material types have generally come from completely different places and have been the product of different organizations and individuals.

Towards the end of the 1920s, spruce was displaced in favor of duralumin. After the Second World War, titanium displaced some uses of aluminum and medium-strength steels, and more recently carbon composites have disrupted the balance yet again. Today, there are three major aerospace material categories: aluminum alloys and Al-MMC, titanium alloys and Ti-MMC, and polymer matrix composites. Vehicle designs strive to use each where they are best suited to meet design requirements. In responding to the worldwide prevalence of carbon-fiber-reinforced composites (CFRC), the aluminum and titanium industries have not been standing still.

The proportion of metallic structures in large commercial airframes currently in development is significantly lower than in comparable previous generation, although, it is still approximately 50%. The rationale for expanded use of CFRC is based on both quantifiable arguments (technical and economic) and less quantifiable parameters. Technically, it is argued that carbon-fiber-reinforced polymer (CFRP) panels have a significant weight advantage particularly in damage tolerance or stiffness-dominated parts. Equally, it is generally recognized that metallic solutions are currently lower cost. The perception that aircraft made with CFRP are more technologically advanced than metallic airframes is less quantifiable. However, the recent emergence of new near-net-shape processing technologies that reduce cost and buy-to-fly ratios are viewed as making metallic materials more attractive for aerospace applications.

Recently designed civil aerostructures for the B787 and A350 have highlighted the interactions between the various material types (see **Table 2.1-1**, **Figure 2.1-3**, and **Figure 2.1-4**) and the differing ways in which the engineering compromises are resolved. Carbon fiber composite components in fuselage and wing structures of these aircraft have been designed to interface with titanium parts where possible. The reason for the extensive use of titanium and carbon fiber in inner structures is due in part to the fact that there are less compatibility issues with this material pairing, particularly regarding corrosion and thermal expansion. Aluminum, however, still remains well positioned to produce affordable aerostructures with its realistic weight/cost trade-off and wing ribs have persistently been designed in this material. In addition, new approaches are being explored to address the compatibility issues between Al and CFRP composites.

In response to the increased competition from CFRP, the metals community is becoming more innovative in search of new approaches to “Lightweighting” metallic structures. Firstly, in response to the weight challenge they have developed very competitive metallic solutions using optimum existing technologies (alloys, new fabrication technologies, and assembly techniques) in innovative ways. This approach has resulted in solutions exceeding 20% weight reduction vs. today’s Aerostructures, at lower cost, and applicable to a wide variety of airframes. Secondly, in many cases combinations of materials represent optimum weight-cost solutions; to enable this, technologies for hybrid joining need to be optimized. Solutions to corrosion of dissimilar materials are needed, including alloy modification specifically designed to improve corrosion at interfaces. Thirdly, to address the perception of lower future potential of metallic structures, new breakthrough metallic technologies are being developed. Also, a more aggressive communication on metallic structures' advantages, for example emphasizing the full recyclability of aluminium, needs to be pursued. Finally, a more balanced co-development strategy is needed between the development of generic solutions for large airframes and more targeted projects addressing a greater variety of specific vehicle development needs. With the excellent suit of commercially available Al and Ti alloys available and continuing research to search out new "lightweighting" solutions and improvements it is unlikely that any future aircraft or space launch vehicle will fly without a significant fraction of aluminum and titanium on board. The chart below shows how the specific yield strength of selected lightweight alloys has improved over the past several decades.



Structural materials are the basis for several important classes of aerospace products. Materials are an essential part of every aircraft and launch vehicle. Improvements to structural materials for flight vehicles have been a main thrust of Langley's research since its formation. The research to improve structural materials has been driven by the desire to improve both the performance and flight safety of all types of vehicles. In general, a balanced approach has been pursued between work to improve existing materials and research to create new materials. The scope of the work has ranged from cooperative programs with material suppliers to improve existing classes of alloys to research directed at development of new classes of materials such as metal matrix composites (MMC), hybrid laminates, and nanostructured alloys. In this section we will give a brief history of the development of Al alloys for commercial aircraft applications and also highlight some of the work done to develop improved materials for other vehicles where more stringent service environments or structural requirements require materials with different properties.

5.1. Historical Development of Al Alloys for Aircraft Applications

Excellent review articles on the historical development of Al alloys for aircraft application have been published by Staley and Lege[1] and by Starke and Staley.[2] The reader is referred to these papers for a listing of the most common aerospace alloys, their compositions, the usual constituent phases in aircraft aluminum alloy products, property-microstructure relationships in aluminum alloys, the solute content of various aircraft aluminum alloys, and the year that the alloys were first discussed.

Starke and Staley[2] also include in their paper an excellent discussion of the many drivers and parameters involved in the development and selection of materials for aircraft. They include, but are not limited to, low structural weight, safety factors, cost, availability, manufacturability, reliability and maintainability. The drivers for materials selection and alloy development for aircraft have changed considerably during this century.

5.1.1. 1930s–1960s

From 1903 to 1930, minimum weight was the major criteria for materials selection for aircraft and all other considerations were secondary. From about 1930 through the 1960s, improved performance was the goal and reduced weight was a principal contributor. Materials development for aircraft continued to focus on aluminum, and there was considerable improvement in the strength/weight ratios of sheet metal alloys as well as the development of other product forms, e.g., extrusions, forgings and thick plate. Experiments with different levels of the alloying elements led to an alloy now known as 2014 which developed higher properties than 2017 after artificial aging. Other experiments led to the development of 2024-T3 that attained a higher yield strength than 2017-T4 by modest amounts of cold deformation followed by natural aging and significantly higher ductility than 2014-T6.

The drive to fly faster was associated with the “improved performance” quest in the 1960s, and two major programs (Soviet and English-French) were initiated in 1962 to develop supersonic commercial aircraft designed to fly at Mach 2+. This led to the development of Al alloy 2618 which had excellent creep resistance at the stress and 100°C temperature requirement for a Mach 2 aircraft.

5.1.2. 1970s

The growth of linear elastic fracture mechanics analyses in the 1960s revealed the need for improvements in the combination of strength and fracture toughness of aluminum alloys. In 1978, certification of new aircraft required that manufacturers demonstrate that fatigue cracks would be detected prior to their reaching the critical length associated with catastrophic failure. The critical crack length and fatigue crack growth characteristics of 2024-T3 provided adequate safety and economical inspection intervals, but the low-yield strength caused a weight penalty. In contrast, its low fracture toughness and inferior fatigue crack growth resistance prevented the high-strength 7075-T6 alloy from being considered for fracture critical applications where loads were tension dominated. The desired improvements in aluminum alloys that drove materials development during the 1970s included an alloy that would develop strength and short-transverse ductility as high as that of 7079-T6 in thick section products along with adequate stress corrosion resistance in the short transverse direction; an alloy that would develop the strength of 7075-T6 with the resistance to exfoliation corrosion of 7075-T76; and, an alloy that would develop strength approaching that of 7075-T6, fracture toughness approaching that of 2024-T3, fatigue crack growth characteristics sufficient to provide economical inspection intervals, and adequate resistance to exfoliation corrosion. Alloy 7050-T74 was developed to fill the need for a material that would develop high strength in thick section products, good resistance to exfoliation corrosion and stress corrosion cracking, and adequate fracture toughness and fatigue characteristics.

5.1.3. 1980s

In the 1980s, costs, the market value associated with increased range, and landing weight fees resulted in a technical focus on weight reduction. Trade-off studies were made to determine which property improvement had the greatest impact on weight savings. These studies showed that a reduction in density was most advantageous, and lithium additions would have the greatest influence on reducing the density of aluminum. Aluminum-lithium alloy development programs were initiated in Great Britain, the United States, France, and Russia. Although an aluminum-lithium alloy, 2020, had been developed in the 1950s and used for wing and tail structure of the RASC reconnaissance aircraft, it was plagued by manufacturing difficulties and low fracture toughness and was withdrawn from the market. In the 1960s, Fridlyander and coworkers developed a low density Al-Li-Mg which includes fatigue resistance and fracture toughness alloy (1420 by their designation).

5.1.4. 1990s

In the 1990s, the reality associated with an aging aircraft fleet resulted in a technical focus on improved damage tolerance and improved corrosion resistance. During the 1980s and 1990s, there was a major focus on the cost of doing business, i.e., acquisition cost, which includes the cost of manufacturing and having environmentally compliant processes, and maintenance cost, which is impacted by material variations, defects, etc. In addition to having high specific strength, damage tolerance, and corrosion resistance, new materials must be amenable to new manufacturing methods and be cost effective. Consequently, the current challenge is to develop materials with improvements in both structural performance and life cycle cost. This requires close cooperation between material producers and the airframer’s design, analysis, manufacturing, and cost experts so that the material properties can be tailored to the intended application.

Two important advances over the past 40 years enable the optimization and effective management of the structural integrity of components in high-performance applications. First, the solid mechanics community established linear elastic fracture mechanics as the premier framework for modeling the damage tolerance of fracture critical components (Irwin and Wells[3] and Paris[4]). Second, materials scientists developed metals with outstanding balances of high-tensile strength and high fracture toughness (Garrison,[5] Wells,[6] Boyer,[7] Starke and Staley,[8] Olson,[9] and Kolts[10]). New nano-scale characterization and high-performance computational methods provide for additional advances in the mechanical performance properties of structural metals. These modern alloys and analysis tools satisfy technological needs for optimization and management of component performance in demanding fatigue and fracture critical applications in the aerospace, marine, energy, transportation, and defense sectors.

References

[1] Staley, J.T. and Lege, D.J.; "Advances in aluminum alloy products for structural applications in transportation", J. Phys. IV, Collogue C7, 3, 179-190,1993.
[2] Starke, Jr., E.A. and Staley, J. T.; "Application of Modern Aluminum Alloys to Aircraft", Prog. Aerospace Sci. Vol. 32, pp. 131-172, 1996.
[3] G.R. Irwin and A.A. Wells; "Selected Papers on Foundations of Linear Elastic Fracture Mechanics," Vol. MS 137, SPIE Milestone Series, SEM, Bethel, CT, 1997, 215-266.
[4] P.C. Paris; "Fracture mechanics and fatigue: A historical perspective". Fatigue and Fracture of Engineering Materials and Structures, 1998, 21, 535-540.
[5] N.R. Moody, S.L. Robinson and W.M. Garrison, Jr.; "Hydrogen effects on the properties and fracture modes of iron-based alloys", Res. Mech., 30, 1990, 143-206.
[6] M.G.H. Wells; "Advances in steels for aerospace applications", Key Engr. Matls., 1993, 77-78, 71-80.
[7] R.R. Boyer; "Beta Titanium Alloys in the 1990s," eds., D. Eylon, R.R. Boyer and D.A. Koss, The Minerals, Metals & Materials Society, Warrendale, PA, 1993, 335-346.
[8] E.A. Starke, Jr. and J.T. Staley; "Application of modern aluminum alloys to aircraft". Prog. Aerospace Sci., 1995, 32, 131-172.
[9] G.B. Olson; "Brains of steel: Designing metallurgists", Advanced Matls. Proc., July, 1997, 72-79.
[10] J. Kolts; "Corrosion Resistant Alloys in Oil and Gas Production," Vol. II, eds., J. Kolts and S.M. Corey, NACE, Houston, TX, 1996, 733-748.

5.2. Al-Li Alloy Research

The following are key facts about aluminum-lithium alloys:

- An Al-Li alloy is an advanced structural alloy comprised primarily of aluminum and lithium with additions of copper, zinc, manganese, magnesium, zirconium, and iron.
- Lithium, the world's lightest metal, decreases the weight of aluminum while improving its strength, toughness, and corrosion resistance and forming characteristics of the alloy. Every 1 wt% addition of Lithium decreases density by 3% and increases the elastic modulus by 6%.[1]
- Early use began with the Al-Li 2020 alloy back in the 1950s by the aerospace industry. Three decades later, Alcoa introduced the 2090 series. Modern versions of the Al-Li alloy include the 2099, 2195, and the 2199.
- Al-li alloys are commonly used in military aircraft and space vessels including the fuel tank on NASA's space shuttle. This enabled it to carry a heavier payload. Modern aircraft manufactures benefit from the Al-Li alloy with typical uses such as wing and

fuselage skins and wing stringers. Weight savings result in less fuel consumption and increased flight range.

- An important material characteristic of the modern Al-Li alloy is the fatigue crack growth performance. This allows aircraft designers to use less material for the same level of safety margins when compared to other alternatives such as composites. Al-Li is an attractive option for damage-tolerant applications found in the aerospace and military industry.
- The new Airbus A350 uses a great deal of Al-Li (estimates as high as 20% have been reported) for the wings and fuselage.

5.2.1. Lithium Additions to Aluminum Alloys: Early Days

Aluminum-lithium alloy research dates back to the 1940s and was performed in the United States, Germany, Great Britain, Russia, and other countries. However, it wasn't until the late 1970s and 1980s that large scale research of Al-Li alloys was sponsored by multiple government and industry laboratories. Trade-off studies were made to determine which property improvements had the greatest impact on weight savings. These studies showed that a reduction in density was the most advantageous and lithium, being the lightest metal, would have the greatest influence on reducing the density of aluminum. The aluminum companies were also interested in developing low-density alloys due to their concern about the competition from non-metallic composites for aerospace materials and the belief that there must be major advancements in aluminum metallurgy for aluminum alloys to stay competitive.

Aluminum-lithium alloy development programs were initiated in Great Britain, the United States, and France and continued in the Soviet Union. The objective of most of these programs was to develop gauge-for-gauge substitutes for the standard alloys with similar properties while maintaining manufacturability. Detailed design studies predicted that aluminum-lithium alloys, meeting predefined alloy development targets, would be able to produce weight savings of the order of 8% to 15% by a combination of density reduction and stiffness enhancement. The approach of most of these Al-Li alloy development programs was to use lessons learned from previous studies of aluminum metallurgy. These included decreasing the iron and silicon content to the minimum economically feasible for high toughness and ductility; replacing manganese with zirconium to form Al_3Zr dispersoids for grain refinement since large manganese-rich dispersoids may be detrimental to ductility by nucleating voids; and not using cadmium for nucleating strengthening precipitates since that element seemed to enhance intergranular fracture in alloy 2020. These research programs resulted in the "second generation" of aluminum-lithium alloys.

5.2.1.1. The Second Generation of Aluminum-Lithium Alloys

The major aluminum producers, Alcoa (U.S.), Pechiney (France), British Alcan (with help from the British Aerospace Establishment), were all involved in the development of aluminum-lithium alloys using the ingot metallurgy approach. Alcoa focused on a 7075-T6 replacement, Pechiney focused on a substitute for 2024-T3 sheet and light gauge products, as did British Alcan.[2] Each of the initial alloys from these producers contained approximately 2% or greater Li, around 2% or more Cu, some Mg, and Zr to control grain structure. The compositions, along with the specific gravity, of some of the initial alloys produced are given in **Table 5.2-1**.

Table 5.2-1: Compositions of Selected 2nd Generation of Aluminum-Lithium Alloy.

ALLOY	Li	Cu	Mg	Si	Fe	Zr	Specific Gravity
2090	1.9-2.6	2.4-3.0	0.25	0.10	0.12	0.08-0.15	2.60
2091	1.7-2.3	1.8-2.5	1.1-1.9	0.20	0.30	0.04-0.10	2.58
8090	2.1-2.7	1.0-1.6	0.6-1.3	0.20	0.30	0.04-0.16	2.53
8091	2.4-2.8	1.8-2.2	0.5-1.2	0.30	0.5	0.08-0.16	2.54
8092	2.1-2.7	0.5-0.8	0.9-1.4	0.10	0.15	0.08-0.15	2.53
8192	2.3-2.9	0.4-0.7	0.9-1.4	0.10	0.15	0.08-0.15	2.51

5.2.1.2. The Third Generation of Aluminum-Lithium Alloys

The development of the third generation of aluminum-lithium alloys can be traced to the late 1980s when Pickens and coworkers, working for the Martin Marietta Corporation (later Lockheed-Martin Corporation), set out to design a weldable aluminum-base alloy having low density for use in aerospace launch vehicles and cryogenic tankage.[3] They used alloy 2219 as a base and added Lithium until the strength peaked at 1.3 wt% Li. Silver and Mg were added as nucleating agents for the T_1 phase based on the work of Polmear.[4] Zirconium was added for grain structure control and to refine the grain structure in the weld zone. The nominal composition of Weldalite™ was Al-(4.6-6.3) Cu-1.3Li-0.4Ag-0.4Mg-0.14Zr-0.06Fe-0.03Si. The alloy could reach a yield strength of 700 MPa through a uniform distribution of T_1. Reynolds Aluminum purchased the production rights from Lockheed-Martin, but the two companies worked together for future alloy development and production capabilities.

The third generation of Al-Li alloys contained less than 2% Li. Subsequent versions of the Weldalite™ family of alloys contained Zn for improved corrosion resistance.[5] Zinc dissolves in grains and shifts the pitting potential of the matrix to less noble and decreases the electro-chemical potential difference between the grain boundary and the matrix, thus improving static and dynamic corrosion properties.[6] Research led to the development of 2195 that was used on the super lightweight tank of the space shuttle that was first flown in 1998. NASA had an extensive program to develop the machining and welding conditions for this alloy for the SLWT. The new alloy and some design changes reduced the tank weight by 3175 kg/7000 lbs over the lightweight tank, previously used, and provided a significant increase in the performance required for the shuttle to reach the International Space Station. The compositions of some other third-generation Al-Li alloys are given in Table 5.2-2.

Table 5.2-2: Chemical Composition of Some Third-Generation Al-Li-X Alloys (wt %).

Alloy	Li	Cu	Mg	Ag	Zr	Mn	Zn
2195	1.0	4.0	0.4	0.4	0.11		
2196	1.75	2.9	0.5	0.4	0.11	0.35max	0.35max
2297	1.4	2.8	0.25max		0.11	0.3	0.5max
2397	1,4	2.8	0.25max		0.11	0.3	0.10
2198	1.0	3.2	0.5	0.4	0.11	0.5max	0.35max
2099	1.8	2.7	0.3		0.09	0.3	0.7
2199	1.6	2.6	0.2		0.09	0.3	0.6
2050	1.0	3.6	0.4	0.4	0.11	0.35	0.25max
2060	0.75	3.95	0.85	0.25	0.11	0.3	0.4
2055	1.15	3.7	0.4	0.4	0.11	0.3	0.5

In 1992, the U.S. Air Force Wright Laboratory, Materials Directorate initiated a program with the University of Dayton Research Institute, with Alcoa as a sub-contractor, to significantly reduce the in-plane anisotropy in aluminum alloys containing more than 2 wt% Li. The initial approach was to introduce an intermediate recrystallization anneal between rolling stages in order to reduce the sharp deformation texture and thereby decrease the alloy's anisotropy.[7] The designed two-step process to both inhibit and promote recrystallization proved highly successful and the anisotropy of both the modulus and yield strength were reduced significantly from 20%–25% for earlier Al-Li alloys to less than 10% for the Air Force alloy. In addition, the short transverse fracture toughness was improved nearly fourfold over alloys with greater than 2.0 wt% Li. The Air Force alloy was designated AF/C-489 with a nominal composition of Al-2.7Cu-2.05Li-0.6Zn-0.3Mn-0.3Mg-0.04Zr.

There have been a large number of research and development activities, focused on Al-Li-X alloys, in many countries, universities, and industrial and government laboratories. NASA played a significant role, both in-house at Langley and throughout sourcing to universities, in the development of processing parameters, property measurement, and treatments for property improvement, and welding technology of Al-Li-X alloys.

Although the early Al-Li-X alloys and the second generation of Al-Li-X alloys had undesirable performance and manufacturing characteristics, fundamental studies identified the root causes of those problems and led to the improved third generation of Al-Li-X alloys having high strength/fracture toughness, fatigue, and corrosion resistance. Rioja and Liu have reviewed more details of the technical achievements involved in these improved properties.[23] Finally, a number of the new alloys are currently being used, such as the following examples:

- The super lightweight tank for the space shuttle (2195)
- The F16 Fighter Aircraft (Weldalite™, 2297)
- The A380 Airbus (2196)
- The Boeing 787 Dreamliner (2099/2199)
- Being considered for the A350 Twin-engine Aircraft (Alcan Alloys 2098/2198)

The properties of the third generation of Al-Li-X alloys can be tailored to meet a variety of needs of future aircraft and spacecraft for weight savings, performance enhancement, and reduced inspection and maintenance. Because aluminum alloys are used in a variety of product forms including sheet, plate, extrusions, forgings, tubes, etc., different processing procedures may be necessary. In addition, different components of aircraft and space vehicles require different sets of properties, and this may require a variety of aluminum-lithium alloys to be used on a particular aircraft or space vehicle, along with other materials, e.g., composites, titanium alloys, etc.

5.2.2. Anisotropy and Delamination Fracture in Al-Li Alloys

Technical issues that have prevented Al-Li alloys from being more widely used in aerospace applications are highly anisotropic material properties and concerns regarding delamination fracture. Delaminations are a grain boundary fracture mode where cracks propagate along grain boundaries in the highly-elongated (lamellar) grain structure common to rolled Al-Li alloys. Non-NASA studies leading up to the year 2000 provided several potential theories for mechanisms controlling delamination fracture as outlined by Lynch:[8]

1. Development of stress concentrations due to "large area fraction of grain boundary precipitates and the adjacent soft PFZs (precipitate free zones)"
2. "Impingement of planar slip bands on grain boundaries"
3. "Segregation of alkali impurities" or liquid-rich phases at grain boundaries
4. "Segregation of hydrogen" or hydride particles and grain boundaries
5. "Segregation of lithium at grain boundaries"

The role that most of these mechanisms played was largely diminished, if not refuted, by Lynch. While some may be contributing factors, these were not identified as the primary cause of delamination. Since 2000, NASA Langley researchers, in collaboration with Marshall Space Flight Center and the University of Illinois, have conducted pioneering research[9,10,11,12,13,14,15,16,17,18] in studying the mechanisms of delamination fracture. This research has better defined the mechanisms of delamination fracture through state-of-the-art experimental and computational advancements. This type of fundamental understanding is valuable for developing fracture-tolerant design standards for these alloys to enable increased deployment in the aerospace community.

As part of their research on delamination of Al-Li alloys, researchers at NASA Langley Research Center examined post-mortem crack-divider compact-tension specimens. Delaminations were found to commonly occur between brass variants, which was unexpected.[12] These brass variants are part of the deformation texture due to rolling and strongly contribute to mechanical anisotropy. By computing grain-specific Taylor factors for deformation composed of normal and shear stresses as identified through finite element simulations, it was observed that the responses of the two brass variants (brass1 and brass2) were markedly different.[10] One variant had a high Taylor factor (hard) and the other a low Taylor factor (soft), indicating significant differences in crystallographic yield strength (hard vs. soft grains) and damage accommodation. A broader assessment of the sample cross-section that contained several delamination cracks revealed that the grain boundaries that cracked were bordered by grains with the largest difference in Taylor factor in the local region.[13] This suggests that a normal-shear stress coupling drives failure to grain boundaries bordered by orientations with poor slip transfer from grain to grain. Additionally, a narrow band of deformation within 2 µm of the boundary was found on only one side, indicating preferential localization near the boundary in only one grain. Tedious sectioning of a separate specimen enabled observation of the delamination fracture surfaces which revealed intense planar slip on only side of the grain boundary, in a Cube grain, whereas there were no signs of slip in the harder brass grain.[16] Electron backscattered diffraction patterns from the fracture surface were used to identify crystal orientation. Additionally, apparent separation of grain boundary T1 precipitate plates from the matrix was observed, suggesting initial void formation at grain boundary precipitates due to intense planar slip.

The impact of normal and shear stresses was further investigated through mechanical testing and computational modeling. McDonald[19] found that the grain boundaries were much weaker under shear (~225 MPa shear strength) than for tensile loading (~500 MPa tensile strength). In simulations using a bi-crystal model, it was found that material anisotropy due to crystallographic orientation led to a normal-shear stress coupling, where loadings that was exclusively shear or normal lead to the development of both normal and shear stresses at the grain scale. The end result of this work is that delamination cracks are sensitive to shear stresses and that there is an orientation dependence on local damage and hence delamination susceptibility.[20]

Motivated by experimental and computational indications that mesoscale material response was driving delamination fracture, Beaudoin[17] pursued high-energy diffraction microscopy (HEDM) experiments at Argonne National Laboratory's Advanced Photon Source. Experimental characterization of the internal strains within four unique crystal orientations was achieved. In-situ tests revealed the development of local shear stresses within grains under uniaxial.[17] A strong heterogeneity was observed for near-brass grains and a rotated cube grain. The rotated cube grain was found to yield well before the brass grains and had a distinct plane strain behavior, indicating a resistance to thinning in the plate normal direction. The rotated cube grain also exhibited signs of increased work hardening. The relative magnitude of the strains within the brass grains was similar; however, the sign of the L-T shear component was found to alternate among brass variants.[18] Elevated mean stresses were observed between boundaries border by crystallographically hard and soft grain pairs, indicating an increased propensity for void growth. Computational results support the notion of incompatibility, specifically among brass1/brass2 grain pairs. This is in agreement with prior experimental studies.[12,13] A viscoplastic, crystal plasticity simulation based on the microstructure from the HEDM experiment produced similar results in agreement with the experiment. Furthermore, the simulation predicted the development of signed dislocation density content along a brass1/brass2 grain boundary, indicating preferential damage accumulation. This is consistent with an increased proclivity for delamination along brass1/brass2 grain boundaries as reported by post-mortem examination of failed fracture toughness specimens. An increased level of shear along the grain boundary and geometric incompatibility in relation to crystal orientation and its impact on slip transfer from grain-to-grain likely contribute to the increased likelihood of delamination fracture between these brass grain pairs.[16]

In summary, the joint NASA and University of Illinois work found that delamination fracture is highly influenced by the local crystallographic texture and distribution of precipitates, most importantly along grain boundaries. The combination of these two factors leads to highly localized deformation along the grain boundary, promoting damage and fracture. The delamination work is contributing toward developing alternative plate processing methods to reduce or eliminate the potential for delamination fracture in these alloys. Similarly, results from this study are aiding in the assessment of current fracture-tolerant design standards and ensuring they are conservative in the presence delamination fracture, in addition to developing improved design protocol for these alloys. In the broader technical community, this work has provided a better understanding of the interaction of hard and soft grains at the microstructural level, giving insight into damage and plasticity modeling at the microscale toward the development of better predictive models.

This type of detailed research at the microstructural level is critical to developing new and improved alloys. The skills developed by the researchers doing these types of studies has enabled the metals group at Langley to do expert failure analysis of the types sited in section 2-10, "Metallic Materials Failure Analysis."

5.2.2.1. Al-Li 2195 Development Story for Super lightweight Tank and Langley's Role

Figure 5.2-1: NASA/McCook Metals Development.

An excellent review of the history and lessons learned on the shuttle external tank was prepared for Joan Funk of NASA MSFC.[21] A significant part of that report has been included to illustrate the many R&D tasks that needed to be addressed to insert a new material into a safety critical man-rated flight system.

In the 1980s, U.S. aluminum manufacturers realized that the increasing use of composites for aircraft structures would soon impact their sales for aircraft, so they resurrected the Al-Li work they had done in the 1950s. Alcoa developed an alloy called Al 2090, which showed good aircraft properties but limited weldability. This alloy was also not available in the thicker plate gages, which ET needed to machine out their tank skins. The Al 2090 is believed to be used in the C-17 transport aircraft.

Martin, as part of their corporate empire, at one time owned an aluminum company. They sold the company but retained the R&D Labs in Baltimore, Maryland. This group began working on developing a high-strength, weldable, cryogenic friendly Al-Li alloy. They called this alloy "Weldalite," which actually covered a family of Al-Li alloys. Martin, now Lockheed Martin, obtained samples of the "Weldalite" alloy under an Independent Research and Development (IRAD) Program and had three dome gores and a quarter of the chord, which attaches the dome to the barrel, formed. These were welded into what the ET calls a "quarter dome."

Forming the Al-Li into dome gores was a learning experience. The forming process for the previous Al-Cu alloy (Al 2219) gores is done by starting with plate in the T3 temper (minus the cold work), cutting the gore to shape from flat stock, stretch forming in a stretch press, which adds cold work to satisfy the T3 temper requirements, aging to T8 temper, and chemical milling to the final configuration.

When this was tried on the Al-Li, the material was so stiff in the T3 temper that it broke the gore supplier's (aircraft hydro forming, AHF) stretch press. Martin and AHF worked out an approach which involved the aluminum supplier delivering the plate in a T0 temper. AHF would then bump form the flat gore stock in one axis, solution heat treat to 985°F, quench in 10 seconds (which gave them a T3 temper minus some of the cold work), and then stretch form to the final contour. This stretch forming supplied the cold work was necessary to get to a T3 temper. The panels were then aged to a T8 temper and chemically milled to final contour. Because the aging time/temperature for Al 2219 resulted in over-aged material for Al-Li, another test program was necessary to establish the optimum aging cycle. Post-delivery solution heat treating and quenching these large curved panels required new ovens and quench tanks since this is usually done on a flat plate at the rolling mills.

NASA's decision to change their orbital inclination of space station to 57°, so that the Russians could fly directly to the station, had a major impact on shuttle weight requirements. The inclination change cost the shuttle 13,500 lbs of payload capability, which put it well below the Station needs. Since the Advanced Solid Rocket Motor Program had already been cancelled, this left it to the external tank (ET) to make up a significant portion of the payload loss. To be conservative, the ET Project proposed to reduce the dry weight of the ET by 7500 lbs using the aluminum-lithium alloy developed by Lockheed Martin under the Weldalite banner. JSC convened a "Non-Advocate Review" team chaired by Bob White, JSC Systems Engineering, and representatives from Langley Research Center and MSFC to evaluate the Lockheed Martin plan. Lockheed Martin proposed delivering the first "super Lightweight ET," to be called SLWT, in 48 months after the go-ahead. This was considered reasonable since Lockheed Martin had delivered the first ET, the main propulsion test tank, in 48 months starting from scratch with no design, an empty plant, and no work force. JSC accepted the 48-month schedule, but waited four months before starting the project and left the end date the same. This brought the span time down to 44 months. Because the space station schedule and NASA's reputation were riding on the ET, the ET Project Office accepted the challenge. The first step after turn-on was to purchase some of the Al-Li material. Although Lockheed Martin Labs had developed the material, Reynolds Aluminum had bought the production rights. When Reynolds mixed up their first batch of production material, its behavior, particularly in the fracture area, was not the same as Lockheed Martin's lab material. When Reynolds could not explain or resolve the differences, Lockheed

Martin Labs, Lockheed Martin Michoud, and MSFC M&P Labs joined in setting up a Taguchi design of experiment (DOE) program. Because Reynolds had no experience in this type of program, Lockheed Martin Huntsville, who had used it extensively in the TPS development programs, taught Reynolds how to perform the DOE. Reynolds was finally able to make the material, but the room temperature/cryogenic temperature fracture toughness ratio for the thick plate was erratic from plate to plate. To aid Reynolds and to insure good material Lockheed Martin, MAF, and MSFC M&P co-located Ph.D. metallurgists at Reynolds for several years.

The next "gotcha" occurred when Lockheed Martin used the IRAD quarter dome to practice straightening "oil cans" induced by weld repairs in the doubly curved dome welds. This shrinkage would cause a flat spot or even a reverse curvature in the vicinity of the repair. For Al 2219 the magnetic hammer developed at MSFC or planishing of the weld repair had been used to correct the oil can. To provide a test practice article, Lockheed Martin chose to induce oil cans into the IRAD dome by making multiple (6 or 8) repairs at the same location. However, when the multiple repairs were tried on Al-Li, the repair area cracked. After examination of the repaired area, it was found that welding Al-Li caused a crystalline structure called an equiax zone of extremely brittle material surrounded by a continuous secondary phase. Repeated repairs caused this zone to grow until the residual stress from the weld shrinkage exceeded the strength of the brittle weld repair causing it to fail.

Al-Li had to be welded with an inert gas purge on the backside of the weld rather than only on the front side, as was common on all other aluminum. An approach to repair the weld cracks in Al-Li was to make alternate side repairs, for example, make repairs by grinding from the backside to grind out the equiax zone and to make the repair from the backside. If a succeeding repair was needed, then sides were again swapped. Since Lockheed Martin's entire high production rate tools were designed to 31 welds and repair for the one side, this meant building a new group of repair fixtures. It was also found that Al-Li could not tolerate as much heat as Al 2219. For Al 2219 repairs, which were made manually, the welds were carefully controlled to a torch speed of 4 inches/minute. Al-Li could not tolerate this much heat and required torch speeds of 10 inches/minute. Lockheed Martin solicited help from all of the other Martin Divisions, MFSC, Langley, JSC, USAF at Wright-Patterson AFB, and the Edison Welding Institute.

The next gate to be passed was whether the material could be welded in the first place. The baseline ET used VPPA welding for most of its welding. Developing tools which could furnish the inert gas backside purge with the plasma torch blowing through the material, a characteristic of VPPA, caused enormous tool design issues with several purge boxes being cut up by the plasma torch.

The tooling for the long LH2 tank barrels (20 ft), which were welded horizontally to permit offloading the tool under a 36-foot crane height, used the standard TIG weld process. This had worked well on Al 2219, but major problems were encountered on the Al-Li. These welds were made in a down hand torch attitude, an attitude where VPPA was not effective. The plasma torch would blow the weld puddle out of the seam. A new technique was needed. Lockheed Martin at MSFC developed a soft plasma arc weld system to resolve this problem.

It was also found that welding with the 4043 weld wire vs. 2319 was more forgiving. However, the 4043, a high-silicon wire, was not as strong as 2319 or the parent Al-Li (now known as Al 2195). On multiple weld repairs the concentration of 4043 would gradually build up until the puddle was almost pure 4043. This brought the strength of the repairs down to about 32 ksi when the test data was processed per MIL-HBK-5 statistical practice. The weld lands on the parent material had to be sized for this weld strength. This of course added weight.

When reflecting on this, NASA and Lockheed Martin questioned whether the method used to develop weld allowables was giving the welds adequate credit. The classical method was to weld a test panel, make a repair of approximately 6 inches, and cut a 1- to 2-inch test specimen out of the center of this repair. Thus, the test specimen was testing entirely repaired material. However, on the real hardware, as the repair yielded, the loads would redistribute and the original weld would pick up some of the load. It appeared that this test method was short changing the weld repair. To test this, a series of 17-inch-wide panels were coated with a photo stress coating which would show the stress pattern under ultraviolet light. Pat Rogers of MSFC's Structures and Dynamics Lab also developed a computer program to display these stress fields with excellent correlation to the photo stress images. When tested on Al 2219, the results were exactly as predicted. The repair yielded, the loads redistributed, and the panel pulled well over the minimum allowable value. But, when this was tried on Al-Li 2195, the material yield strength was so high the loads remained concentrated in the repair. Instead of the 32 ksi obtained previously, the welds were failing around 18 ksi. Since extensive parts had been machined with weld lands sized for 32 ksi repair capability, this had the potential to be a real show stopper. In tracking down the cause of the discrepancy, it was determined that the repair weld shrinkage stress was trapped in the joint and this reduced the joint capability. An approach was developed to planish the weld bead, forcing it back into the joint and spreading the joint to get rid of the shrinkage stress. This requires scribing and measuring the joint before every repair, making the repair, and planishing the bead to eliminate the shrinkage. Planishing weld beads is not a precisely controlled process and frequently forms other cracks leading to additional weld repairs as high as R19 (19 welds overlapping). This need to planish all repairs was a major driver in selecting the 4043 weld wire since it was easier to planish. Because of the difficulty in making and planishing multiple repairs, a verification ground rule was established that every "first repair of its kind" had to be replicated on three 17-inch-wide panels, which were then tested on a universal test machine, either at room temperature or cryogenically depending on where the critical stress condition existed. This rule, as well as others relating to the fracture characteristics of the material, was staffed through both the Lockheed Martin Fracture Control Board and the MSFC Fracture Control Board. To illustrate the difficulty in making some of the repairs, the first 17-inchwide test panel on an R17 repair (17 repairs overlapping) took 800 man-hours to prepare. Actions taken to reduce the need for planishing are addressed in the weld wire replacement discussions at the end of this section.

Another of Lockheed Martin's weight saving approaches was to abandon the hogged out longitudinal "T" stiffeners with mechanically fastened ring frames and to machine a rectangular waffle pattern directly into the skin panels of the LH2 tanks. This waffle, called an orthogrid, provided almost half of the SLWT weight saving. McDonnell Douglas had flown a triangular pattern called an isogrid, but orthogrids had not been used before on propellant tanks although some payload fairings had used this approach. McDonnell Douglas, however, published some research in iso- and orthogrids which turned out to be very useful to Lockheed Martin. One problem with the orthogrid is forming to the circular arc without crippling the vertical legs. Lockheed Martin and MSFC did extensive development in the MSFC PEC to investigate forming techniques. The classic method of forming this type of configuration is to machine flat in a T3 temper, fill the pockets with a low melting alloy, roll, and melt the filler material out and then age to a T8 temper. To find a lower cost approach, rolling the flat machined material, both with and without a soft aluminum cap sheet, and bump forming with contoured shoes on a numerically controlled press were also tried. When Lockheed Martin competed the part to industry, the bump forming with the numerically controlled press was selected. This has performed very well. After forming, the plate is aged to a T8 temper in a restraining fixture to insure final contour. To certify the integrity of these skin panels, the plate is ultrasonically scanned at the rolling mill. After the panels are formed and aged, they are inspected with a Type III penetrant (ultrasensitive) by two totally independent sets of eyes. Each inspector has a matrix to follow to ensure that every pocket is scanned. Previously, on the Al 2219 tanks for both Boeing S-IC and ET the machined skins were penetrant inspected with a Type II penetrant for a number of skin panels. This post-machining inspection was dropped when nothing was found over a large number of samples. Machined plates are always ultrasonically scanned at the rolling mill and are still scanned for Al 2219 deliveries.

Because of the thick plate necessary to hog out the ET skins, it is necessary for the stress analysis to be performed in three dimensions. For the Al 2219 isotropic material conventional analysis tools were available. However, Al 2195 tends to be anisotropic in that the properties through the material (short transverse direction) are somewhat weaker than the long or long transverse directions. It thus became necessary to modify analysis tools, by both Lockheed Martin and MSFC, to design and analyze these parts. The material behaves almost like a composite which has only the strength of the resin in the short traverse direction. The analysis tools developed for composites were adapted for Al-Li.

It was mentioned earlier that the cryogenic/room temperature fracture toughness ratio of the Reynolds Al-Li was erratic from plate-to-plate with each plate being a furnace lot. Since the ET propellant tanks are proof tested at room temperature and flown cryogenically, the ratio is most important. Al 2219 is approximately 10% tougher at cryogenic condition than at room temperature. This provides that flaws, which are just below critical at room temperature, have room to grow at flight temperatures. The whole issue of the ET fracture-based designs is beyond this paper, but Don Bolstad of Lockheed Martin has published several papers. However, the erratic nature of this ratio was most critical to the SLWT. To resolve it a decision was made to perform a simulated service test on every plate. Failure of this test resulted in the plate being re-melted and re-processed.

The simulated service test consisted of cropping two specimens from the end of each plate. Electro deposition machining (EDM) notches were machined in each sample. The first sample was stressed to failure during development; the second was stressed to the stress level expected during proof test at room temperature. The sample was then stressed 13 times to the level expected during loading of propellants at cryo temperatures then stressed to maximum expected flight stress at cryo temperature. This cycle of loading stress and flight stress was repeated three times to meet the four life program requirements with the exception that on the fourth cycle, the sample was broken and had to exceed a predetermined percentage of the failure stress of the first sample. This is still being done on all 32 barrel plates of every LH2 tank.

Since the orthogrid panel had never been flown in this application, the stress community desired a repeat of the original ET structural test program. However, neither the test fixture used for the LH2 tank test nor the funding was available for this level of testing. A test requirements panel consisting of the Lockheed Martin Chief Engineer, retired Martin Corporate Chief Engineer, MSFC ET Chief Engineer with MSFC Lab support, and Bob Ryan of MSFC arrived at an approach that was called the Aluminum–Lithium Test Article (ALTA). Since the failure mode of concern in the orthogrid was compression buckling, the ALTA was structured to verify this mode. It consisted of a single ET barrel with a forward LH2 dome and an aft LO2 dome. Because there were four orthogrid patterns on the SLWT, each was repeated over a 90°arc.

A second failure mode was also tested on the test article. The ET LO2 tank aft dome has a stability failure mode when the LO2 is only in the center of the dome near the end of flight. LO2 at 3 g tends to punch out the center of the dome while pulling inward on the upper part of the dome. This condition was tested on the standard weight ET using barium sulfate solution (driller's mud) during the ET structural test program. However, the aft dome of the SLWT was extensively redesigned by removing the ribs and adding thickness. Therefore, the ALTA aft dome was tested with a dense solution (steel shot in a viscous medium) before the side wall testing took place. The test involved contracting with several cement mixers to keep the shot in suspension, pumping it into the dome, and immediately pumping to out when the test condition had been met.

On the sidewall test, the tank was pressurized to minimum flight limit pressures and the jacks loaded to induce design ultimate compression load in the tank wall. The pressure was then gradually decreased until the tank failed. It failed explosively at over 200% of design limit internal net load, well over the requirement of 140%. This certified the orthogrid concept for compression stability.

Although ALTA was able to test and verify the three LH2 tank upper barrel configurations, the aft barrel, with its welded-in longerons, could not be adequately tested for in-flight stability. After much evaluation, the test requirements team recommended that, rather than trying to take one barrel to 140% of design load, as was usually done, every SLWT should be tested as part of its proof test to 115% in this area. The first test was heavily instrumented to verify the structural model and load paths, and all subsequent SLWTs have repeated this test, although without instrumentation. It may be remembered that for orbiter 099, the structural test vehicle was only tested to 120% and then converted to a flight vehicle, *Challenger*.

The verification committee, headed by Bob Ryan and Bob Mora, also established that, when a change could not be tested and was a change from the previous flight configuration, it had to be verified by two independent analytical models with a Factor of Safety greater than 2.0. For the LO2 tanks ogive stability, Lockheed Martin used an analytical tool called equivalent cylinders. To obtain a second validation, Dr. Mike Nemeth of Langley Research Center was asked to build a Structural Analysis of General Shells (STAGS) nonlinear stability model of the ogive. As noted earlier, the ogive of the mated ground vibration test (MGVT) buckled while filling with water, a precursor to the MGVT testing. The data from this failure was fed into the Langley model which predicted the failure precisely without Dr. Nemeth knowing about the MGVT failure. This, of course, added credence to the model which was used to support the redesign. The same approach of independent models was also used on the SLWT intertank where Lockheed Martin used the model developed for the original ET, while MSFC Structures and Dynamics Lab developed a totally independent model.

Another area of long-standing concern for the ET has been the joint where the cold cryogenic LH2 tanks joined the warm intertank. This was verified by test on the original Structural Test Program for the standard weight ET. The joint concept was not changed on either the lightweight ET or the super lightweight ET, so the analysis tools developed for the standard weight ET remained valid for the later variants.

Lockheed Martin recognized, when starting the SLWT, that the conventional serial design process would not support the SLWT schedule. They chose to go to the Product Development Team approach. This involved breaking the design effort into a family of design packages such as intertank, domes, hydrogen barrels, etc. Teams consisting of design engineering, stress engineering, materials engineering, process engineering, manufacturing engineering, manufacturing planning, quality engineering, and material procurement personnel were convened for each design package. The product of these teams was complete packages of drawings, process specifications and procedures, manufacturing planning packages, and purchasing requirements. NASA Chief Engineer's representatives were assigned to each team to ensure real-time coordination of issues or concerns. The performance of these teams varied with the personnel working in the team but, on the whole, they were valuable in meeting the very tight SLWT schedule.

The approach of having a high–level independent team review and develop the verification program ground rules and content proved very valuable both from a content standpoint and in selling the adequacy of the program to outside reviewers. One such reviewer was an Aerospace Safety Advisory Panel consultant who expressed extreme concern in the fracture-based design of the propellant tanks. Neil Otte, then S&E, and Don Bolstad from Lockheed Martin spent many hours proving the soundness of the ET approach. This effort forced ET personnel to relook at their assumptions and analytical practices to prove the project was going in the right direction. Their major finding was "Don't relax on the extra care required for 2195 Al."

In an attempt to insure material availability and to bring the cost down, Lockheed Martin had Alcoa qualify as a second source for Al-Li 2195. Although Reynolds considered their process proprietary and would not release details to Alcoa, Alcoa was able to replicate the material independently and was qualified as a second source for the thin plate from which the dome and ogive gores and LO2 tank barrel panels were made. However, Alcoa was not qualified for the thick plate for which the LH2 barrel panels were machined. Reduced build rate made it impractical to contract with the second 2195 supplier.

Thus, the super lightweight external tank ended up with aluminum-lithium ogive gores, LO2 panels (4), LH2 barrel panel (32), LO2 tank aft dome gores (12), LH2 tank forward dome gores (12), and LH2 aft dome gores (11). The LH2 aft dome gore into which the big machined forgings for the LH2 feed line and the LH2 recirculation line were welded was left as 2219 aluminum to eliminate the need to develop the weld processes in aluminum-lithium.

Many of the thin-gage mechanically fastened materials in the intertank, skins, stringers, doubler, etc., were changed to Alcoa's aluminum-lithium 2090. This went well with no significant problems.

In summary, despite a large number of problems in materials and manufacturing process, the Lockheed Martin and NASA team delivered the first SLWT on a schedule which supported the first International Space Station schedule, within budget, and meeting the performance goals.

Although the first SLWT, ET-96, met the program objectives, its producibility deficiencies would have made continued manufacturing of this tank risky from a schedule standpoint and overly costly. Therefore, Lockheed Martin and NASA established a program for a second generation super lightweight external tank to resolve these issues. The first step was to find other weight saving candidates so weight could be put back into the hard-to-build areas. Lockheed Martin, in their manufacture of the F-16 fighter at Fort Worth, had adopted another aluminum-lithium alloy, 2297, for the major bulkhead of the aircraft. This part was machined flat from thick plate in its final temper and was not welded. While this application was foreign to most ET applications, the thrust panels in the intertank come close. These thrust panels are machined flat in a T3 (softer) temper, bump formed to the circular radius, and aged to final configuration. Lockheed Martin and the MSFC Materials Lab started a development program to investigate whether the use of this lighter, stronger alloy (2297) was possible in this application. Because Lockheed Martin was on their fifth supplier of these difficult to form parts, there was some apprehension in the NASA Project Office. However, they were able to prove that it could be done with a significant weight saving.

Changing the thrust panels opened the door to several producibility changes whose weight increases were offset by the thrust panel. The entire dome gores and ogive gores could be converted back to Al 2219, which Lockheed Martin was comfortable welding. Because of advanced modeling and analysis techniques since the LWT was designed in 1978, these parts are somewhat lighter than the LWT, but heavier than the SLWT. With the new thrust panels and the further optimization of the dome gores, ogive gores, and orthogrid LH2 barrel panels, the tank still met its weight goals. Welding of these second generation domes and ogives drastically reduced the repairs.

A second producibility enhancement was the introduction of a new welding process developed by the Welding Institute. Several United States aerospace manufacturers had been working with the MSFC Productivity Enhancement Center to develop this process called friction stir welding. Friction welding has been used for some time, particularly in oil well drill pipes and in the assembly of the injectors on the SSME. Friction stir welding, while similar, uses a rotating spindle that heats the material to be joined 38 well short of melting, as opposed to arc welding, and joins material in a semi-molten state. It is often called solid state welding.

Another technology implemented into the ET manufacture was the use of digital X-ray. Martin and MSFC started working on this in the late 1970s, but a large mainframe computer was needed to process the results. Since that time sensor technology and computer capability have now made this viable with a considerable savings in manpower for X-raying weld repairs and elimination of environmentally undesirable materials in the processing of film. Since ET has 0.6 miles of welds, just the X-ray film and filing systems are a significant cost. At this time Lockheed Martin has completed the certification of digital X-ray on one tool and progressing towards a second. Plans are in place to completely convert all X-ray positions to digital. This is particularly useful in repairs because the repair technician can see his grind out and repair process as he goes along rather than taking a picture, waiting until it is processed, then grinding some more, taking another picture, and so forth. Also, since the pictures are digital, they can be computer enhanced, enlarged, or focused to provide better visibility.

Many lessons were learned from the SLWT effort:

1. Thoroughly research and develop changes before they are committed to the program. NASA jumped into aluminum-lithium before it was well understood.
2. Only researching changes in the laboratory is insufficient. They must be tried in the production environment before committing them to the program.
3. For long–duration programs expect and prepare for vendor changes.

4. Document and obtain the title to qualification test procedures and unique equipment. The next vendor will need them.
5. If at all possible, follow Deming's guidelines to select suppliers based on capability rather than cost. Work with your supplier to get their quality up and cost down. Recompeting for price only is inviting disaster.
6. Particularly in the area of non-metallics, qualify back-up suppliers with independent sources of materials because, over time, some of your initial suppliers and key material sources will be lost.
7. Design, as much as possible, so that no entry is required at the launch site, but put access panels where they may be needed and where accessible from existing work stands. The two rollbacks instituted by ET at Kennedy Space Center were caused by woodpeckers and hail damage to the ogive which is inaccessible from the launch stand.
8. Finally, no NASA Project Manager can be successful if he does not have an outstanding contractor.

References

[1] Rao, K.T.V., Ritchie, R.O.; 1992; "Fatigue of Aluminum-Lithium Alloys." International Materials Reviews, 37, Pp. 153-186.
[2] Rioja, Roberto J., Liu, John, 2012; "The evolution of Al-Li base products for aerospace and space applications", Metallurgical and Materials Transactions A, Published online: 31 March 2012.
[3] Pickens, J.R., Heubaum, F.H., Langan, T.J. and Kramer, L.S.; 1989a, "Al-(4.5-6.3) Cu-1.3 Li-0.4 Ag-0.4 Mg-0.14 Zr alloy weldalite 049", In Aluminium-lithium alloys Eds. Sanders, T.H., Starke, E.A., 3, Pp.1397-1411.
[4] Polmear, I.J.; 1986, "Develop of an experimental wrought aluminum alloy for use at elevated temperatures," Eds. Starke, E.A.Jr., Sanders, T.H.Jr., Aluminum Alloys, Their Physical and Mechanical Properties, EMAS, West Midlands, UK, Pp.661-674.
[5] Rioja, R.J., Cho, A., Pretz, P.E., 1990; "Al-Li alloys having improved corrosion resistance containing Mg and Zn", U.S. Patent 4,961,792.
[6] Kobayashi, K., Ohsaki, S., Kamio, A., Tsuji, Y.; 1991, "Effect of Zn addition on corrosion resistance of 2090 and 2091 alloys," In Aluminum-Lithium, 2, Eds. Peters, M. Winkler, P.-J., Informationsgesellschaft, Verlag, Pp.673-678.
[7] Jata, K.V., Hopkins, A.K. and Rioja, R.J.; 1996, "The anisotropy and texture of Al-Li alloys", Material Science Forum, 217-222, Pp. 647-652
[8] Lynch, S.P., Muddle, B.C., Psang, T.; 2001; "Ductile-to-Brittle Fracture Transitions in 8090 Al-Li Alloys." Acta Materialia, 49(15), Pp. 2863-2874.
[9] Kalu, P.N., Wagner, J.A.; "A Microtexture Investigation of the Fracture Behavior of Al-Li Alloy, 2090-T81", Proceedings in TMS Annual Meeting. Las Vegas, NV (1995).

[10] Beaudoin, A., Obstalecki, M., Tayon, W., Hernquist, M., Mudrock, R., Kenesei, P., and Lienert, U.; "In situ assessment of lattice strain in an Al-Li alloy", Acta Materialia. 61(9), 2013. pp. 3456–3464.

[11] Birt, M. J.; Hafley, R. A.; Wagner, J. A.; Lisagor, W. B.; "The fracture resistance of 1420 and 1421 Al-Mg-Li alloys", Scripta Metallurgica et Materialia (ISSN 0956-716X); 28; 8; p. 919-923, Apr 15, 1993.

[12] Tayon, W. A.; Crooks, R. E.; Domack, M. S.; Wagner, J. A.; Beaudoin, A. J.; McDonald, R. J.; "Mechanistic Study of Delamination Fracture in Al-Li Alloy C458 (2099)", Conference Paper LF99-7508 presented at 12th International Conference on Fracture (ICF) 2009; 12-17 Jul. 2009; Ottawa; Canada, Jul 12, 2009.

[13] Tayon, Wesley A.; Crooks, Roy E.; Domack, Marcia S.; Wagner, John A.; Elmustafa, A. A.; "EBSD and Nanoindentation-Correlated Study of Delamination Fracture in Al-Li Alloy 2090", Journal of Experimental Mechanics, 50(1), 2010.

[14] Hales, S.J., Hafley, R.A.; "Texture and anisotropy in Al-Li alloy 2195 plate and near-netshape extrusions", Materials Science and Engineering: A 257 (1998) pp. 153-164.

[15] Crooks, R., Wang, Z., Levit, V., and Shenoy, R.; "Microtexture, microstructure and plastic anisotropy of AA2195", Materials Science and Engineering. A257, 1998. pp. 145-152.

[16] Tayon, W.; "Exploration of Incompatibility in Al-Li Alloys using High-Energy Diffraction Microscopy and a Crystal Plasticity Model", MS Thesis, University of Illinois at Urbana-Champaign, 2012.

[17] Beaudoin, A. J., Obstalecki, M., Storer, R., Tayon, W., Mach, J., Kenesei, P., and Lienert, U.; "Validation of a Crystal Plasticity Model Using High Energy Diffraction Microscopy", Modelling and simulation in materials science and engineering. 20(2), 2012.

[18] Beaudoin, A., Obstalecki, M., Tayon, W., Hernquist, M., Mudrock, R., Kenesei, P., and Lienert, U.; "In situ assessment of lattice strain in an Al–Li alloy", Acta Materialia. 61(9), 2013. pp. 3456-3464.

[19] McDonald, R., and Beaudoin, A.; "Utilizing the mesoscale grain boundary stress to estimate the onset of delamination in 2099-T861 aluminium-lithium", Modelling and simulation in materials science and engineering. 18(6), 2010.

[20] McDonald, R.; "Characterization of Delamination in 2099-T861 Aluminum-Lithium", PhD Thesis, University of Illinois at Urbana-Champaign, 2009.

[21] Lessons Learned From Space Shuttle External Tank Development - A Technical History of the External Tank -October 30, 2002 Prepared for: Second Generation RLV Program Office and Joan G. Funk Cryotank Element Manager Marshall Space Flight Center Under NASA/MSFC Contract NAS8-00021 Prepared by: Myron A. Pessin Reviewed and Edited by: Glenn E.Webb, Program Manager, Madison Research Corporation. http://www.nasa.gov/pdf/2241main_shuttle_et_lesson_021030.pdf

5.3. Russian Cooperative Programs

The low density and good mechanical properties of AI-Li alloys make them attractive for many structural applications, especially in the aerospace industry.[1] Research and development efforts in Russia and the United States have focused on advanced Al-Li alloys for aerospace applications where reduced structural weight is a critical goal.[2,3] The All-Russia Institute of Aviation Materials (VIAM) has developed a new Al-Li alloy series with attractive characteristics.

These characteristics include moderate to high strength, good weldability, good elevated temperature and cryogenic mechanical properties, high corrosion resistance, and superplastic formability. This new alloy series includes Al-Cu-Li alloys (1450, 1460), Al-Mg-Li alloys (1420, 1424), and Al-Cu-Mg-Li alloys (1440, 1441). Various extruded and forged semi products, plates, and hot-rolled sheets of these alloys are produced on an industrial basis.

Alloy 1441 has the potential to substitute for D16 Al or 1163 Al on aircraft fuselage structures. (D16 Al and 1163 Al are Russian analogs of 2024 Al and 2524 Al, respectively.) Compared to these Al-Cu-Mg alloys, 1441 Al-Li alloy has similar strength but exhibits 7% lower density and 12% higher modulus, as well as other improved properties. In addition, VIAM and Kamensk-Uralsky Metallurgical Plant have optimized the cold rolling process to produce coils of 1441 alloy sheet as thin as 0.5 mm.

In 1994, NASA Langley Research Center started cooperative research activities with VIAM and the All-Russia Institute of Light Alloys (VILS) in Moscow, Russia, to evaluate 1441 Al-Li alloy for fuselage skin applications. The work included cold rolling and heat treatment process development, characterization of microstructure and mechanical properties of cold-rolled sheet, and evaluation of durability of fuselage panels fabricated with 1441 Al-Li skin. The mechanical properties of cold rolled sheet and the durability of the fuselage panels are reported in a paper by Bird, Dicus, Fridlyander, and Sandler.[4]

Results on the work conducted at LaRC to evaluate the fatigue behavior of 1441 Al-Li sheet and the pressurization fatigue life of fuselage panels using 1441 AI-Li skin was reported in a paper by Bird and Dicus.[5]

Four fuselage panels fabricated by Tupolev Design Bureau under contract to VIAM using 1441 AI-Li were subjected to cyclic pressurization and depressurization to simulate flight conditions. Two panels were tested at LaRC and two were tested at Tupolev. In addition, the SN fatigue behavior of 1441 Al-Li sheet was evaluated. Results from the tests conducted at LaRC and at VIAM and Tupolev are reported in the paper by Bird and Dicus.[5]

A brief description of the panel tests follows. **Figure 5.3-1** shows a photograph of one of the fuselage panels.

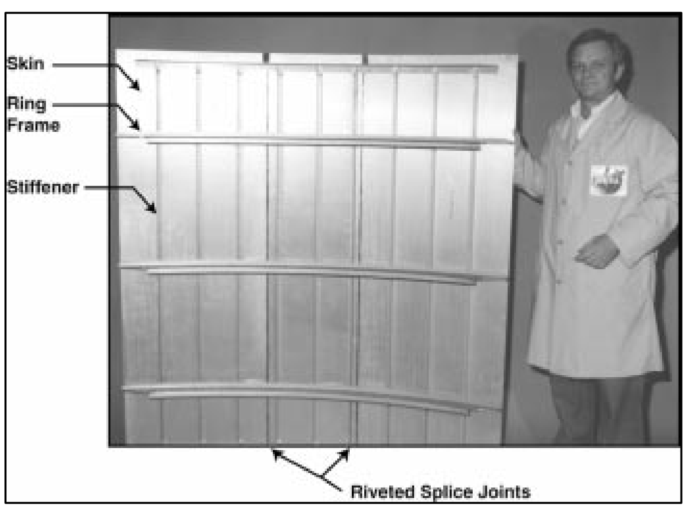


Figure 5.3-1: Fuselage Panel with 1441 Al-Li skin.

The panels were singly-curved and were fabricated by Tupolev Design Bureau (TDB) using the Tupolev-204 fuselage design, having dimensions of approximately 1.5 m in length and 1.5 m in width, with a radius of curvature of 1.9 m. Each panel contained two riveted longitudinal single skin overlap joints with different rivet spacing. Nine longitudinal blade stiffeners fabricated from V95pchT2 Al (analog to 7475 Al) alloy were riveted to each panel. In addition, three ring frames fabricated from 1441 Al-Li alloy were riveted to the panel circumference. Two panels were tested in Russia at TDB and two were tested at LaRC. In both cases, the panels were mounted in back-to-back fashion in a pressurization fixture and tested simultaneously to a peak pressure of 65 kPa at a rate of approximately 3 cycles per minute. This peak pressure corresponded to a maximum hoop stress of 70 Mpa. The test fixture used at Tupolev employed hinges for panel attachment on the straight edges and flexible seals that allowed the curved edges of the panel to deflect, whereas the panels tested at LaRC were constrained along all four edges. The pressurization tests were interrupted periodically to visually examine the riveted joints in each panel for fatigue cracking. The results of the panel pressurization fatigue tests[5] are shown in **Figure 5.3-2**. Results provided by VIAM from a Tu-204 fuselage panel constructed using conventional 1163 Al skin and tested at TDB are shown for comparison. The conventional panel failed after 163,000 pressurization cycles. Both 1441 Al-Li panels tested at TDB accumulated 250,000 cycles without failure and without initiation of fatigue cracks. However, one of the panels tested at LaRC failed catastrophically along one of the riveted splice joints after 193,000 pressurization cycles. Fractographic analysis revealed that fatigue cracks initiated and propagated in the 1441 Al-Li skin on the interior side of the overlap joint along a rivet line. Thus, these cracks were not observed until fracture occurred. The other panel tested at LaRC remained intact, but examination revealed the existence of small fatigue cracks, less than one inch in length, in the riveted joints. The difference in pressurization fatigue life of the 1441 Al-Li panels tested at LaRC and Tupolev was attributed to the different stress states developed as a result of the different panel constraints. In all cases, however, the panels with 1441 Al-Li skin had a longer pressurization fatigue life than did panels with conventional 1163 Al alloy skin.

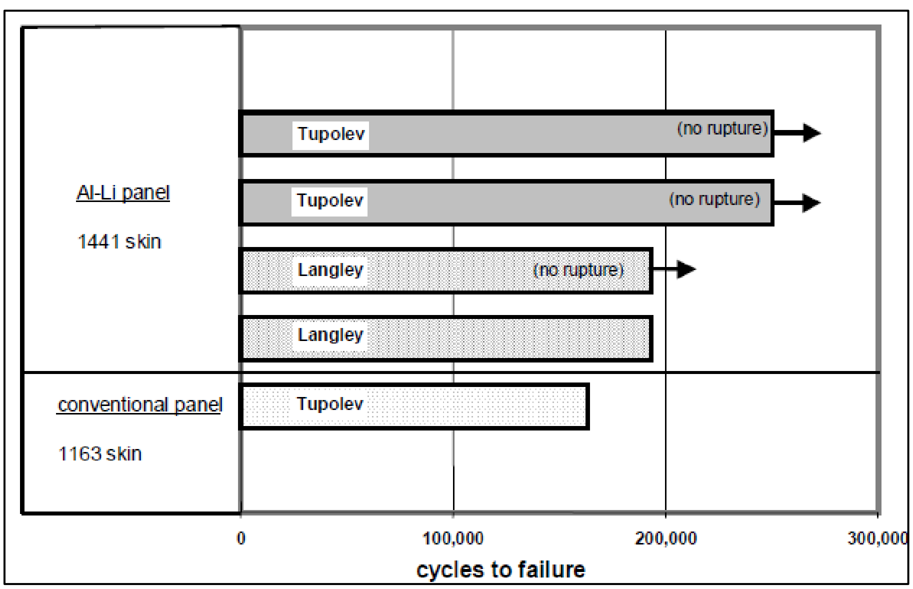


Figure 5.3-2: Tu-204 Fuselage Panel Pressurization Fatigue Behavior.

Another research activity in which the Russians cooperated was the characterization of Al-Cu-Li alloys 2090 near–net–shape extrusions.[6] Low density aluminum-lithium alloys offer significant cost-saving advantages over conventional aluminum alloys where weight is a premium. However, the material cost of Al-Li alloys is approximately three to five times higher than 2219 Al alloy, near–net–shape manufacturing processes (including extrusion, spin forming, and roll forging), in which material scrap is reduced to ~15 percent, is an attractive area of research for launch vehicle structures.

The Langley team engaged partners for this study. A collaborative team effort was established between several laboratories to examine and evaluate the properties of Al-Cu-Li alloy 2090 in the form of a near–net–shape extrusion. The team included Langley Research Center, Marshall Space Flight Center, the National Institute of Standards and Technology (NIST), Philips Laboratory, Air Force Systems Command, and private industry (Alcoa and Boeing Aerospace) laboratories in the United States, together with VIAM, and VILS in the Commonwealth of Independent States. The 2090 extruded panel investigated is shown in **Figure 5.3-3.** The panel was sectioned to provide specimens for characterization and testing. The test matrix is shown in **Table 5.3-1**. This table is included to show the extent of the cooperative testing between the partners on the Langley Near-Net Shape Team. The detailed results from this study are reported in the literature.[6]

Figure 5.3-3: Extruded 2090 Panel in As-Received Condition.

Table 5.3-1: Test Matrix to Characterize 2090 Near-Net-Shape Extruded Panels.

Tests	Laboratories					
	LaRC	MSFC	NIST	Alcoa	Boeing Aerospace	VIAM, VILS
Panel	2, 4, 6, 11	2, 3, 11	3, 6	1, 6, 10	4, 7	5, 12
Wet chemistry	(a)			(a)		(a)
Hydrogen concentration				(a)		(a)
Optical metallography	(a)	(b)		(a)		(a)
TEM						(a)
Texture	(b)			(a)		
Tensile (ASTM E8)						
RT	(a)	(a)		(a)	(a)	(a)
LN_2		(a)			(a)	(a)
LH_2 or LHe		(a)				(a)
Fatigue						(a), (e)
Fracture toughness						
RT	(b), (c)		(a), (d)		(a), (d)	(a), (f), (g)
LN_2	(b), (c)		(a), (d)		(a), (d)	(a), (f)
LH_2 or LHe	(b), (c)		(a), (d)			(a), (f)
Corrosion						
General corrosion		(b)		(a)		(a)
Stress corrosion	(a)	(b)				(a)
Weldability		(a)			(a)	(a)
Inspection						
Dimensions and internal flaws					(a)	

[a]Complete.
[b]In progress.
[c]K_R.
[d]K_{Ie}.
[e]LCF, dA/dN at 25°C and –253°C.
[f]K_{CU}.
[g]Impact.

References

[1] Altenpohl, Dietrich G.; “Aluminum: Technology, Applications, and Environment”, sixth edition. Aluminum Association, Inc., Washington, D.C. and the Minerals, Metals & Materials Society, Warrendale, Pennsylvania, 1998, pp. 340-342.

[2] Graham, R.H.: Rioja, R.J.: and Newman, J.M.; “AI-Li Alloy Development”. Aluminum-Lithium, Volume I, M. Peters and P.-J. Winkler, eds. Proceedings of the Sixth International Aluminum-Lithium Conference in Garmisch-Partenkirchen, FRG, 1991, pp. 15-24.

[3]Fridlyander, J.N; Bratukhin, A.G.; and Davydov, V.G.; “Soviet Al-Li Alloys of Aerospace Application”. Aluminum-Lithium,Volume I, M. Peters and P.-J. Winkler, eds. Proceedings of the Sixth International Aluminum-Lithium Conference in Garmisch-Partenkirchen, FRG, 1991, pp. 35-42.

[4] Bird, R. K.; Dicus, D. L.; Fridlyander, J. N.; Sandler, V. S; “Al-Li Alloy 1441 for Fuselage Applications”, Aug. 31, 2004. http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20040086797_2004090781.pdf.

[5] Bird, R. Keith and Dicus, Dennis L.; “Evaluation of Pressurization Fatigue Life of 1441 Al-Li Fuselage Panel”, NASA/TM-1999-209684.

[6] Birt, M.J., Domack, M.S., Hafley, R.A. , and Pollock, W.D.; “Characterization of Al-Cu-Li Alloy 2090 Near Net Shape Extrusion”, NASA/TM-1998-207668, May 1998.

5.4. High-Temperature Al Alloy Development for Supersonic Aircraft

5.4.1. Drivers for the Development of High Temperature Aluminum Alloys

As early as the 1950s, when supersonic fighters were being developed, there was interest in developing a supersonic commercial airliner. In the 1960s, major aerospace companies in the United States, Europe, and the Soviet Union initiated plans to construct a supersonic transport (SST). The joint Anglo-French program to develop the *Concorde* caused great concern in the U.S. aerospace industry and prompted Congress to begin funding a SST design effort at Lockheed and Boeing. However, environmental concerns associated with sonic boom and engine exhaust damage to the ozone layer led to cancelation of the program in the U.S. The Anglo-French program moved forward, resulting in the Concord, a Mach 2 aircraft, and the Soviet Union produced the Tu-144, both of which used an aluminum alloy, e.g., 2618, for the airframe. Since aluminum alloys cannot be used at temperatures exceeding 220°F this places a limit on the speed of an aluminum airframe to Mach 2. The last passenger flight for the Tu-144 was in June 1978, and NASA last flew it in 1999. Concorde's last commercial flight was in October 2003. Safety and economic issues were associated with the decision to discontinue operation of these aircraft.[1]

The concerns over the sonic boom and the effect of the exhaust of a SST on the ozone layer were reduced somewhat by the results of two studies. In 1995, David Fahey of the National Oceanic and Atmospheric Administration found that the drop in ozone would be from 1% to 2% if a fleet of 500 SSTs were operated and this would not be a showstopper for advanced SST development.[2] NASA researchers were convinced that the sonic boom could be avoided by waiting until the aircraft was at high altitude before reaching supersonic speeds.[3]

In the early 1990s, market projections indicated that there was a substantial potential demand for a high-speed civil transport (HSCT) to operate in the long-range international market. Preliminary design and technology development efforts were begun to better understand the technical and economic feasibility of the HSCT. These studies showed that an airplane designed to fly between Mach 2.0 and 2.4, with a capacity of 250 to 300 passengers and a range of at least 5000 nautical miles had the best opportunity of meeting the economic objectives. Materials and processes used by the aerospace industry in the 1990s could not satisfy the cost and performance requirements for a Mach 2.0–2.4 aircraft and, therefore, would require significant technology development. Consequently, one of the key development issues for an economically viable HSCT airframe revolved around the development of materials and processes which would allow a complex, highly-stressed, extremely weight-efficient airframe to be fabricated and assembled for a dollar-per-pound not greatly different from a mature airframe of aircraft during that time period.[4]

With the support of the major aircraft manufacturers, Boeing and Douglas, and aluminum producers, Alcoa and Reynolds, NASA initiated a program in 1992 for the development of high-temperature aluminum alloys under the NASA-University of Virginia Light Aerospace Alloy and Structural Technology Program. The two primary objectives of the program were (1) to identify the most promising aluminum-based materials with respect to major structural use on the HSCT and to further develop the materials to ensure that they met the design requirements, and (2) to assess the material through detailed trade and evaluation studies with respect to their structural efficiency on the HSCT.[4]

5.4.2. NASA-UVA Light Aerospace Alloy and Structure Technology Program: Aluminum-Based Materials for High-Speed Aircraft (HSR)

The research team consisted of Alcoa, Allied-Signal, Boeing, McDonnell Douglas, Reynolds Metals, and the University of Virginia. Four classes of aluminum alloys were investigated (1) I/M 2XXX containing Li (Reynolds) and I/M 2XXX without Li (Alcoa), (2) I/M 6XXX (Alcoa), (3) two P/M 2XXX (Alcoa and Allied-Signal), and (4) two different aluminum-base metal matrix composites (Alcoa and UVA). The I/M alloys were targeted for a Mach 2.0 aircraft, and the P/M and MMC alloys were targeted for a Mach 2.4 aircraft.[4]

Boeing and McDonald Douglas conducted design studies using several different concepts including skin/stiffener (baseline), honeycomb sandwich, integrally stiffened (including extruded stringers, orthogrid, and isogrid concepts) and hybrid adaptations (conventionally stiffened thin-sandwich skins). The design concepts were exercised with respect to the wing box (upper), wing box (lower) wing strake, and the crown, window belt, and keel areas of the fuselage. The results of these studies indicated that the preferred concept depended greatly upon the part of the aircraft being considered, but that many had advantages over the baseline skin-stringer design.

All team members were involved in the materials studies. The High-Speed Research (HSR) Program was interested in aluminum alloys primarily as a backup material in case the speed requirement was reduced from Mach 2.4 to about Mach 2.0. Researchers at NASA Langley were involved in evaluating the properties of all of the alloys to determine their feasibility for use in the HSCT.[5,6] Early in the program, it was determined that the strengths of I/M 6XXX alloys were too low for the target application, and research on that class of alloys was discontinued. Although the microstructures of the P/M alloys were very stable at the temperatures of interest for a Mach 2.4 aircraft, both ductility and fracture toughness decreased as the temperature increased from ambient temperature and research on the P/M materials was also discontinued. Research on the Alcoa MMC was also discontinued due to poor high-temperature properties, although some basic work on MMCs was continued at the University of Virginia to the end of the grant.

5.4.3. NASA In-house HSR Aluminum Alloy Development

Several different high-temperature Al alloys were studied by NASA under the HSR Program. These studies usually involved the effect of high-temperature exposure on microstructure stability,[7] fatigue and fracture performance,[8] and creep[9,10] performance of Al-Cu-Mg, Al-Cu-Mg-Ag, and Al-Cu-Li-Mg-Ag alloys. The fracture toughness versus yield strength of four of the new Al alloys studied by NASA are compared with Al alloy CM001 used on the Concorde and Al alloy 1143 used on the Russian SST. The data is for specimens before and after exposure for 10,000 and 30,000 hours at 225ºF. It should be noted that the improvements observed before exposure were retained after 30,000 hr at 225ºF. Other improvements observed are noted in **Figure 5.4-1**.

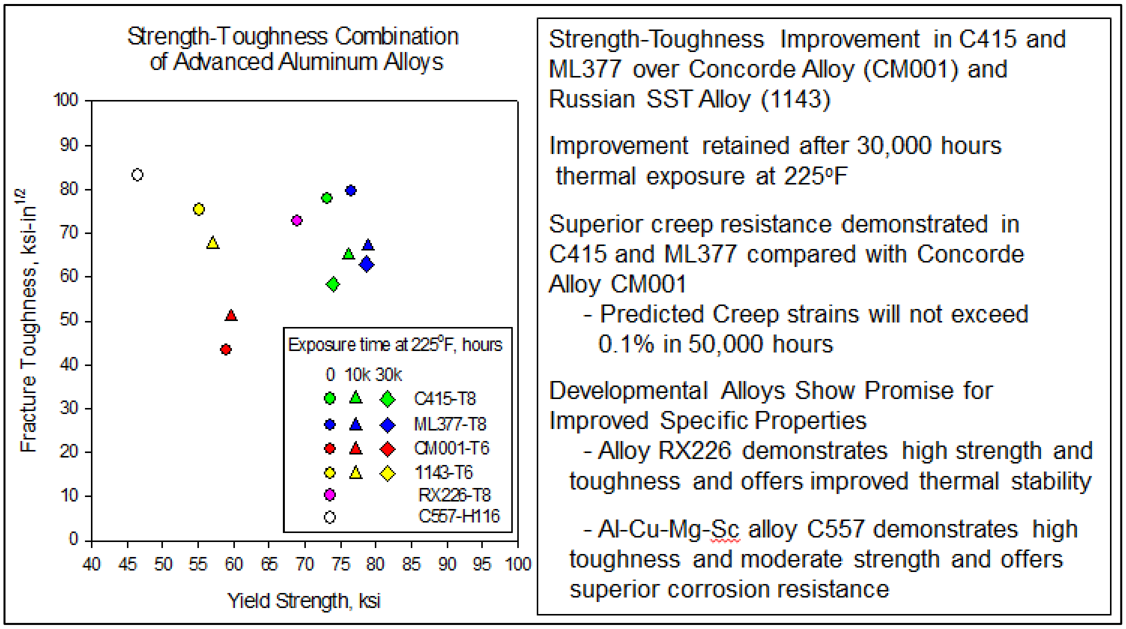


Figure 5.4-1: Elevated Temperature Al Alloys Demonstrate Property Improvements over Existing SST Alloys.

Two lithium-free 2XXX alloys (Alcoa) based on 2519 and identified as C415 and C416 were found to have attractive mechanical properties and thermal stability. The elevated temperature yield strengths of four of the high-temperature Al alloys studied by NASA under the HSR Program are shown in **Figure 5.4-2**. The chemical compositions of C415 and C416 are:

AlloyCuMgMnAgZrFeSi

C4155.00.80.60.50.130.060.04

C4165.40.50.30.50.130.060.04

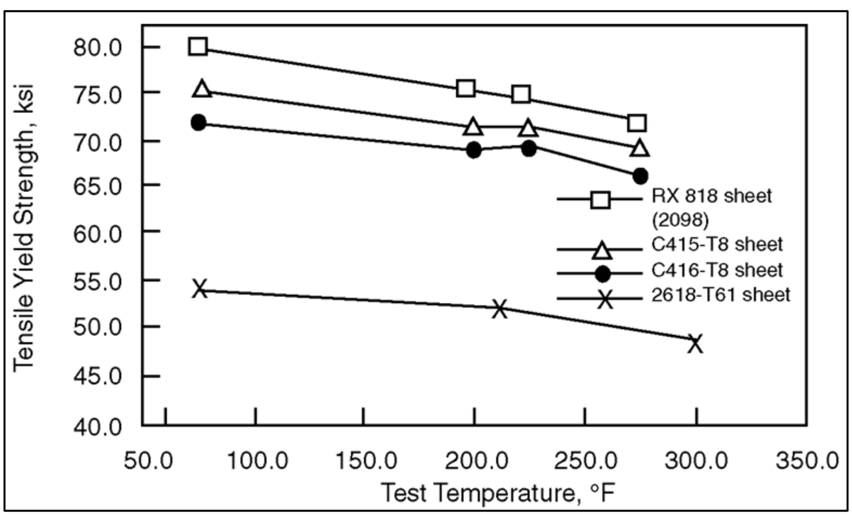


Figure 5.4-2: Elevated Temperature Yield Strength of New HSR Aluminum Alloys.

Alloy C415 exhibited higher room temperature and elevated temperature strength than alloy C416, while alloy C416 appeared to be more thermally stable and more creep resistant than alloy C415. Although the HSR Program discontinued funding for the development of aluminum technology in December 1996,[4] the alloys developed on the program had attractive properties[11] and research and development work continued in-house at NASA Langley[12] and at the aluminum companies. The research on C415 and C416 resulted in the development of 2040 (C415), which is currently used for forged aircraft wheels[13] where elevated temperature properties are important (**Figure 5.4-3**). Aluminum aircraft wheels are subjected to demanding operating conditions during service such as heat, carbon dust, runway and aircraft fluids, and high-energy braking events. Alloy 2040 possesses an enhanced combination of desired materials properties and produces wheel designs lighter in weight than those of other aluminum wheel alloys,[13] e.g., 2014 and 7050 (**Figure 5.4-4**).

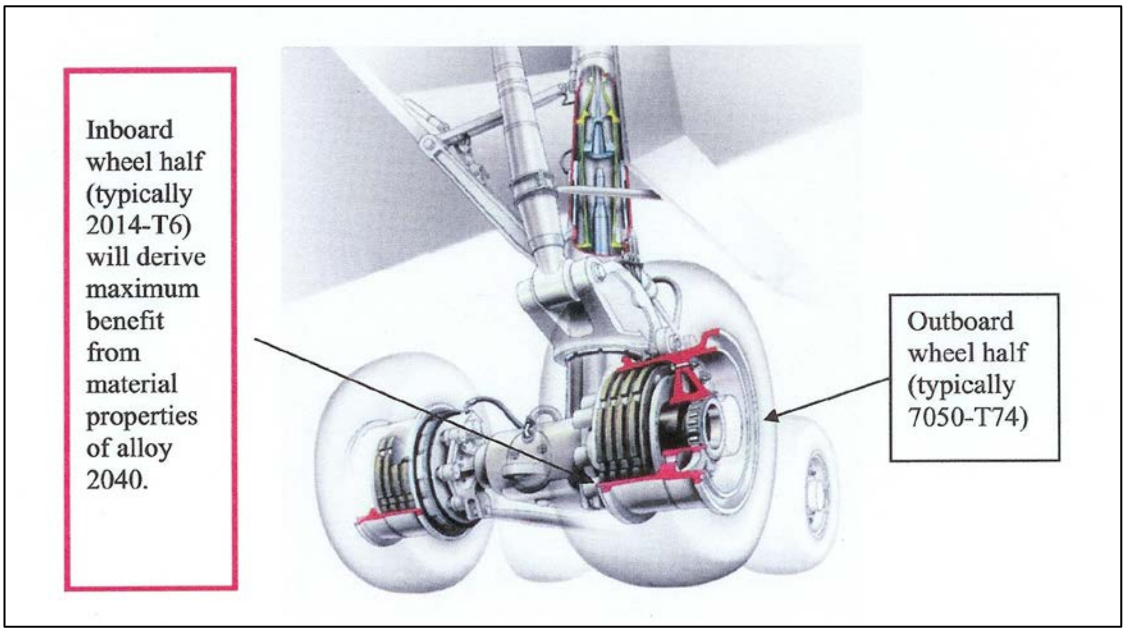


Figure 5.4-3: Alloy 2040 is targeted for use at the inboard wheel half, which is subjected to high thermal and mechanical loads.[13]

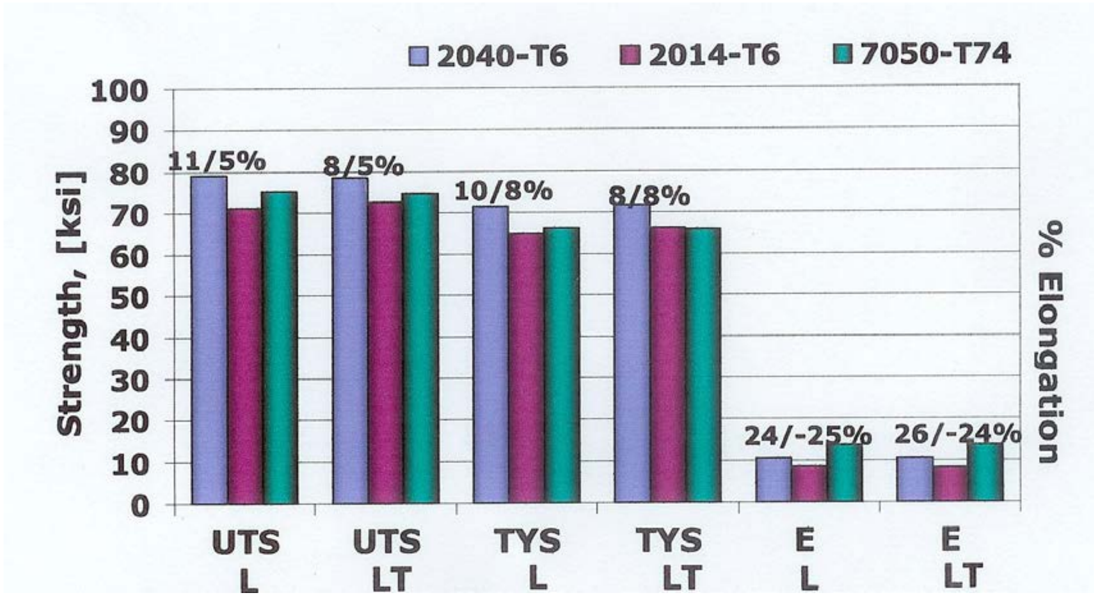


Figure 5.4-4: 2040-T6 exhibits superior nominal static tensile properties than those of other forged aluminum wheel alloys.9

Research and development at (Reynolds Metals) resulted in the development of two lithium-containing alloys designated RX818 and ML377. Their compositions in weight percent are shown in Table 5.4-1.

Table 5.4-1: Chemical Composition in Weight Percent.

Material	Cu	Li	Mg	Ag	Zr	Mn
RX818	3.7	1.0	0.5	0.3	0.14	0.0
ML377	3.5	1.0	0.4	0.4	0.12	0.3

RX818 had the higher strength, but both RX818 and ML377 exhibited good strength and elongation combinations. RX818 sheet was highly anisotropic, (20% lower strength) at 45° to the rolling direction. It was later determined that the anisotropy was very sensitive to thermomechanical processing.[14] Both alloys showed promising thermal stability based on relatively short-time data. RX818 was registered as 2098 in 2004 under McCook Metals. The alloy has been implemented on the F16 fighter plane (**Figure 5.4-5**), and SpaceX space launch systems. ML377 was also registered as 2050 in 2004 and has been extensively evaluated by researchers at NASA Langley.[15] The Al-Li alloy 2050 is being used for the lower wing structure in the A380 Aircraft.[16]

Figure 5.4-5: The Al-Li alloy 2098, developed under the NASA-sponsored High-Temperature Aluminum Alloy Program is used in the F16 Fighter Aircraft.

Even though the NASA high-temperature aluminum alloy development program was terminated in 1996, the research and development led to significant achievements, resulting in new aluminum alloys. Research conducted under the HSR Program led to development of 2040, 2098, and 2050, which are currently being used in a number of aerospace systems. NASA Langley followed this program with research and development on other promising high-temperature aluminum alloys,[17, 18] including dispersion-strengthened alloys[19] and alloys containing Sc16, which may be used in future aerospace systems.

References

1 Supersonic Aircraft, Wikipedia, http://en.wikipedia.org/wiki/Supersonic_aircraft

2 Lipkin, Richard; "SST Emissions Cut Stratospheric Ozone," Science News, October 7, 1995.

3 U.S. Supersonic Commercial Aircraft, Assessing NASA's High Speed Research Program, National Research Council, National Academy Press, Washington, D.C. 1997.

4 E.A. Starke, Jr.; NASA-UVa Light Aerospace Alloy and Structure Technology Program Supplement: Aluminum-Based Materials for High Speed Aircraft, Final Report, December, 1997.

5 Domack, Marcia S.; "Fracture Toughness Testing of Candidate Aluminum Alloys," HSR Metallic Materials Task Review, May 21, 1996.

6 Domack, M.S., Dicus, D.L., Edahl, R.A., Chellman, D.J.; "Effect of High Temperature Exposure on the Strength-Toughness Behavior of Elevated Temperature Service Aluminum Alloys," Aluminum Alloys – Their Physical and Mechanical Properties. Proceedings of the 6th International Conference on Aluminum Alloys, ICAA-6, Volume 2, p. 1081 (1998).

7 Kazanjian, S. M., Wang N., Starke, E. A.; "Creep Behavior and Microstructural Stability of Al-Cu-Mg-Ag and Al-Cu-Li-Mg-Ag Alloys," Materials Science and Engineering A234-236 (1997), pp. 571-574.

8 Reynolds, A. P. and Crooks, R. E.; "The Effect of Thermal Exposure on the Fracture Behavior of Aluminum Alloys Intended for Elevated Temperature Service," Elevated Temperature Effects on Fatigue and Fracture, ASTM STP 1297, R. S. Piascik, R. P. Gangloff, and A. Saxena, Eds., American Society for Testing and Materials, 1997, pp. 191-205

[9] Kazanjian, S. M., Wang N., Starke, E. A.; "Creep Behavior and Microstructural Stability of Al-Cu-Mg-Ag and Al-Cu-Li-Mg-Ag Alloys," Materials Science and Engineering A234-236 (1997), pp. 571-574
[10] Wang, N., Kazanjian, S. M., Starke, E. A.; "Microstructure and Creep Behavior of Al-Cu-Mg and Al-Cu-Mg-Ag Alloys," The Third Pacific Rim Conference on Advanced Materials and Processing, M. A. Imam, R. DeNale, S. Hanada, Z. Zhong, D. N. Lee, Eds., (1998), pp. 713-718
[11] A.P. Reynolds and Qiong Li; "The Effect of Elevated Temperature Exposure on Fracture Resistance and Fracture Path in a Precipitation Strengthened Aluminum Alloy," Scripta Materialia, Vol. 34, No. 11, 1996, pp. 1803-1806.
[12] R. A. Edahl and M. S. Domack; "Effect of Thermal Exposure on Tensile Properties of Aluminum Alloys for Elevated Temperature Service", NASA/TP-2004-212988.
[13] L. Steele, L. Mueller and R. Sawtell; "Aluminum Alloy 2040 for Demanding Aircraft Wheel Applications," Technical Paper furnished by Alcoa Technical Center.
[14] A. Cho, Z. Long, B. Lisagor, T. Bales, M. Domack and J. Wagner; "Effect of Thermomechanical Processing on Texture and Mechanical Properties of Al-Cu-Li Alloy Plate," Proceedings of the 10th International Conference on Aluminum Alloys, ICAA-10, 2006.
[15] Hafley, Domack, Hales, Shenoy; "Evaluation of Aluminum Alloy 2050-T84 Microstructure and Mechanical Properties at Ambient and Cryogenic Temperatures," NASA/TM-2011-217163, July 2011.
[16] Total Materia, www.keytometals.com/page.aspx?ID=Home&LN=FI.
[17] Cynthia L. Lach and Marcia S. Domack; "Mechanical Properties of RX226-T8 Plate as a Function of Orientation and Through Thickness Plate Location," Paper presented at AeroMat 2002, Orlando, FL, June 2002.
[18] Cynthia L. Lach and Marcia S. Domack; "Characterization of Al-Cu-Mg-Ag Alloy RX226-T8 Plate, NAASA/TM-2003-212639.
[19] A.P. Reynolds and J.S. Lyons; "Isotropic and Kinematic Hardening in a Dispersion Strengthened Aluminum Alloy", Metallurgical and Materials Transactions A, Vol. 28A, 1997, pp. 1205-1211.

5.5. Magnesium Alloys

5.5.1. Early Uses of Magnesium in Aerospace

Magnesium has long been used in aircraft construction. The development of the Italian and German aircraft industry in the 1930s involved the use of many magnesium parts. Mostly the products used were castings, but the lightweight of magnesium also attracted the use of extrusions and sheet and plate. The German aircraft industry used magnesium for engine bearers. This development was led by Prof. Hertel of Junkers. The famous JU87 Stuka dive bomber as well as the Junkers JU88 used forged magnesium pieces for attaching their engines to the airframes. The FW 190D and ME 109 and ME 110, famous WWII German aircraft, used two 18 kg forged bearers for attaching each engine.[1]

In 1942, a Dow Chemical ad stated, “Straight from the mind of the chemists and engineers has come the formula to win wings from the sea. Through the efforts of Dow the ocean is yielding its magnesium. For the first time in history man is successfully tapping this inexhaustible benefit of a metal whose phenomenal lightness gives swiftest wings to the airplane so essential to our victory drive. When victory is ours that extraordinary weight-savings metal hundreds of millions of pounds annually will be available for innumerable industrial and domestic purposes. Magnesium will lighten the tasks of man in countless ways as yet undreamed of, except in the minds of far-seeing engineers and who are already planning the future.” During World War II, magnesium was heavily used in aircraft components.[2]

In 1946, Convair produced the first B-36 Peacemaker Bomber (**Figure 5.5-1**) that was operated by the United States Air Force from 1949 to 1959. It incorporated 8620 kg (19,000 lbs) of magnesium: 5555 kg (12,200 lbs) of sheet, which covered 25% of the exterior, 700 kg (1500 lbs) of magnesium forgings, and 300 kg (660 lbs of magnesium castings (**Figure 5.5-2**). When General Curtis LeMay headed SAC (1949–57), he turned the B-36 arm, through intense training and development, into an effective nuclear delivery force, forming the heart of the Strategic Air Command. Its maximum payload was more than four times that of the B-29, and exceeded that of the B-52. The B-36 was slow and could not refuel in midair, but could fly missions to targets 3400 mi (5500 km) away and stay aloft as long as 40 hours. Moreover, the B-36 was believed to have “an ace up its sleeve”: a phenomenal cruising altitude for a piston-driven aircraft, made possible by its huge wing area and six 28-cylinder engines, putting it out of range of all piston fighters, early jet interceptors, and ground batteries.[3]

Figure 5.5-1: The Convair B-36 Peacemaker in Flight.

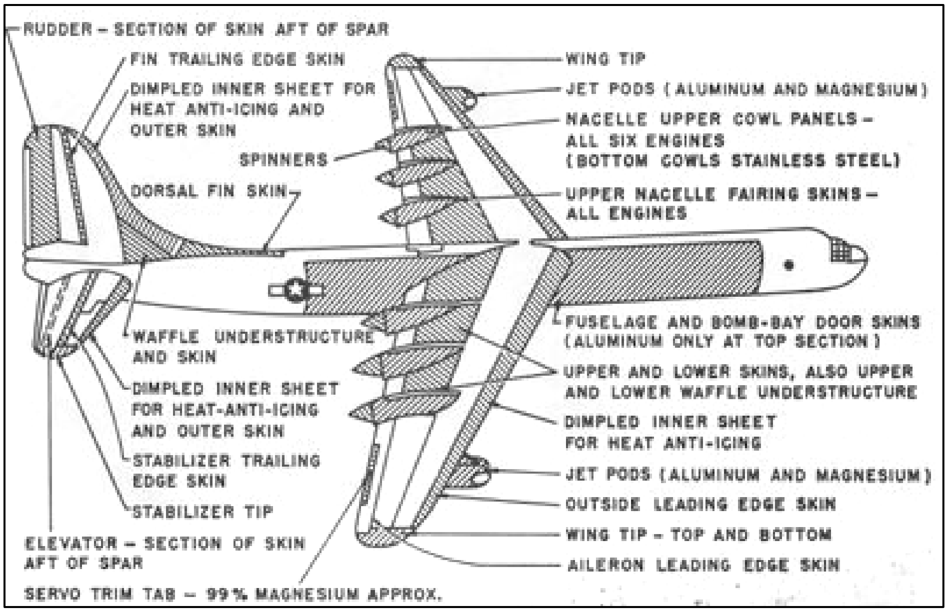


Figure 5.5-2: Distribution of Magnesium in the B-36 Peacemaker2

There are examples of other military aircraft and helicopters that were built along the time of the B-36 that included hundreds of kilograms of magnesium products. These include the experimental modification of the Lockheed F-80C that was of magnesium construction and the Soviet Union TU-95MS that used 1550 kg of magnesium. In 1949 Sikorsky developed the H-19 Chicasaw Helicopter (**Figure 5.5-3**). It holds the distinction of being the U.S. Army's first true transport helicopter and as such played an important role in the initial formulation of Army doctrine regarding air mobility and the battlefield employment of troop-carrying helicopters. The H-19 had the highest percentage (by weight) of magnesium castings and sheet of any helicopter then in service (17%).[1] The significant difference in the application of magnesium in the former Soviet Union and Western countries is the amount of magnesium components in civil aircraft. This is primarily due to the Soviet Union's utilization of military aircraft as prototypes for civil aircraft. The civil aircraft Tupolev TU-134 was manufactured in 1963, had 1325 magnesium parts with a total weight of 780 kg.[3] However, from the TU-134 to the TU-304 there was a significant decrease in the use of magnesium, from 780 kg to 44 kg.[4]

Currently, the Western aerospace industry, including Airbus, Boeing, and Embracer, does not use magnesium for structural applications in commercial aircraft. The situation is different for the helicopter industry where magnesium is used in cast gearboxes and transmissions and some other non-structural elements.

Figure 5.5-3: Sikorsky H-19 “Chicasaw” Helicopter.

5.5.2. Reasons the Aerospace Industry Reduced the Application of Magnesium

Although Magnesium is the lightest structural metal it acceptance and use in aerospace applications has been limited for the following reasons:

1. Flammability of magnesium
    a. Contrary to common opinion, flammability never was the main reason for magnesium restriction
    b. Magnesium meets all requirements of FAR/JAR standards for flammability resistance
    c. There is no case of aircraft/helicopter accident because of magnesium ignition
2. Corrosion resistance
    a. The real reason for magnesium restriction in the past
    b. Neutral salt spray test (ASTM-117) has much higher acceleration rate on magnesium than on aluminum
3. Lack of strength and formability of magnesium alloys

5.5.3. Magnesium and Its Alloys

Magnesium is the lightest structural metal with a density of 1.738 g/cm[4], considerably lower than aluminum, titanium and iron.[5] Due to its attractive specific properties, it has been, and will continue to be, considered for structural applications in a wide variety of aircraft and helicopters.

However, magnesium has a number of problems that are of concern to the design engineer and which have limited its use. Its corrosion resistance was initially a problem, but it was found that this was due to the normal presence of trace impurities of iron, nickel, and copper, and improving the purity of the base metal essentially eliminated this problem.[6] Magnesium's position on the electromotive chart leads to extensive corrosion when in contact with other metals, so often coatings are applied to isolate magnesium from other materials.

There are two major magnesium alloy systems. One contains 2%–10% aluminum with minor additions of zinc and manganese. These alloys may be used at temperatures up to 120°C. The second system contains elements such as rare earths, zinc, thorium, silver, silicon, and a small amount of zirconium to refine the grain structure.[7] This second class of alloys usually possess better elevated temperature properties but are more expensive because of the higher cost of the alloy additions.[7] Magnesium's very high reactivity with oxygen results in a low ignition temperature, which is a major safety issue, i.e., it may rapidly burn when exposed to fire by accident.[8] Although the ignition of magnesium was studied extensively during the 1930s–1960s, this problem received little additional attention until recently.[9] Due to interest in using magnesium for pistons, etc., there has also been major efforts to improve its creep resistance. Improvement of both of these properties, ignition temperature and creep, has been primarily associated with the addition of rare earth metals to the base alloy.[10]

5.5.4. Opportunities for Magnesium in Aerospace

Weight reduction has always been important in the aerospace industry. Aluminum is the traditional light metal for aerospace structures and there have been significant improvements over the past decades in aluminum alloys. These include reducing the density by the addition of lithium, improvements in corrosion and fatigue resistance, fracture toughness, and strength. However, weight reduction using aluminum alloys will become more difficult by small advances in properties of this alloy system. Alternatives include the use of laminates, low-density structural plastics, or fiber reinforced composites. However, the application of non-metallic materials is not always possible in some areas due to lack of low or elevated temperatures, electric conductivity issues, as well as cost. Magnesium offers a metallic solution to reduce weight. But before this can happen major improvements in a number of properties need to be made. There are a number of R&D projects at the present time in the European Union, the United States, Israel, France, and Austria directed at improving the properties of magnesium for use in the aerospace industry. In particular, the Israeli Company AMTS has been developing a complete range of solutions for applying wrought magnesium within the aerospace industry.

For commercial aircraft, these include cockpit instrument panel, service door inner panel, and rudder pedal. In addition, Israel is using magnesium in unmanned aerial vehicles, and of course helicopters. Boeing has also been active in examining magnesium for aerospace applications with a focus on interior applications, e.g., seat frames. Some of the objectives4 of current R&D programs are

1. development of new magnesium wrought products (sheets and extrusions), that provide significantly improved static and fatigue strength properties, as high as 5083 for non-structural applications and 2024 for secondary structural applications;
2. simulation and validation of forming and joining technologies for the innovative material and application;

3. development of environmentally friendly surface protection systems and advanced design concepts;
4. development of material models and failure criteria for the prediction of forming processes, plastic deformation and failure behavior of components.

Examples of some recent improvements in magnesium alloys are given below:

Improvements in Flammability: On April 18, 2013, Japanese scientist Yoshihito Kawamura, a professor at Kumamoto University, and his colleagues announced that they have developed two strong, nonflammable magnesium alloys that could be used in aircraft construction. One of the two magnesium alloys contains an undisclosed rare earth element as an ingredient. It remains strong even at high temperatures and can withstand temperatures of up to 875°C before igniting. The other alloy contains a non-rare earth element and has an ignition temperature of at least 1050°C. The U.S. Federal Aviation Administration bans the use of magnesium alloys in civil aircraft because they typically have low ignition temperatures of around 500°C. In 2001, Kawamura and coworkers developed a magnesium alloy that had ignition temperatures of at least 620°C. Subsequent advances in global research and development on magnesium alloys have led to calls for lifting the ban on their use in aircraft. The two new alloys were sent to the FAA, where they underwent combustion tests that confirmed their heat resistance.[1]

Improvements in Corrosion Resistance: As mentioned earlier, improvements in corrosion resistance were made after the discovery that the presence of iron, nickel, copper, and cobalt in magnesium alloys strongly reduces corrosion resistance. This is due to their low solid solubility limits and the fact that they have the right electrochemistry to behave as active cathodic sites that reduce water while causing the loss of magnesium from the alloy. Consequently, improvements in corrosion resistance can be achieved by keeping these elements low in magnesium alloys. However, maintaining very low and precise control of these elements in magnesium significantly increases the price of the alloy. Recently, a team of researchers at Monash University in Australia, led by Professor Nick Birbilis, has attempted to apply an additive known as a cathodic poison to a standard magnesium structural alloy. Cathodic poisons act by capturing atomic hydrogen within the structure of a metal thus preventing the formation of free hydrogen gas which is required to balance the corrosive chemical processes. A number of alloying elements, including arsenic, antimony, sulfur, selenium, and tellurium, are known to act in this manner in other alloy systems. The Monash team found that the addition of about one-third of a percent of arsenic to the magnesium alloy reduced its corrosion rate in a salt solution by a factor of nearly ten. The arsenic effect is now being trialed as a functional additive to existing commercial alloys.[11]

Improvements in Strength: The application of magnesium alloys has been hindered by their relatively low strengths, ~100–250 MPa for commercial casting Mg alloys, and limited ductility (elongation of 2%–8% at room temperature). Outside of traditional precipitation control, Mg-alloy strengthening typically is done by grain refinement or rapid solidification/powder metallurgy, which may be used to obtain yield strength of ~600 MPa in an Mg-Zn-Y alloy with uniform distribution of long-period ordered structures. A new approach relies on the introduction of a high density of stacking faults with nanoscale spacing for a high density of barriers to block and pin dislocations and retention of work hardening for enhanced ductility. This method has resulted in yield strengths of ~575 MPa and ultimate strengths of ~600 MPa with uniform elongation of ~5.2%.[12]

Improvements in Sheet Production: There have been a number of recent manufacturing methods to improve the properties of magnesium alloy sheets and the size of available sheet material. Examples are the production of high-strength and high-ductility sheets (350 MPa yield strength and 35% elongation) with fine grain size by dynamic recrystallization during rolling at temperatures above 473 K and subsequent annealing.[13] Liaoning Yingkou Yinhe Mag&Al Co., Ltd has successfully developed wide rolling strips by semi-continuous casting and billet production with a width from 1625 mm to 1750 mm. At present, they have produced hot rolled plates of 10–100 mm thick and 15001600 mm wide. Cold rolled sheet of 1.2°2 mm thick, 1500 mm wide, and 5000 mm long have been successfully developed.[14]

It is obvious that with all of the current research and development activities around the world on magnesium alloys will soon result in the opportunity for lightweighting many aerospace structures with this lightest structural metallic materia. NASA is well positioned with the facilities and expertise to make significant contributions to needed improvements to magnesium alloys, especially in the area of developing manufacturing technologies.

References

1 David C. Brown and Robert E. Brown; Eds., Magnesium Monthly Review, Volume 42, No. 3, 2013.

2 Suveen N. Mathaudhu; “DoD Perspectives on Mg Science and Technology: The Quest for Lightweight Structure and Armor Materials,” Paper presented at the NSF Magnesium Workshop, Arlington, Virginia, 19 May 2011.

3 Convair B-36, Article from Wikipedia, The Free Encyclopedia, April, 28, 2014.

4 I. Ostrovsky and Y. Henn; “Present State and Future of Magnesium Application in Aerospace Industry,” Paper presented at the International Conference New Challenges in Aeronautics, ASTEC’07, August 19-22, 207, Moscow.

5 I.J. Polmear; Light Metals: Metallurgy of the Light Metals, J. Wiley & Sons, 1995, p.3.

6 Hisao Watarai; “Trend of Research and Development for Magnesium Alloys – Reducing the Weight of Structural Materials in Motor Vehicles,” Science and Technology Trends, Quarterly Review No. 18, January 2006, pp. 84-97.

7 Robert E. Brown; “Magnesium in the 21st Century,” Advanced Materials & Processes, January 2009, pp. 31-33.

8 Zeng Xiaoqin, Wang Qudong, Lu Yizhen, Zhu Yanping, Ding Wenjiang, Zhao Yunhu; “Influence of Beryllium and Rare Earth Additions on Ignition-Proof Magnesium Alloys,” Journal of Materials Processing Technology, Vol. 112, 2001, pp. 17-23.

9 N.V. Ravi Kumar, J.J. Blandin, M. Suéry and E. Grosjean; “Effect of Alloying Elements on the Ignition Resistance of Magnesium Alloys”, Scripta Materialia, Vol. 49, 2003, pp. 225-230.

10 L.L. Rokhlin; “Magnesium Alloys Containing Rare Earth Metals, Structure and Properties”, Volume 3 of the series Advances in Metallic Alloys edited by J.N. Fridlyander and D.G. Eskin, Taylor & Francis, London, 2003.

11 David C. Brown and Robert E. Brown; Eds., Magnesium Monthly Review, Volume 42, No. 7, 2013.

12 W.W. Jian, G.M. Cheng, W.Z. Xu, H. Yuan, M.H. Tsau, Q.D. Wang, C.C. Koch, Y.T. Zhu and S.N. Mathaudhu; "Ultrastrong Mg Alloy via Nano-spaced Stacking Faults", Materials Research Letters, Vol. 1, No. 2, 2013, pp. 61-66.

13 Miao Qing, Hu Lianxi, Wang Guojun and Wang Erde; "Fabrication of Excellent Mechanical Properties AZ31 Magnesium Alloy Sheets by Conventional Rolling and Subsequent Annealing", Materials Science and Engineering A, Vol. 528, 2011, pp. 6694-6701.

14 David C. Brown and Robert E. Brown; Eds., Magnesium Monthly Review, Volume 42, No. 5, 2013.

5.6. Titanium Alloys and Titanium Aluminides

5.6.1. Titanium

Table 5.6-1 gives a quick overview of some of the properties of Titanium and titanium aluminides compared to superalloys.[1] The primary attributes that make titanium an attractive material include an excellent strength-to-weight ratio, providing weight savings attractive to the aerospace and petrochemical industries; corrosion resistance, particularly appealing to the aerospace, chemical, petrochemical and architectural industries; and biological compatibility, of interest to the medical industry. The chemical industry is the largest user of titanium due to its excellent corrosion resistance, particularly in the presence of oxidizing acids. The aerospace industry is the next largest user primarily due to its elevated (and cryogenic) temperature capabilities and weight savings due to its high strength and low density; with increased use of polymeric graphite fiber reinforced composites on aircraft, the low coefficient of thermal expansion is also an important factor. The ballistic properties of titanium are also excellent on a density-normalized basis.

Table 5.6-1: Properties of Titanium Aluminides, Titanium-Based Conventional Alloys and Superalloys

Property	Ti–based	Ti_3Al–based	TiAl–based	Superalloys
density, g / cm^3	4.5	4.1–4.7	3.7–3.9	8.3
modulus, GPa	96–100	100–145	160–176	206
yield strength, MPa	380–1150	700–990	400–650	–
tensile strength, MPa	480–1200	800–1140	450–800	–
creep limit, ℃	600	760	1000	1090
oxidation limit, ℃	600	650	900	1090
ductility, % at RT	20	2–10	1–4	3–5
ductility, % at HT	high	10–20	10–60	10–20
structure	hcp / bcc	DO_{19}	$L1_0$	fcc / $L1_2$

5.6.1.1. Weight Savings

The high strength and low density of titanium (~40% lower than that of steel) provide many opportunities for weight savings. The best example of this is its use on the landing gear of the Boeing 777 and 787 aircraft and the Airbus A380. **Figure 5.6-1** shows the landing gear on the

777 aircraft. Many of the parts are fabricated from Ti-10V-2Fe-3Al. This alloy is used at a minimum tensile strength of 1193 MPa; it is used in replacement of high-strength low-alloy steel, 4340 M, which is used at 1930 MPa. This substitution resulted in a weight savings of over 580 kg. [2]

Figure 5.6-1: Boeing 777 Landing Gear.
http://blog.seattlepi.com/aerospace/files/2011/02/boeing-777-gear.jpg.

The Boeing 787 used the next-generation high-strength titanium alloy, Ti-5Al-5V-5Mo-3Cr, which has slightly higher strength and some processing advantages. The use of titanium in landing gear structures should also significantly reduce the landing gear maintenance costs due to its corrosion resistance. The low density and high strength make it very attractive for reciprocating parts, such as connecting rods for automotive applications. Again, the price is too high for family vehicles, but the U.S. Department of Energy is investing in a substantial effort to make titanium components for automobiles and trucks affordable. (Titanium is successfully utilized for high-end racing cars, where cost is not that much of an issue.)

The Boeing 777 uses 13,000 lbs of Ti-10V-2FE-3Al in the landing gear. This is a beta alloy that is heat-treated to 160,000 to 170,000 pound/square inch. Other alloys used in a variety of applications for this plane include commercially pure titanium, Ti- 3Al-2 ½ Sn, Ti-6Al-4V, Ti-6AL-2SN-4ZR-2MO-2SI, and a beta alloy Ti-3Al-8V-6Cr-4Mo-4Zr. This latter alloy according to Boyer can be heat-treated to 200,000 psi. In addition to the uses in the airframe, the Boeing 777 has approximately 25,000 lbs of titanium alloy in the engines.

The Air Force F-22 uses approximately 42% (9000 lbs) of titanium alloys in the airframe; although several alloys are now available, the largest amount is still Ti-6Al-4V. The Pratt & Whitney engines for this plane, the F119-PW-100, contain Ti-6Al-4V and the newer alloy Ti-6Al-2Sn-4Zr-2Mo-0.2Si.

Titanium has a very tenacious nascent oxide which forms instantly upon exposure to air. This oxide is the reason for the excellent corrosion resistance. Corrosion is not a factor for titanium in an aerospace environment. Titanium does not pit, which has resulted in excellent service experience. Titanium and its alloys have excellent resistance under most oxidizing, neutral, and inhibited reducing conditions. With regard to stress-corrosion cracking (SCC), commercially pure and most titanium alloys are virtually immune unless there is a fresh, sharp crack in the presence of stress. If the titanium is cracked in air, the protective oxide will immediately re-form, and SCC may not occur. If the crack is initiated in sea water, for instance, then SCC could occur on certain high-strength alloys or high oxygen grades of commercially pure titanium. Even here, the SCC may be mitigated if the part is not loaded immediately.

Titanium is compatible with the graphite fibers in the polymeric composites. There is high galvanic potential between aluminum and graphite, and if the aluminum comes into contact with the graphite in the presence of moisture the aluminum would be corroded away. It can be isolated from the composite by methods such as a layer of fiberglass, but in areas that are difficult to inspect and difficult to replace, titanium is used as a conservative approach. In addition, the coefficient of thermal expansion (CTE) of titanium, while higher than that of graphite, is much lower than that of aluminum. Even in the operating temperature range of fuselage structure, about –60°C at cruise to +55°C on a hot day, the difference in CTE using aluminum structure attached to the composite would result in very high loading. This is not an issue with titanium structure; the longer the component, the bigger the issue would be for utilizing aluminum.

The primary factor limiting more extensive use of titanium is its cost. With a significantly higher cost than aluminum and steel alloys, titanium utilization must be justified for each application. There are several factors contributing to this. High energy is required for separation of the metal from the ore. Ingot melting is also energy intensive; in addition, its high reactivity requires melting in an inert atmosphere using a water-cooled copper retort or hearth, depending on the melting technique. Machining is also very high cost, on the order of 10–100 times slower than the machining of aluminum alloys. It was recently pointed out by Froes[3] that a kilogram of aluminum sheet could be purchased for a lower cost than that of a kilogram of titanium sponge, the starting material. This sponge still must be multiple-melted with a master alloy addition, forged or forged and rolled to a size appropriate for sheet bar, put into a pack with multiple sheet bars, rolled to the appropriated thickness and etched and ground to the final thickness to obtain the titanium sheet.

With these factors in mind, much of the research and development at Boeing and other original equipment manufacturers and fabricators is being devoted to a reduction of the buy-to-fly ratio of titanium components. For instance, a 40 kg plate may be used to machine out a 5 kg part, meaning almost 90% of the titanium is turned into chips (scrap). Reduction of that buy-to-fly ratio then means one is procuring a reduced weight of a very expensive material, and also reducing the amount of machining being done on that material. Several technologies are being pursued to accomplish this. These include welding, greater use of extrusions where appropriate, superplastic forming and superplastic forming with diffusion bonding, hot stretch forming to obtain more precise formed shapes, and even powder metallurgy. With regard to welding, both fusion and solid-state welding are being investigated. Laser welding, electron beam and friction stir and linear friction welding are being studied. Alloys with improved machinability are also being pursued. Another approach being explored by NASA and partners is free-form fabrication using electron beam deposition.

Recent advancements in titanium[4] have included development of lower cost alloys, reduction of processing costs by methods such as powder metallurgy, welding, improvements in forming technologies, use of appliqués in corrosion applications, etc. There has also been considerable effort to develop models that are intended to enable a less costly more rapid alloy/heat treatment development. These models will take into account chemistry, texture development throughout the processing steps, and microstructure evolution through each of the thermomechanical and thermal processes involved in fabrication of mill product, forgings, etc. At least initially these models will be premised on physical models and neural networks.

Most of the titanium research and development efforts in the future will focus on cost reduction. These efforts involve or could involve development of lower cost titanium reduction; lower cost alloys; improved mill processing including melting, welding, forming, and any technologies that could be employed to reduce component, thus system, costs. Affordable performance improvements could involve increased mechanical properties and higher temperature capabilities. Tribological coatings with improved fatigue performance would also be of interest.

5.6.1.2. Titanium Alloys for High-Speed Aircraft

During the late 1990s NASA devoted considerable effort to characterizing Ti alloys for high-speed aircraft fuselage structures. Titanium alloy development at that time was underway primarily to optimize combinations of strength, toughness, and stiffness for selected applications to airframe structures while maintaining other critical properties such as fatigue and crack growth resistance at acceptable levels. Table 5.6-2 shows the alloys[5] under consideration and lists some of the rationale for including each one in the list.

Table 5.6-2: Candidate Advanced Titanium Alloys for High-Speed Aircraft Structures

Alloy type	Alloy	Density gm/cm^3	Chemistry	Rationale
α/β	Ti-6-4	4.43	Ti-6Al-4V	Industry Standard-Baseline
	Ti-6242S	4.54	Ti-6Al-2Sn-4Zr-2Mo-0.08Si	Creep strength, tough, high temp.
	Timetal 550	4.60	Ti-4Al-4Mo-2Sn-0.5Si	Good SPF, toughness
	Ti-62S	4.43	Ti-6Al-1.7Fe-0.1Si	High modulus, sheet,plate-forgings
	Ti-62222	4.54	Ti-6Al-2Sn-2Zr-2Cr-2Mo-(Si)	Good SPF, Strength, toughness.
	Corona X	4.42	Ti-5.0Al-5.5Mo-2Cr-1Ni-0.1O_2	Good strength, toughness
	Beta CEZ	4.68	Ti-5Al-2Sn-4Mo-2Zr-2Cr-1Fe	High strength, toughness - forgings
	SP 700	4.54	Ti-4.5Al-2Fe-2Mo-3V	Low Temp. SPF, very tough
	Ti-10-2-3	4.65	Ti-10V-2Fe-3Al	High strength, toughness-forgings
Meta-stable β	Timetal 21S	4.93	Ti-15Mo-2.7Nb-3Al-0.2Si	Heat treatable to wide range of properties, readily produced in strip, cold rollable, potentially low cost.
	LCB	4.79	Ti-4.5Fe-6.8Mo-1.6Al	
	Beta C	4.82	Ti-3Al-8V-6Cr-4Mo-4Zr	

The alloys range from mature (Ti-6242S, Timetal 550, Ti-10-2-3, Beta-C, e&), to relatively new (Ti-62222, SP 700, Ti-62S, Beta CEZ, Timetal 21s), to limited experience or experimental (LCB, Corona X). Ti-6242s is a mature alloy developed for high-tensile and creep strength and high-temperature stability. However, in the current programs, the alloy is used in the RX2 condition, a heat treat process developed by researchers at Rockwell International that yields a very high modulus (>130 GPa) while maintaining relatively high strength and toughness. Ti-62222 saw limited development until it was selected as the baseline for the F-22 fighter aircraft. That application is primarily for thick section components and performance in sheet product form is largely unknown. Likewise, Ti-10-2-3, Beta CEZ, and Beta-C were developed primarily for uses in heavy section parts. Corona X is an experimental alloy derived from Corona 5 that was developed by Rockwell and the Navy as a moderate-strength, high-toughness alloy.[6] In thick sections, it shows improved strength and toughness over Corona 5. SP 700 is a relatively new high-formability alloy developed by NKK Corporation. It has very good superplastic forming characteristics at temperatures below 800°C and has relatively high toughness. Timetal-21s is a high-strength alloy developed for improved oxidation resistance. It has very good resistance to hydraulic fluids such as Skydrol. Timetal LCB was developed as a high-strength, low-cost alloy and has been marketed primarily for coil spring applications. All the alloys are being evaluated in sheet product form. Data given herein are from sheet product ranging from 1 mm to 2 mm thick.

NASA also funded work under the High-Speed Civil Transport Program with the airframe companies[7] and with the material suppliers to search for Ti alloys that would be acceptable for airframe applications for the Mach 2.0 to 2.4 speed range (**Figure 5.6-2**).

Results from the Boeing study showed that Beta21S, a metastable beta alloy, was very problematic in stretch forming operations, and it was dropped from the HSCT evaluation program in favor of Ti-6-2-2-2-2 an alpha-beta alloy. NASA, Lockheed Martin Aeronautical Systems, McDonald Douglas Aerospace, and Boeing all participated in evaluating Ti alloys for the HSCT Program.

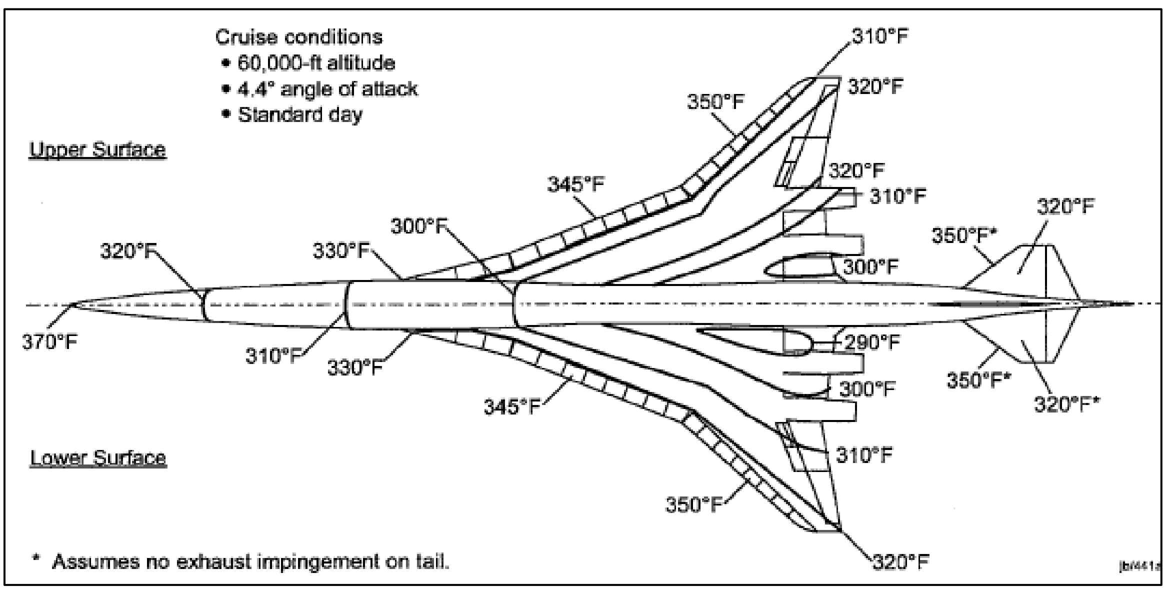


Figure 5.6-2: HSCT Study Configuration and Thermal Profiles.

As part of the metallic materials work performed under the NASA High-Speed Research Program William D. Brewer, R. Keith Bird, and Terryl A Wallace[8] conducted research on the effects of heat treatment, service temperatures from −54°C to +177°C, and selected processing on the mechanical properties of several candidate β and α-β titanium alloys. Included are β alloys Timetal 21S, LCB, Beta-C, Beta-CEZ, and Ti-10-2–3 and α-β alloys Ti-62222, Ti-6242S, Timetal 550, Ti-62S, SP-700, and Corona-X. The emphasis is on strength and toughness properties of rolled sheet product and on the superplastic properties and processing of the materials.

Titanium matrix composites were also the focus of a significant amount of research during the 1990s. Reports by Brewer,[9] and Unnam and Tenney[10] capture the basic thrust of the research performed in search of high-temperature material systems for high-speed airframe applications.

5.6.2. Titanium Aluminides

Steve Hales coauthored a key paper[11] on research done at Langley on TiAl material. In this study, Hales and coworkers plasma sprayed pre-alloyed γ-TiAl powder onto a sacrificial mild steel foil substrate. A typical deposit (plus substrate foil) was 15.2 cm wide by 91.4 cm long. This is then sectioned into sheets of suitable size for vacuum hot pressing (7.6 cm x 12.7 cm). The substrate foil is then removed via chemical milling using a 50% nitric acid-50% water solution and the remaining deposit is bright dipped in a 44% nitric acid, 6% hydrofluoric acid, and 50% water solution to remove any residuals. The vacuum hot press (VHP) operates at temperatures up to 1200°C and a vacuum level in the 10^{-3} to 10^{-4} Pa range. Multiple plies (up to 6) of as-deposited material were layed-up in 12.7 cm x 7.6 cm molybdenum die which was coated with boron nitride as a release agent. Parametric studies were conducted to examine optimum times and temperatures for consolidation. They were able to produce 0.36 mm thick plies of γ-TiAl material with alloy composition close to that of the starting powders, including low interstitial content. The strength of the RF plasma spray deposited and VHP consolidated materials compared favorably with the tensile properties of γ-MET sheet processed via more conventional means.

Hales[12] and Vasquez also studied synthesis of nano-crystalline γ-TiAl using high-energy ball milling and brief secondary processes. One of their prime objectives was to produce nano-crystalline γ-TiAl in quantities and sizes large enough for valid mechanical property evaluation. Bulk nano-crystalline γ-TiAl material, in the form of a 7.6 cm x 12.7 cm x 0.53 mm thick panel, was successfully produced using a combination of ball milling, plasma spray deposition and VHP consolidation.

References

[1] F. H. Froes; “Titanium Aluminidies: Science, Technology, Applications and Synthesis by Mechanical Alloying”, J. Mater. Sci. Technology, Vol. 10, 1994.

[2] R.R. Boyer; “Thermec” 2003, International Conference on Processing and Manufacturing of Advanced Materials (Zurich: Trans Tech Publications, 2003).

[3] F.H. Froes and M.A. Imam; “Cost Affordable Developments in Titanium Technology and Applications,” Cost Affordable Titanium III, ed. M.A. Imam, F.H. Froes, and K.F. Dring (Zurich: Trans Tech Publications, 2010), pp. 1–12.

[4] Rodney R. Boyer and James C. Williams; “Developments in Research and Applications in the Titanium Industry in the USA”,

[5] Brewer, W. D., Bird, R. K., Wallace, T. A.; “Titanium Alloys and Processing for High Speed Aircraft”, NASA Technical Report, NAS1-20220, Jan. 01, 1996.

[6] Martin, P.L.; "Toughness-Strength Trend in Alloys Derived from Ti-4.5Al-5Mo-1SCr." Proceedings of the Eighth World Conference on Titanium. Birmingham, England 1995, pp 940-947.
[7] Shultz, P. and Hoffman, D.; "Materials Research for High Speed Civil Transport and Generic Hypersonics- Metals Durability" NASA Contractor Report 198326. (Contract NAS1-20013, Task 9)
[8] William D. Brewer, R. Keith Bird, and Terryl A Wallace; "Titanium alloys and processing for high speed aircraft", Materials Science and Engineering: A Volume 243, Issues 1-2, 15 March 1998, Pages 299-304.
[9] Brewer, W. D. and Unnam, J.; "Interface Control and Mechanical Property Improvements in Silicon Carbide/Titanium Composites", NASA Technical Paper 2066, Aug. 1982.
[10] Brewer, W. D., Unnam, J., and Tenney, D. R.; "Mechanical property degradation and chemical interactions in Borsic/titanium composite", Conference Proceedings (See A79-43228 18-23), The enigma of the eighties: Environment, Economics, Energy; Twenty-fourth National Symposium and Exhibition; Society Advanced Materials and Engineering, c. 1979, pp. 1288-1298, Publication date Jan. 01, 1979.
11 Stephen J. Hales, Mohammad Saqib and Joel A. Alexa; "An innovative Method for Manufacturing TiAl Foil", Gamma Titanium Aluminides 2003, Edited by Kim,Clemens,Rosenberger. TMS (The Minerals, Metals & Materials Society, 2003.
[12] Hales, Stephen J. and Wasquez, Peter; "Synthesis of Nano-Crystalline γ-TiAl Materials", Gamma Titanium Aluminides 2003; Edited by Kim,Clemens,Rosenberger; TMS (The Minerals, Metals & Materials Society, 2003.

5.7. Aluminum Metal Matrix Composites (B/Al, Borsic/Al, Gr/Al, SiC/Al)

Aluminum composites are materials in which a reinforcement, typically a ceramic-based material, is added with the purpose of improving the material's properties. Of the variety of ceramic materials that can be used as reinforcements, silicon carbide (SiC) and aluminum oxide (Al_2O_3) are the two that have seen the greatest use as a result of their favorable combination of density, price, and property improvement potential. Reinforcements also come in a variety of forms: continuous fibers, whiskers, and particulates. When these reinforcements are combined with an aluminum matrix, the resulting material has significant increases in elastic modulus (stiffness), wear resistance, and, in some cases, strength and fatigue resistance. In addition, the coefficient of thermal expansion of aluminum is reduced by the addition of the reinforcement, while the material retains the high thermal conductivity and low density inherent in the aluminum alloy. These types of property changes, not generally possible through conventional alloying methods, have been the source of the excitement about aluminum composites.

The reinforcement material is embedded into the matrix. The reinforcement does not always serve a purely structural task (reinforcing the compound), but is also used to change physical properties such as wear resistance, friction coefficient, or thermal conductivity. The reinforcement can be either continuous, or discontinuous. Discontinuous MMCs can be isotropic and can be worked with standard metalworking techniques, such as extrusion, forging or rolling.

In addition, they may be machined using conventional techniques, but commonly would need the use of polycrystalline diamond tooling.

5.7.1. Manufacturing and Forming Methods

MMC manufacturing can be broken into three types: solid, liquid, and vapor.

The solid state methods include the following:

- Powder blending and consolidation (powder metallurgy): powdered metal and discontinuous reinforcement are mixed and then bonded through a process of compaction, degassing, and thermo-mechanical treatment (possibly via hot isostatic pressing (HIP) or extrusion).
- Foil diffusion bonding: layers of metal foil are sandwiched with long fibers, and then pressed through to form a matrix.

The liquid state methods include the following:

- Electroplating/Electroforming: a solution containing metal ions loaded with reinforcing particles is co-deposited forming a composite material.
- Stir casting: discontinuous reinforcement is stirred into molten metal, which is allowed to solidify.
- Squeeze casting: Molten metal is injected into a form with fibers preplaced inside it.
- Spray deposition: Molten metal is sprayed onto a continuous fiber substrate.
- Reactive processing: A chemical reaction occurs, with one of the reactants forming the matrix and the other the reinforcement.

The vapor deposition is as follows:

- Physical vapor deposition: The fiber is passed through a thick cloud of vaporized metal, coating it.

The in situ fabrication technique is as follows:

- Controlled unidirectional solidification of a eutectic alloy can result in a two-phase microstructure with one of the phases, present in lamellar or fiber form, distributed in the matrix.

5.7.2. Applications

Metal matrix composites have found limited specialty applications where the performance can justify the use of more expensive materials. MMCs are nearly always more expensive than the conventional materials they are replacing. As a result, they are found where improved properties and performance can justify the added cost. These applications are found most often in aircraft components, space systems, and high-end or "boutique" sports equipment. Reducing manufacturing cost is key to increasing the scope and volume of applications.

In the automotive industry, MMC's have been used for several different parts such as disc brakes, driveshafts, and engines. 3M sells a preformed aluminum matrix insert for strengthening cast aluminum disc brake calipers allowing them to weigh as much as 50% less while increasing stiffness. Ford offers a MMC driveshaft upgrade. The MMC driveshaft is made of an aluminum matrix reinforced with boron carbide, allowing the critical speed of the driveshaft to be raised by reducing inertia. The MMC driveshaft has become a common modification for racers, allowing the top speed to be increased far beyond the safe operating speeds of a standard aluminum driveshaft. Honda and Toyota have used aluminum metal matrix composite cylinder liners in some of their engines. Porsche also uses MMCs to reinforce the engine’s cylinder sleeves in the Boxster and 911.

Specialized bicycle manufactures have used aluminum MMC compounds for their top of the line bicycle frames for several years. The F-16 Fighting Falcon uses monofilament silicon carbide fibers in a titanium matrix for a structural component of the jet’s landing gear.

Aluminum matrix composites were first developed to meet very high performance defense and aerospace needs. Continuous fiber reinforced aluminum was used in the space shuttle (**Figure 5.7-1**) and Hubble Space Telescope (**Figure 5.7-2** and **Figure 5.7-3**). Typical properties of three unidirectional MMCs are shown in **Table 5.7-1**, and properties of three discontinuous reinforced MMCs in **Table 5.7-2.** As material cost became a more significant consideration, the emphasis shifted toward particulate-reinforced materials, with the goal of a lower cost, high-volume product that could be used in automotive and commercial aerospace applications. Many of the major aluminum companies, as well as others, had metal matrix composites development programs in the 1980s and early 1990s. Alcan, through its Duralcan subsidiary, established a 25 million pound-per-year production capability for particulate-reinforced aluminum composites. The Aluminum Association convened the Aluminum Metal Matrix Composites Working Group, a product of which was the ANSI H35.5 standard that established a nomenclature system for aluminum composites (available from the Aluminum Association online at www.aluminum.org). These efforts were important in moving the field forward.

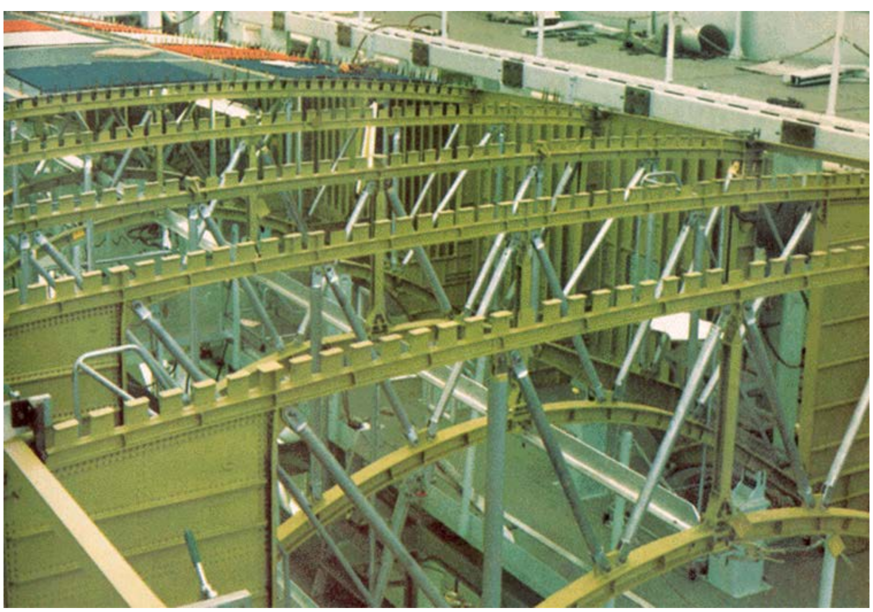


Figure 5.7-1: Mid-Fuselage Structure of Space Shuttle Orbiter Showing Boron-Aluminum Tubes. (Photo courtesy of U.S. Air Force/NASA). http://www.tms.org/pubs/journals/JOM/0104/Rawal-0104.html.

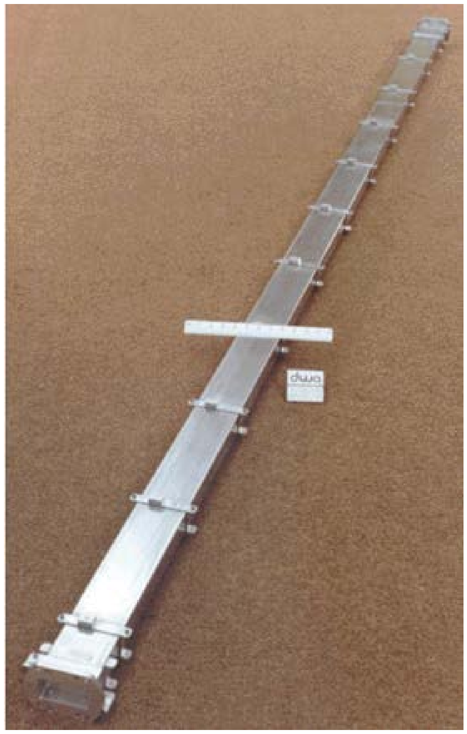


Figure 5.7-2:The P100/6061 Al High-Gain Antenna Wave Guides/Boom for the Hubble Space Telescope (HST) Shown Before Integration in the HST.

Figure 5.7-3:The P100/6061 Al High-Gain Antenna Wave Guides/Boom for the Hubble Space Telescope (HST) Shown on the HST as it is Deployed in Low-earth Orbit from the Space Shuttle Orbiter.

Table 5.7-1: Material Properties of Unidirectional Metal-Matrix Composites for Space Applications.

Properties	P100/6061 Al (0°)	P100/AZ91C Mg (0°)	Boron/Al (0°)
Volume Percent Reinforcement	42.2	43	50
Density, r (gm/cm^3)	2.5	1.97	2.7
Poisson Ratio n_{xy}	0.295	0.3	0.23
Specific Heat C_p (J/kg-K)	812	795	801
Longitudinal			
Young's Modulus (x) (GPa)	342.5	323.8	235
Ultimate Tensile Strength (x) (MPa)	905	710.0	1100
Thermal Conductivity K_x (W/m-K)	320.0	189	—
CTE_x (10^{-6} /K*)	-0.49	0.54	5.8
Transverse			
Young's Modulus (y) (GPa)	35.4	20.7	138
Ultimate Tensile Strength (y) (MPa)	25.0	22.0	110
Thermal Conductivity K_y (W/m-K)	72.0	32.0	—

* Slope of a line joining extreme points (at –100°C and +100°C) of the thermal strain curve (first cycle).

Table 5.7-2: Material Properties of Discontinuous Reinforced Aluminum Matrix Composites http://www.tms.org/pubs/journals/JOM/0104/Rawal-0104.html

Properties	Graphite Al GA 7-230	Al6092/SiC/17.5p	Al/SiC/63p
Density, r (gm/cm^3)	2.45	2.8	3.01
Young's Modulus (GPa)	88.7	100	220
Compressive Yield Strength (MPa)	109.6	406.5	
Tensile Ultimate Strength (MPa)	76.8	461.6	253
Compressive Ultimate Strength (MPa)	202.6	—	
CTE (x-y) (10^{-6} /K)	6.5-9.5	16.4	7.9
Thermal Conductivity (W/m-K) (x-y)	190	165	175
(z)	150		170
Electrical Resistivity (m-ohm-cm)	6.89	—	

''Despite the successful production of MMCs such as continuous-fiber reinforced boron/aluminum (B/Al), graphite/aluminum (Gr/Al), and graphite/magnesium (Gr/Mg), the technology insertion has been limited by the concerns related to ease of manufacturing and inspection, scale-up, and cost. Organic-matrix composites continued to successfully address the system-level concerns related to microcracking during thermal cycling and radiation exposure, and electromagnetic interference shielding; MMCs are inherently resistant to those factors. Concurrently, discontinuously reinforced MMCs such as silicon-carbide particulate (p) reinforced aluminum (SiCp/Al) and Gp/Al composites were developed cost effectively both for aerospace applications (e.g., electronic packaging) and commercial applications.

The primary advantage of MMCs over counterpart organic-matrix composites is the maximum operating temperature. For example, B/Al offers useful mechanical properties up to 510°C, whereas an equivalent B/Ep composite is limited to about 190°C. In addition, MMCs such as

Gr/Al, Gr/Mg, and Gr/Cu exhibit higher thermal conductivity because of the significant contribution from the metallic matrix.

When continuous-fiber reinforced MMCs were no longer needed for the critical strategic defense system/missions, the development of those MMCs for space applications came to an abrupt halt. Major improvements were still necessary, and manufacturing and assembly problems remained to be solved. In essence, continuous-fiber reinforced MMCs were not able to attain their full potential as an engineered material for spacecraft applications. During the same period, Gr/Ep, with its superior specific stiffness and strength in the uniaxially-aligned fiber orientation, became an established choice for tube structures in spacecraft trusses. Issues of environmental stability in the space environment have been satisfactorily resolved.

MMCs are routinely included as candidate materials for primary and secondary structural applications. However, simply having the best engineered material with extraordinary strength, stiffness, and environmental resistance is no guarantee of insertion. The availability and affordability of continuously reinforced MMC remains a significant barrier to insertion.

Designers who often make the decision of material selection must become more familiar with the properties, commercial availability and life-cycle affordability of existing discontinuously reinforced metals. Material performance must be integrated with innovative design and affordable manufacturing methods to produce systems and subsystems that provide tangible benefits. However, in the absence of system-pull and adequate resources, it is difficult to surmount the technical and cost barriers.

Four principles that shape the future application of advanced materials include system solutions, economical manufacturing processing, diverse markets, and new technologies. In terms of system solutions, the decision regarding designs, processes and materials must be made synergistically to attain maximum benefit. No single mission or system application can sustain the cost of developing new materials and processes. Thus, the use of discontinuous reinforced aluminum (DRA) in diverse markets such as automotive, recreational, and aircraft industries has made DRA MMC affordable for spacecraft applications such as electronic packaging. Building upon the success of DRA in electronic packaging and in structural applications in the automotive and aeronautical fields, DRA is also being evaluated for truss end fittings, mechanism housings, and longerons. Work has also been performed on the creep performance of discontinuously reinforced alloys.[1]

During the development of MMCs, significant advancements were made on the fundamental science and technology front, including a basic understanding of composite behavior, fiber-matrix interfaces, surface coatings, manufacturing processes, and thermal-mechanical processing of MMCs. Subsequently, the technology experience benefited the latter development of high-temperature intermetallic-matrix composites.

References

[1] Taminger, K. M. B.; “Analysis of Creep Behavior and Parametric Models on Unreinforced 2124 and 2124+SiCw,” Masters Thesis, Department of Materials Engineering and Science, VPI&SU, Blacksburg, VA, February 1999.

5.8. Titanium Metal Matrix Composites

In the 1980s–1990s there was a major DoD/NASA sponsored program, the Integrated High-Performance Turbine Engine Technology Program directed at the development of continuous silicon carbide fiber-reinforced titanium matrix composites (TMC) for high-performance rotating engine hardware. That program ran for over a decade but there were fabrication and test failures that lead to a review to assess the causes of the failures and to make recommendations for solutions that would reduce the risk. Although the Review Committee believed that TMCs would play an important strategic role in future commercial and military aerospace systems (see AFRL-ML-WP-TR-1998-4071, dated April 1998) this particular program was terminated. However, there has been some insertion of TMCs into aircraft engines. In 1995, the nozzle actuator piston rod for the Pratt and Whitney F115 engine in the F-22 aircraft became the first TMC technology bill of materials flight component.[1] In 1999, production of a TMC compression exhaust nozzle link for the General Electric F110 engine for the F-16 aircraft was produced and continues to be produced by FMW Composites System, Inc. (private communication with Dr. Robert E. Schafrik of GE Aircraft Engines). FMW Composites announced a number of years ago that Boeing was going to use a TMC part on the 787, which would have been the first commercial application. However, the part was expensive and over-designed and replaced with a monolithic titanium tube having a little thicker wall than the designed TMC part.

In the 1970s, Langley kept the dream of hypersonic flight alive. This effort, which has important links back to studies made at Langley as early as the 1950s, also found application in the National Aero-Space Plane (NASP). The focus of this program, which Langley led, was to create the technology base for an entirely new family of aerospace vehicles capable of flying at high Mach numbers to the edges of the atmosphere and beyond. The NASP Program, known as the X-30, was discontinued in the early 1990s.

In 1986, TMC received attention during the NASA/DARPA program to develop the airframe for a hypersonic vehicle, i.e., the National Aerospace Plane. In his 1986 State of the Union address, President Ronald Reagan called for “a new Orient Express that could, by the end of the next decade, take off from Dulles Airport, accelerate up to 25 times the speed of sound, attaining low-Earth orbit or flying to Tokyo within two hours.” The NASP was designed to take off and land from conventional runways using air-breathing propulsion concepts to achieve orbit.[2] Research suggested a maximum speed of Mach 8 for a scramjet-based aircraft, as the vehicle would generate heat due to atmospheric friction, which would thus cost considerable energy. The project showed that much of this energy could be recovered by passing hydrogen over the skin and carrying the heat into the combustion chamber: Mach 20 then seemed possible. Design conditions for structural sizing of the airframe were selected from a combination of maneuver load factors, dynamic pressures, and aerodynamic heating. Representative structural temperatures, shown in **Figure 5.8-1**, were used for establishing the requirements for active cooling, thermal protection systems and material selection. (A picture of the wind tunnel model of the X-30 is shown in **Figure 5.8-2**). These temperatures required the development of high-temperature lightweight materials, including alloys of titanium and aluminum known as gamma and alpha titanium aluminide, advanced carbon/carbon composites, and titanium metal matrix composite with silicon carbon fibers.[3] TMC was the advanced material identified as most promising for NASP airframe structure applications. TMC exhibits distinct advantages in the 700°F to 1500°F temperature range over other materials.[2] Primary TMC coated reinforcing fibers were SCS-6 and SCS-9 with matrices that included Ti-15-3, Ti-6-4, TIMETAL®21S, and titanium aluminide. Although there are a number of methods for producing TMCs, a laminate processing combining matrix and fibers into a consolidated TMC laminate using foil-fiber-foil was selected for manufacturing test articles for NASP.

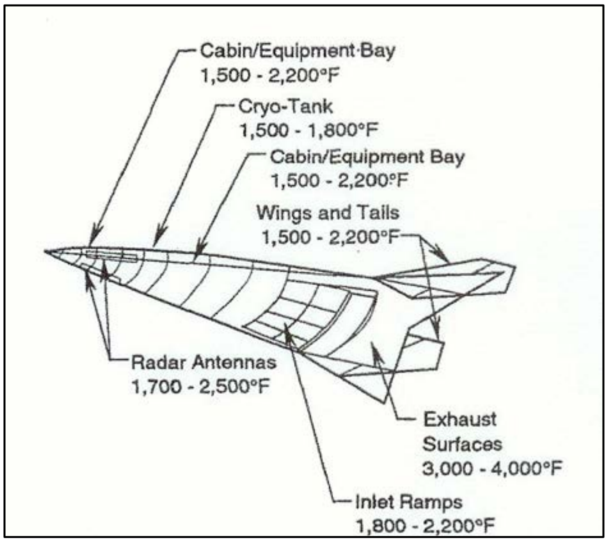


Figure 5.8-1: Representative Surface Temperatures for the NASP.

Figure 5.8-2: X-30 Model in a Wind Tunnel.

An excerpt from a Report published by the Defense Science Board Task Force on NASP Program published in November 1992 describes some of the challenges facing NASA, Air Force, and NASP Industry Team in developing the required high-temperature materials to make NASP become a reality.[4] At the beginning of the NASP Program, lightweight materials with sufficient high-temperature capabilities were not available to meet NASP single-stage-to-orbit (SSTO) requirements. The NASP design lacked maturity in that thermal/structural analysis associated with both the engine and airframe designs were very limited. There was no funded plan in place to validate thermal/structural component concepts, loads, or design tools. Improvements in high-temperature strength, oxidation resistance, and fabrication quality were needed for titanium matrix composite airframe fuselage panels and support structures. Advancements in thermal protection system (TPS) materials were needed to protect the vehicle flow path and engine nozzle surfaces. Refractory composite (RC) materials which could meet this need required improvements in oxidation resistance and development of lightweight designs and fabrication methods. Actively cooled structural designs applicable to very highly heated regions such as ramps, nozzles, and leading edges were just beginning to be developed. Materials for high-temperature engine applications also had not been developed or demonstrated for NASP requirements.

In October 1987, Phase 2 of the NASP Program was initiated. Under this phase of the NASP contract, structural analysis tools were developed and materials and structures risk reduction activities (Task D of each contractor's contract) were initiated. Significant contributions were made as a result of these activities as follows:

- Developed automated thermal/structural design and analysis tools to evaluate the complex structural response of the NASP vehicle
- Defined and initiated technology development programs to validate component concepts, design tools, and weights to meet the NASP Phase 2D exit criteria
- Defined non-uniform and dynamic engine and airframe pressure and acoustic loads
- Defined and initiated plans to develop facilities to test structural components under X-30 conditions
- Fabricated large (up to 8 ft × 8 ft × 4ft) cryotank and fuselage structures, representative of those in the vehicle design and successfully tested them with combined liquid hydrogen cryogen, external heating, and applied fuselage bending loads
- Fabricated and tested large (up to 4 ft × 8ft) TMC and C-C wing structures
- Initiated development of IM-7/977-2 carbon epoxy for cryogenic tankage

In late 1987, the NASP Materials and Structures Augmentation Program was initiated at the recommendation of the Defense Science Board. The objective was to develop materials, manufacturing processes, and structural concepts that would enable the United States to achieve the NASP goal of demonstrating a SSTO space-capable aircraft. This program has been a cooperative effort between five prime engine and airframe contractors, several government agencies and a large number of subcontractors. The consortium carried out research and development in five key material areas: (1) titanium matrix composites; (2) titanium aluminides, (3) refractory composites, (4– high-conductivity composites, and (5) high specific creep strength materials. Activities and accomplishments of this consortium include the following:

- Defined low-to-moderate risk baseline materials
- Conducted preliminary and detailed thermal/structural analyses to substantiate material selection, design concepts, and weights
- Tested thousands of material and structural coupons to determine properties and response to NASP environments

- Developed a new titanium matrix alloy (Beta 21S) with capabilities that exceed the required life at temperatures of 1500°F (higher than 1200°F previously available) in both low pressure hydrogen and air atmospheres

Developed and tested high-quality titanium matrix composite fuselage structural panels to demonstrate load and thermal cycling capability

- Developed and demonstrated manufacturing methods and processes for lightweight refractory composite TPS designs (carbon-carbon and carbon silicon carbide)
- Developed reliable carbon-carbon oxidation protection systems for 50 to 100 hours at peak temperatures up to 2600°F
- Developed and demonstrated fasteners, attachment concepts and joints for the various material systems and structural requirements
- Conducted limited manufacturing scale-up demonstrations

One of the TMCs selected for evaluation at NASA Langley was a cross-plied laminate of Ti-15V-3Cr-3Al-3Sn (Ti-15-3) matrix reinforced with continuous silicon-carbide fibers (SCS-6). Test articles were subjected to a complex TMF loading profile using test techniques that were developed to conduct a simulation of a generic hypersonic flight profile.[5] TMCs exhibit unique mechanical behavior due to fiber-matrix interface failures, bridging of matrix cracks, thermo-viscoplastic behavior of the matrix at elevated temperatures, and the development of significant thermal residual stresses in the composite due to fabrication. Therefore, standard testing methodology had to be developed to reflect the uniqueness of this type of material system and NASA Langley researchers were intimately involved in these developments.[6]

Gamma titanium aluminides, e.g., Ti-48Al-2(Cr or Mn)-2Nb and derivatives were also considered during the NASP Program due to their attractive properties for high-temperature structural applications, e.g., low density, good oxidation and burn resistance, and high-temperature strength retention. The applications include airframe hot structures and thermal protection systems for reusable hypersonic flight vehicles. However, the gamma titanium aluminide alloys are prone to both oxidation and oxygen embrittlement when exposed to the severe service conditions of the planned NASP. Researchers at NASA Langley made significant progress in the development of ultrathin lightweight sol-gel coatings for environmental protection of these alloys.[7] Although, the gamma titanium aluminides were not used on the NASP Program due to its termination, they have been used for low-pressure turbine blades in the GENx engine for the Boeing 787 and 747-8 aircraft, which represent the first production application of this class of material. A less obvious, but important, benefit of these lighter air foils is the reduced loads on the low pressure turbine disk which allows considerable weight to be eliminated from this component.[8]

Although there were many achievements in materials, structural, and propulsion technology on the NASP Program, it was terminated in 1993 due to budget cuts and technical concerns. NASA has continued work in hypersonic flight on an unmanned scramjet-powered research aircraft development designated X-43 “Hyper-X.” The Hyper-X was essentially an unmanned scaled-down X-30. The X-43 set a world speed record at Mach 9.8 on November 16, 2004. The X-43A, attached to its modified Pegasus rocket booster, took off from Armstrong Flight Research Center at Edwards Air Force Base, California, tucked under the wing of the B-52B launch aircraft. The booster and X-43A were released from the B-52B at 40,000 feet and the booster's engine ignited, taking the X-43A to its intended altitude and speed. The X-43A then separated from the booster and accelerated on scramjet power to a brief flight at nearly Mach 10.

NASA's Langley Research Center, Hampton, Virginia, and Armstrong jointly conduct the Hyper-X Program. ATK-GASL (formerly Microcraft, Inc.) at Tullahoma, Tennessee, and Ronkonkoma, New York, built the X-43A aircraft and the scramjet engine, and Boeing Phantom Works, Huntington Beach, California, designed the thermal protection and onboard systems. The booster is a modified first stage of a Pegasus rocket built by Orbital Sciences Corp, Chandler, Arizona.

In-house expertise also exists in the development of metal matrix composites. Research on fabrication, joining, and characterization of continuously reinforced titanium was performed at LaRC more than ten years ago in the National Aerospace Plane and generic hypersonic programs. Significant experience and infrastructure for performing world-class research on MMCs still exists for fabricating, designing, joining, and characterizing MMCs, and work is being proposed to renew research in the field of MMCs for cryotanks and launch vehicle applications. MMCs take advantage of high-strength ceramic fibers in a compliant metal matrix, which is quite similar to the function of ceramic plates connected by proteins in naturally-occurring shell structures.

References

[1] D.B. Miracle; "Aeronautical Applications of Metal-Matrix Composites," ASM Handbook: vol. 21, Composites, pp. 1043-1049

[2] Timothy M. Wilson; "Applications of titanium Matrix Composite to Large Airframe Structure," in AGARD Report 796, Characterization of Fibre Reinforced Titanium Matrix Composites, 77 meeting of the Structures and Materials Panel, Bordeaux, France, September 1993.

[3] http://en.wikipedia.org/wiki/Rockwell_X-30.

[4] http://www.dod.mil/pubs/foi/Science_and_Technology/DSB/596.pdf.

[5] W.S. Johnson and M. Mirdamadi; "Prediction of Thermal and Mechanical Stress-Strain Responses of TMCs Subjected to Complex TMF Histories," in AGARD Report 796, Characterization of Fiber Reinforced Titanium Matrix Composites, 77 meeting of the Structures and Materials Panel, Bordeaux, France, September 1993)

[6] W.S. Johnson, D.M. Harmon, P.A. Bartolotta and S.M. Russ; "ASTM and VAMAS Activities in Titanium Matrix Composites Test Methods Development," in in AGARD Report 796, Characterization of Fiber Reinforced Titanium Matrix Composites, 77 meeting of the Structures and Materials Panel, Bordeaux, France, September 1993)

[7] R.K. Bird, T.A. Wallace, and S.N. Sankaran; "Development of Protective Coatings for High-Temperature Metallic Materials," Elevated Temperature Coatings: Science and Technology IV, New Orleans, LA, USA, 11-15 Feb. 2001, AIME, pp. 181-196)

[8] Rodney R. Boyer and James C. Williams; "Developments in Research and Applications in the Titanium Industry in the USA," in Ti-2011, Proceedings of the 12th World Conference on Titanium, China National Convention Center (CNCC), Beijing, June 19-24, 2011).

5.9. Smart Materials

The goals of applying smart devices to aeroelastic problems are to control the aerodynamic and/or structural characteristics of air vehicles to improve flutter characteristics and reduce gust, buffeting and maneuver loads of fixed-wing vehicles and to reduce dynamic responses and loads on rotorcraft. These benefits also result in reduced emissions and increased performance and safety. In many cases, applications of smart devices will take advantage of the inherent flexibility in air vehicles to create more efficient structural designs. At NASA Langley, much of the effort in the area of controlling dynamic aeroelastic phenomena is focused towards applying piezoelectric-based actuators for active strain actuation because of their high bandwidth, the wealth of knowledge available on piezoelectrics and previous experience with piezoelectric-based devices. Research using other smart materials is being conducted in the Smart Wing Program in collaboration with the Defense Advanced Research Projects Agency (DARPA), the Air Force Research Laboratories (AFRL), and the Northrop Grumman Corporation. In this program, shape memory alloys, Terfenol-D, and piezoelectric actuators are being used for wing shape control for improved aerodynamic and aeroelastic performance. Only the metallic actuator technologies will be covered in this monograph.

5.9.1. Shape Memory Alloys (SMA)

Shape memory alloys are a class of smart materials that undergo a solid-solid phase transformation in response to changes in temperature and/or applied stress. The interaction of temperature and applied stress in driving the phase transformation can be used to exploit phenomena such as the shape memory effect and pseudo-elasticity. Both phenomena are manifestations of diffusionless, thermoelastic, martensitic transformation. Extensive work has been done to characterize shape memory alloy materials, both qualitatively through theoretical models[1,2] and quantitatively for particular alloy compositions.[3,4,5] However, much is yet to be learned about their metallography, thermoelastic characteristics, and potential for biomimetic applications.

In most of the applications, the shape memory alloy (SMA) actuator(s) behave in a manner analogous to muscle tissue in a biological system. For example, SMAs have been embedded in composite structures in a constrained recovery configuration such that the recovery stresses induced due to an elevated thermal environment (e.g., high-speed aerospace vehicles or structures in the vicinity of jet exhaust) cause an adaptive structural stiffening effect. This technology has tremendous potential for improving the dynamic response, sonic fatigue, and noise transmission characteristics of flexible structures in harsh environments and is very weight-efficient relative to conventional approaches. A similar restrained recovery application entails embedding actuators in a structure in agonist-antagonist pairs at off-axis locations to allow shape control of the structure (e.g., jet engine inlet, aerodynamic control surfaces). This approach has enormous implications for drag reduction by reducing flow separation (hinge less control surfaces) and also has significant weight benefits. This latter application can also be accomplished, without embedding the actuators, by placing the actuators within a cavity formed by the structure and allowing them to work against the “bias-spring” stiffness of the structure. Finally, other restrained-recovery, biomimetic applications exist, such as thermally activated release devices and actuators for robotic movement. This work is highly multi-disciplinary and requires the efforts of personnel with experience in metallography, metallurgy, mechanical testing, composite fabrication, actuator integration, thermoelasticity, and structural dynamics/structural acoustics. The work performed at Langley was done by an interdisciplinary team from the Metals and Thermal Structures Branch, the Advanced Materials and Processing Branch, the Structural Acoustics Branch, and the Test and Development Branch. Extension of this work to control surface shape control included participation of researchers from the Aeroelasticity Branch, the Configuration Aerodynamics Branch, and instrumentation personnel.

Programs combining aeroelasticity and control systems have been in existence at LaRC for more than 10 years. Several projects relating aeroelasticity and controls were performed. Aircraft wing adaptability to changing flight conditions was explored by incorporating sensors and actuators on the surface or embedding them within the structure. This work was inspired by birds and insects that use their wings in complex ways like rotating the wing, flexing the tip, and subtly changing the camber. Research was targeted at multifunctionality that allowed the same structure to maneuver very efficiently in all realms of flight, in ways not currently achieved by man-made flight vehicles. The incorporation of torque tubes down the center of the wing to allow rotation, incorporation of control surfaces into the structure for smoother wings and modification of wing stiffness by allowing spar rotation were considered to build more biologically representative wings. A significant element of this research was the development of sensors and actuators compatible with these goals. Studies of the effects of embedded sensors on material properties were included in the program to help evaluate the advantages and drawbacks of these types of "smart structures."

The Smart Wing project was part of the Aircraft Morphing Program for several years. In that program, smart materials were used to twist and bend airplane wings during flight to morph the aircraft shape into one that is optimal for different flight conditions. Several smart concepts were studied in the Morphing Program. The first concept used tubes of shape memory alloy material to twist the wing from root to tip. The schematic in **Figure 5.9-1** depicts the wing twist concept**.** When these tubes were actuated, the flexible wing structure twists along its span. This action increases the angle of the tip of the wing, thereby increasing the lift force on the wing. The tubes twisted the wing 1.25 degrees and increased the ability of an aircraft to roll by 8%. The structure was designed so that when the torque tube cools, the wing returns to its previous shape. The second concept was allowing shape memory alloy wires or tendons to be stretched, and then embedded in the top and bottom surfaces of a flap. When electric current was applied to the tendons on the bottom of the wing, those tendons shrink and bend the surface downward. Electric current applied to the SMA tendons on the top of the wing bend the surface upward. The system was designed so that if power was not applied, the flap remained in a neutral or undeflected configuration. Tests of the hingeless surface showed an 8% increase in lift over conventional wings.

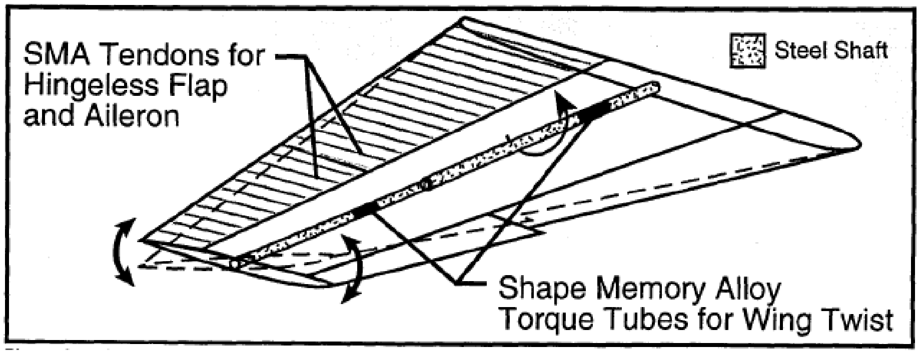


Figure 5.9-1: Schematic of Smart Concepts on the Smart Wing Model.[6]

NASA Langley participated in two major cooperative programs where SMAs were studied for active control of aircraft structures: (1) the Smart Wing Program, and the Active Twist Rotor Program. A brief description of the DARPA/AFRL/NASA Smart Wing Program is presented to illustrate to type of work performed.

5.9.2. DARPA/AFRL/NASA Smart Wing Program

The overall objective of the DARPA / Air Force Research Labs / NASA Smart Wing Program was to design, develop and demonstrate the use of smart materials and structures to improve the aerodynamic performance of military aircraft including improvements in lift-to-drag ratio, maneuver capabilities and aeroelastic effects. The approach included (1) designing, fabricating and testing scaled semi-span and full-span wind-tunnel models; (2) addressing power, reliability, packaging, and system integration issues; and (3) laying the ground work for technology transition in a follow-on program.

The Smart Wing Program was led by the Northrop Grumman Corporation who was awarded DARPA contracts for Phase I, which began in March 1997, and Phase II, which began in August 1998. Phase I and Phase II contracts were monitored by the Air Force Research Laboratory at Wright Patterson Air Force Base. Wind tunnel testing[7] was performed at the NASA LaRC in the Transonic Dynamic Tunnel (TDT), (**Figure 5.9-2**). Other members of the large team of researchers on the program include Lockheed Martin Astronautics and Control Systems, Naval Research Labs, Mission Research Corporation, Rockwell Science Center, Fiber & Sensor Technologies, Inc., Etrema Products, Inc., SRI International, University of California, Los Angeles, Georgia Institute of Technology, and the University of Texas at Arlington.

Figure 5.9-2: "Smart" Model in the Langley Transonic Dynamics Tunnel.

During Phase I of the program, a 16% scaled semi-span model ("Smart Wing") of the F/A-18 aircraft was designed and fabricated incorporating three key features: (1) hingeless, smoothly contoured trailing edge control surfaces, (2) variable span-wise wing twist, and (3) fiber optic pressure and strain transducers. Another identically scaled model of conventional construction (hinged control surfaces and no wing twist) was fabricated and used as a baseline for comparison. On the Smart Wing model, the hingeless aileron and flap are actuated using shape memory alloy tendons. The hingeless control surface concept reduces the separated flow region on the wing thereby increasing lift to drag ratio. On the Smart Wing model, wing twist is accomplished through the use of two SMA-actuated torque tubes. The first wind-tunnel test in Phase I took place at the LaRC TDT in May 1996. During the test, 1.25 degrees of twist was achieved using the SMA torque tubes resulting in approximately an 8% improvement in rolling moment. The hingeless control surfaces deployed up to 10 degrees, providing between an 8% and 18% increase in rolling moment and approximately an 8% increase in lift. The second wind-tunnel test of Phase I took place in June–July 1998 using a redesigned torque tube and hingeless control surfaces. During this test, 5 degrees of twist was achieved resulting in a 15% increase in rolling moment. In addition, 10 degrees of deflection on the hingeless control surfaces were obtained with improved controllability and repeatability.

Shape memory alloys have been investigated at Langley for a variety of different applications including enhanced nondestructive evaluation (NDE) sensors, fatigue-crack-growth measurement, use in hybrid composites for noise reduction, and structural dampening. Terryl Wallace[8,9] worked with Jim Newman and coworkers to investigate a self-repairing aluminum-based composite system developed using a liquid-assisted healing theory in conjunction with the shape-memory effect of wire reinforcements. Wallace and coworkers were able to demonstrate that, a proof-of-concept, shape memory alloy self-healing (SMASH) technology could be used to repair fatigue cracks propagating through the matrix.

References

[1] Tanaka, K. and Nagaki, S.; "A Thermomechanical Description of Materials with Internal Variables in the Process of Phase Transformation", Ingenieur-Archiv, 51,287--299, (1982).

[2] Brinson, L. C.; “One Dimensional Constitutive Behavior of Shape Memory Alloys: Thermomechanical Derivation with Non-Constant Material Functions”, Journal of Intelligent Material Systems and Structures, 4(2), 229-242 (1993).

[3] Liang,C. and Rogers, C. A.; “One-Dimensional Thermomechanical Constitutive Relations for Shape Memory Materials”, Journal of Intelligent Material Systems and Structures, 1,(1990).

[4] Cross, W. B., Kariotis, A. H., and Stimler, F. J.; “Nitinol Characterization Study”, NASA CR-1433 (1969).

[5] Jackson, C. M., Wagner, H. J., and Wasilewski, R. J.; “55--Nitinol The Alloy with a Memory: Its Physical Metallurgy, Properties, and Applications”, NASA SP-5110 (1972)

[6] Anna-Maria McGowan, W. Keats Wilkie, Robert W. Moses, Renee C. Lake, Jennifer Pinkerton Florance, Carol D. Wieseman, Mercedes C. Reaves, Barmac K. Taleghani, Paul H. Mirick, and Matthew L. Wilbur; “Aeroservoelastic and structural dynamics research on smart structures conducted at NASA Langley Research Center”, NASA TP, Jan 01, 1997. http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20040110282_2004109760.pdf.

[7] Antcliff, Richard R. and McGowan, Anna-Marie R.; “Active Control Technology at NASA Langley Research Center”, Symposium on Active Control Technology for Enchanced Performance Operational Capabilitites of Military Aircraft, Land Vehicles and Sea Vehicles, Braunschweig, Germany,8-11 May 2000.

[8] Wright, M. Clara; Manuel, Michele; Wallace, Terryl; “Fatigue Resistance of Liquid-assisted Self-repairing Aluminum Alloys Reinforced with Shape Memory Alloys”, NASA/TM-2013-216629.

[9] Wright, M. Clara; Manuel, Michele; Wallace, Terryl; Newman, Andy; Brinson, Kate, “Self-Repairing Fatigue Damage in Metallic Structures for Aerospace Vehicles Using Shape Memory Alloy Self-healing (SMASH) Technology”, Conference Paper ARMD NARI Seedling Phase II Webinar; 18-19 Mar. 2015.

6. MANUFACTURING TECHNOLOGIES

6.1. Langley's Past Manufacturing Experience

Before discussing some of the current projects being worked at Langley in manufacturing technologies a few selected pictures from past efforts at Langley have been included to illustrate past accomplishments of the Langley group. **Figure 6.1-1** show a rolled steel cylinder to illustrate that Langley's manufacturing technology development has been done with industry and has addressed scale-up to production size components or subcomponents.

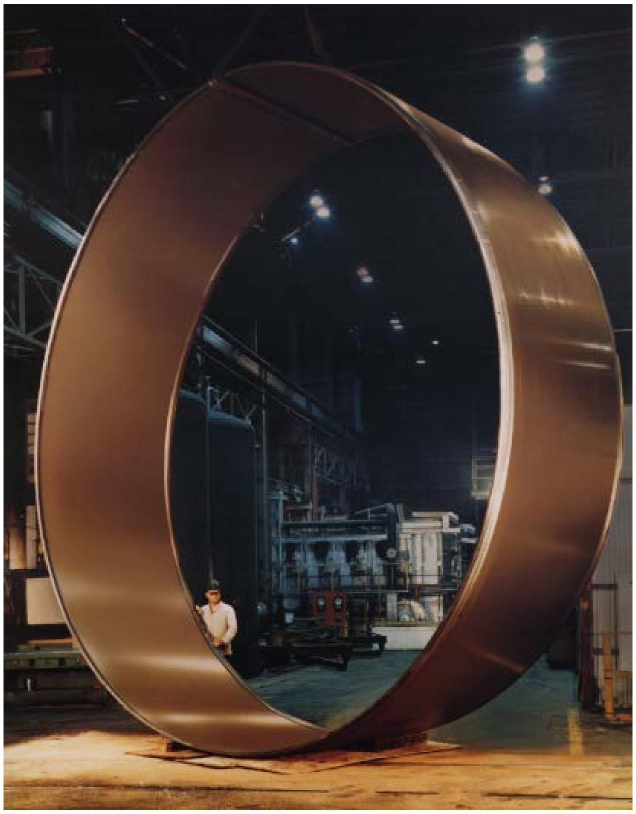


Figure 6.1-1: Rolled Steel Cylinder.

The late 1980s and early 1990s was a very active period for research on advanced metals for aerospace vehicles, as illustrated in **Figure 6.1-2**. The programs that supported this research are shown in the left column, and thrust of the research is shown in the figure for each activity.

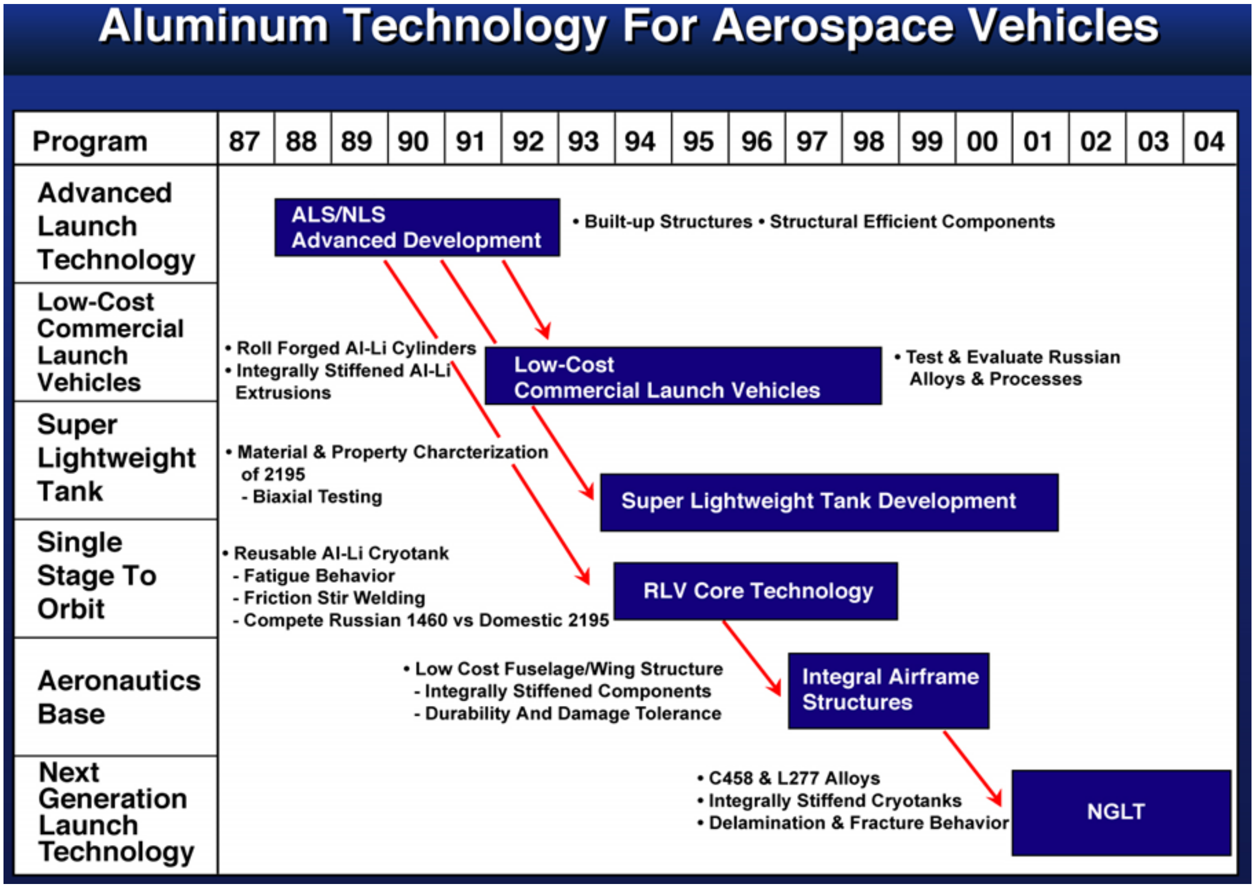


Figure 6.1-2: Aluminum Technology Development for Aerospace Vehicles at NASA Langley.

Highlights of the rich history of Langley's research in advanced fabrication processes to structural panels and subcomponents for advanced vehicle concepts is covered in the following sections. Langley's research was directed at developing a solid technology foundation on which new approaches for fabricating complex aerospace structures could be built.

6.2. Near-Net-Shape Fabrication Technologies

6.2.1. Integral Airframe Structures Program

Near-net-shape manufacturing is initial production of a part that is very close to the final net shape, reducing the amount of subsequent machining, etc., in order to reduce the final cost of the part, both in labor and materials. The methods include extrusion, spin forming and roll forging. One example is NASA's Integral Airframe Structures (IAS) Program. [1] Airframes of commercial aircraft are primarily of riveted aluminum skin and stringer construction where complete parts are built up from individually fabricated detail components. IAS is an alternate approach in which the part is "integrally stiffened" where the skin and stringers are integrated into a single piece of structure.[1] Integral structures can be less expensive to manufacture than built-up structures in both labor cost and materials and result in an overall lighter component (**Figure 6.2-1**).

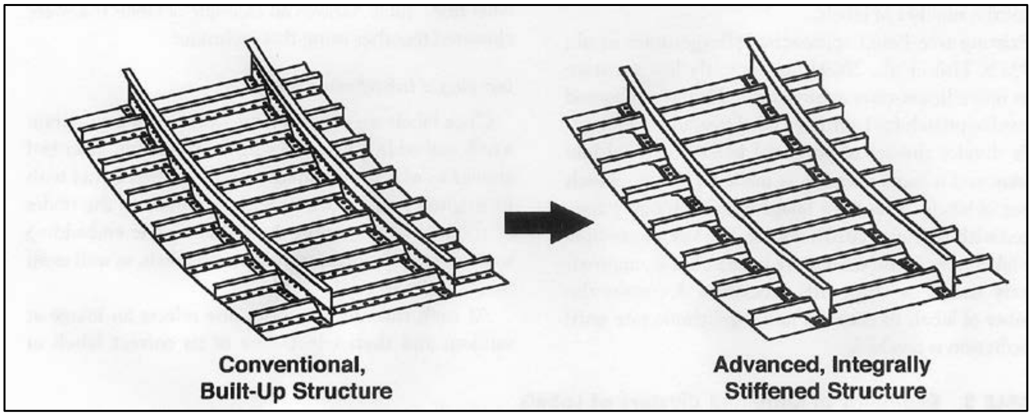


Figure 6.2-1: Examples of Conventional Built-Up Structure and Advanced Integrally Stiffened Structure.

Fabrication, analysis, and testing of a large pressure panel at Boeing yielded results that were very promising for IAS-type structures. Fabrication and assembly were fast and efficient. To manufacture the test panels, skin-stringer panels and frames were machined from aluminum plate. Mechanical bend forming (bump forming) was used to form the panels to contour. Cost studies by NASA and Boeing indicated that, as compared to conventional built-up fabrication methods, high-speed machining of structure from aluminum plate would yield a recurring cost savings of 61%. Part count dropped from 78 individual parts on a baseline panel to just 7 parts for machined IAS structure, so a significant reduction in part count was clearly achieved. Additional experience was gained in near-net-shaped extrusions for fuselage panels.[1]

The NASAIAS Program investigated, and gained significant experience toward validating, the feasibility of using "integrally stiffened" construction for commercial transport aircraft fuselage structure. The objectives of the program were to build and test structure that was less expensive than current "built-up" structure, yet equal in structural performance and weight. The IAS Program has shown significant results toward the advancement and application of integrally stiffened fuselage structure. Testing performed as part of this program provided valuable data and experience for designing integral fuselage structure.[1,2]

6.2.2. Near-Net-Shape Extrusion

It is possible to extrude wide panels with integral stiffeners, and this technology has been applied to transport aircraft in the former Soviet Union where the facilities to produce extrusions exist.[3] NASA Langley, along with Boeing, have been considering extruded integral-stiffened panels for aircraft structural applications as opposed to riveted aluminum skin and stringer construction or integrally machined thick plate. An example of an integrally stiffened extruded panel[4] is shown in **Figure 6.2-2**.

Figure 6.2-2: Extruded 2090 Integrally Stiffened Panel.[4]

This technology can also be used in launch vehicle cryotanks and dry bay structures and can significantly impact cost, weight, and safety.[5] Near-net-shape forming has the potential to reduce metal scrap rate (machining chips) in the production of launch vehicle structures from the current rate of 90% to 5%, thus reducing part count, cost, and assembly time. The increase in safety and reduced weight comes through the elimination of welds (defects) and weld land (ET has 30,000 inches of welds). An example of an integrally stiffened extrusion of a cryotanks barrel panel is shown in **Figure 6.2-3.**[5] The extruded tube is split lengthwise, flattened, and then curved by bump forming to the appropriate curvature to form a cryogenic tank barrel panel.

In order to take full advantage of this technology, the properties, including strength, fatigue resistance, corrosion resistance, thermal management, etc., must meet or exceed that of conventionally processed material. The effect of crystallographic texture and grain shape on the mechanical and corrosion properties of near-net-shape extrusions must be understood if these products are to find application in launch vehicles or aircraft structures. NASA Langley had an extensive program to characterize the texture, microstructure and properties of near-net-shape extrusions, both sheet and plate. Some of this research and development was conducted in cooperation with Russian researchers from the All-Russia Institute of Aviation Materials (VIAM). **Figure 6.2-4** shows schematics of the extrusion and location of samples for characterization.[6] In this program, the texture of four Al-Cu-Li alloys (the Russian alloy 1460, and 2090, 2096, and 2195) that were being considered for both launch and aircraft vehicles were characterized and catalogued for use in other microstructural and property studies. Alloy 2090, an early version of the low-density Al-Cu-Li alloys, was the first to be considered for these applications. An extensive characterization of this alloy[7] served as a baseline for further studies of Al-Cu-Li alloys. Other studies included characterization of the Russian alloy 1441 for probable fuselage applications.[8,9]

Figure 6.2-3: Extrusion of an Integrally Stiffened Barrel Section for Cryotanks.

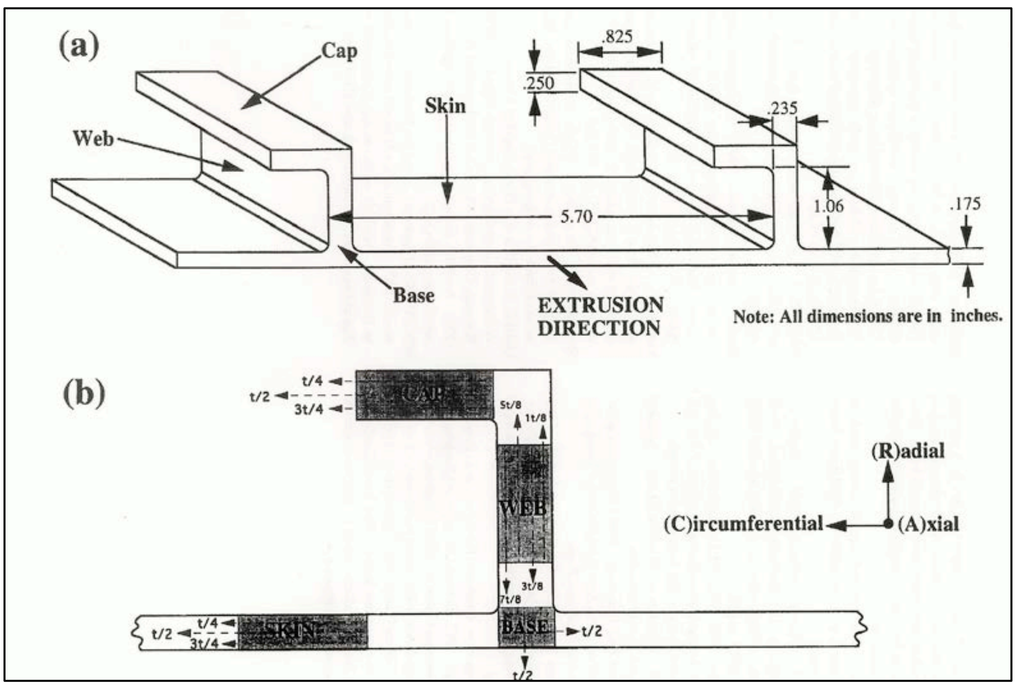


Figure 6.2-4: Schematics Showing (a) the Dimensions of the Near-Net-Shape Extrusions and (b) the Locations of Specimen Extraction for Texture Analysis.[6]

6.2.3. Shear/Roll Forming

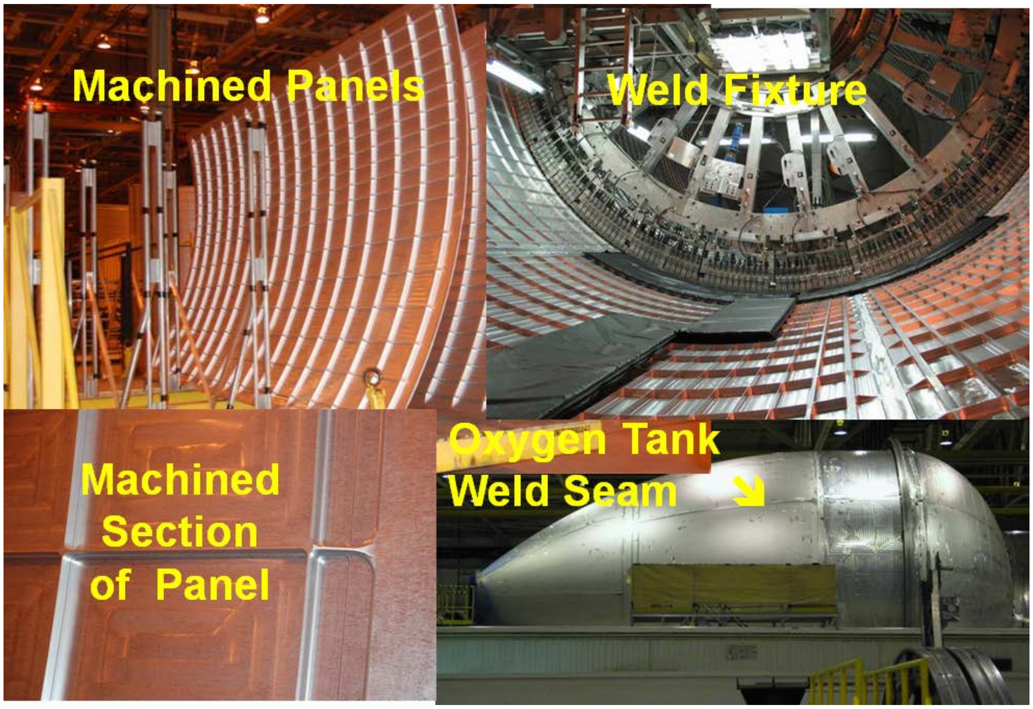


Figure 6.2-5: Conventional Fabrication of Current Generation Cryotanks.

The conventional approach for manufacturing cryogenic tanks for space launch vehicles is illustrated in **Figure 6.2-5**. The conventional approach involves lots of machined parts and extensive welding to manufacture a tank. Welding results in a knock down in properties which is compensated for by increasing section thickness at weld lands. For the super lightweight shuttle tank the weld lands added approximately 1600 lbs.

To overcome the issues of welding, Langley has championed near-net shape technologies as discussed in previous sections. One of the advanced approaches they have researched is sheer/flow forming. Shear forming, also known as flow forming, is a near-net-shape manufacturing technique in which seamless cylindrical structures are produced by reducing the wall thickness and extending the length of ring-shaped preforms. Shear forming was originally developed for steel, and Ladish was the supplier of D6AC steel flow formed cylinders for the space shuttle solid rocket boosters (SRB). The shear forming of aluminum is in the early stages of development. There are two methods of shear forming: the counter-roller method and the mandrel method. NASA Langley worked with engineers at Ladish Co. of Cudahy, Wisconsin to develop the technology of shear-formed large cylinders of aluminum alloys for space applications. An example of one of these cylinders that was formed using the counter-roller method is given in **Figure 6.2-6**. By eliminating welds from a multi-piece construction of large cylinders, the shear forming process is both safer and cheaper. Extensive research has also been conducted to characterize the metallurgical microstructure of shear formed components. An example of the type of characterization research conducted can be found in a paper by Troeger, Domack, and Wagner.[10] In this study, they investigated the processing-microstructure-property relationships for shear-formed cylinders of the Al-Cu-Li-Mg-Ag alloy 2195 for space applications and the Al-Cu-Mg-Ag alloy C415 for airframe applications. Cylinders that had undergone various amounts of shear-forming strain were studied to correlate the grain structure, texture, and mechanical properties developed during and after shear forming.

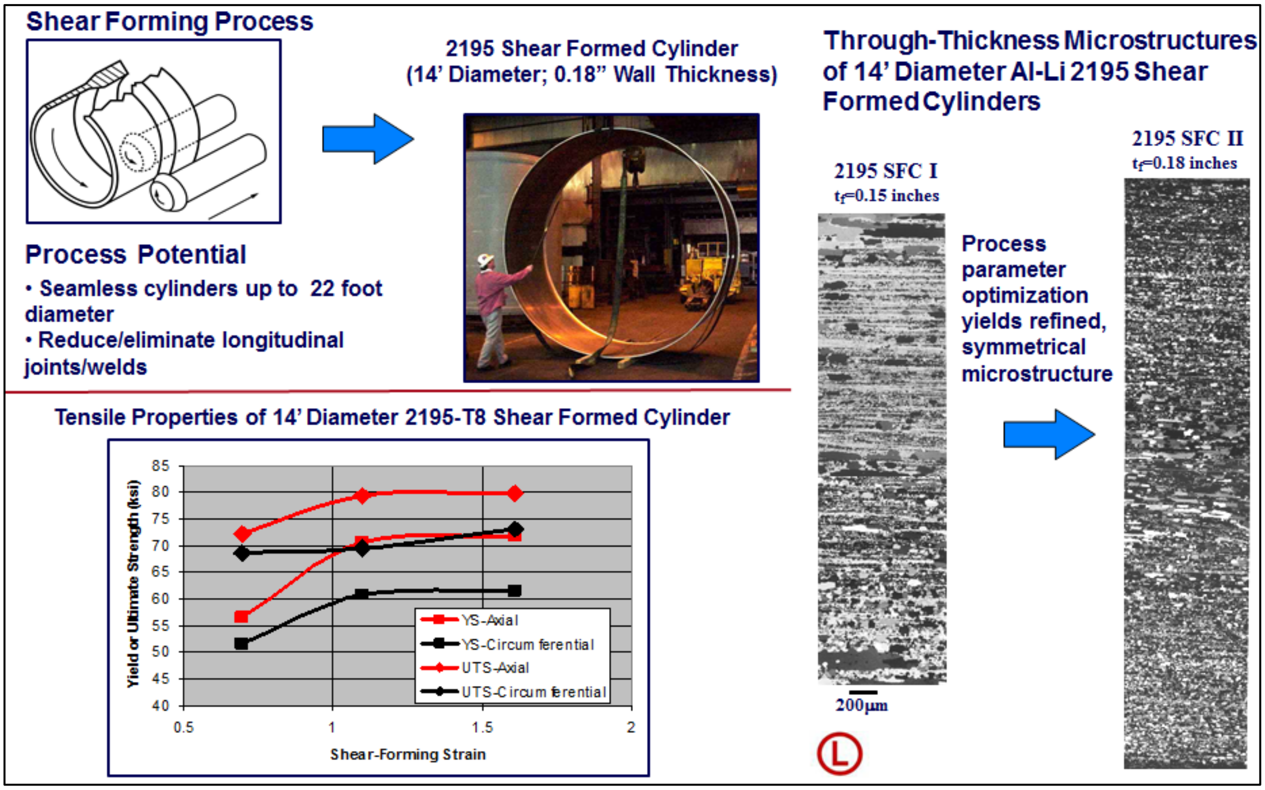


Figure 6.2-6: Example of the Shear Forming Process and a Shear Formed Cylinder made from 2195 Aluminum.

Additional research performed at Langley on spin forming is recorded in key reports by Hoffman[11, 12] and coworkers. The NASA Engineering and Safety Center (NESC) sponsored developmental work aimed at accelerating deployment of spin forming for fabrication of elements of the Orion Multi-Purpose Crew Vehicle (MPCV).

The NESC Phase I activity, spin forming aluminum crew module (CM) forward pressure vessel bulkhead (FPVBH), demonstrated the feasibility of spin forming a single-piece FPVBH using either Al alloys 2219 or 2195 (**Figure 6.2-7**). John Wagner and Marcia Domack teamed up with Spincraft and Lockheed Martin Michoud Assembly Facility to utilize this technique to create a model of the FPVBH.

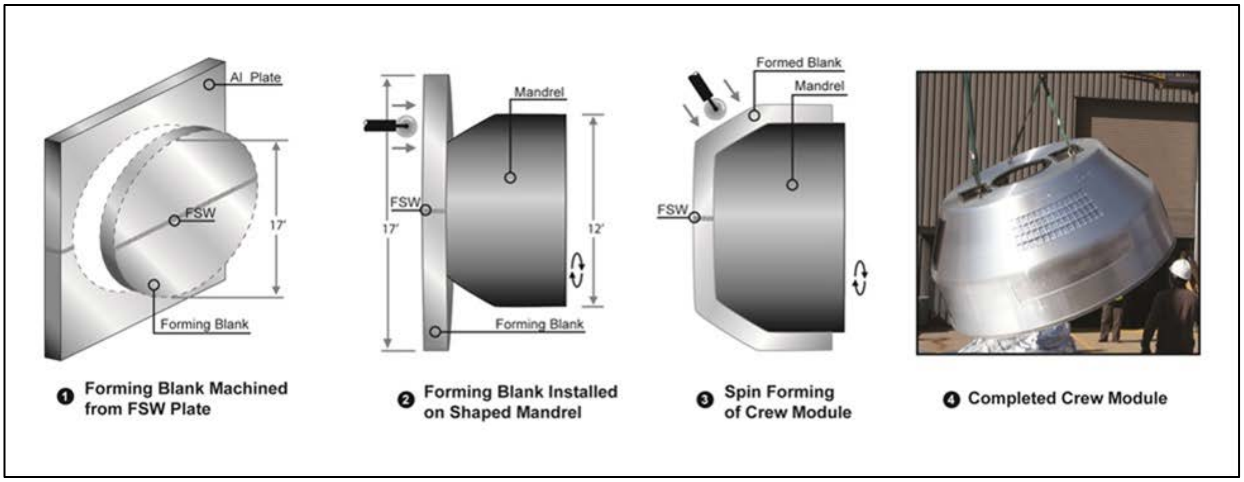


Figure 6.2-7: Schematic of Spin Forming a Single-Piece MPCV Forward Pressure Vessel Bulkhead.

This innovative manufacturing technique is a forming process in which a disc of metal is revolved at controlled speeds on a machine similar to a lathe. What makes it unique is that the spin forming process can create the complex crew module shape out of one piece of metal. A normal build would require several pieces of material being welded together into a capsule shape. Consequently, the spin forming process results in fewer welds, which reduces the chance of defects and which makes the capsule safer for the astronauts. When building the 60,000-pound external tank for the shuttle, fabricators started with 600,000 lbs of material. Roughly 90% of the material was machined away. The current Orion fabrication plan also requires lots of machining. The spin-forming process is considered near-net shape and requires much less machining and welding, so it will save material, labor costs, and reduce the possibility of defects.[15] **Figure 6.2-8** shows the spin-formed model being lowered into the laboratory at NASA's Langley Research Center.

Figure 6.2-8: The Spin-Formed Model Being Lowered into the Laboratory at NASA's Langley Research Center.

It should also be noted that the Langley team made significant advancements in the understanding of microstructural changes that occur in processes where Friction Stir Welding (FSW) is combined with spin forming. Plate-size limitations for Al-Li alloy 2195 require that two plates be FSW together to produce a spin-forming blank of sufficient size to form the crew module. Subsequent forming of the FSW results in abnormal grain growth (AGG) within the weld region upon post-forming solution heat treatment (SHT), which detrimentally impacts strength, ductility, and fracture toughness. Hales[13] and coworkers[14] investigated the occurrence of AGG within the FSW following deformation through hot rolling and spin forming, and developed intermediate annealing treatments (IAT) to improve microstructural stability prior to SHT. Among their findings was the discovery that the incorporation of an IAT before SHT successfully stabilized the 25% hot rolling microstructure at the t/4 region by promoting continuous rather than abnormal grain growth and reducing the percentage of low angle grain boundaries (stored energy).

Steve Hales did an excellent job studying the influence on solution heat treatment on abnormal grain growth and was awarded a patent on a method to suppress abnormal grain growth in aluminum alloys. This patent was licensed to industry.

Based on the Phase I feasibility results, the MPCV Program requested that a Phase II spin forming activity be conducted to address specific objectives (processing and preliminary properties) associated with spin forming the aft bulkhead. The spin-forming process would enable a single-piece aluminum alloy 2219 aft bulkhead and single-piece cone resulting in the elimination of the current multiple-piece welded construction, simplify CM fabrication, and lead to an enhanced design.

The spin forming was done by Spincraft. The Al 2219-F plate material used by Spincraft to spin form the aft bulkhead measured 2.3 inches × 141 inches × 141 inches and was supplied by Alcoa North American Rolled Products—Davenport Works, Davenport, Iowa. The tooling used for the spin forming is shown in **Figure 6.2-9.** A comprehensive testing and analyses program was conducted on the spin-formed dome to fully characterize the part. The NESC report gives a wealth of data and is an example of the excellent work performed by the Langley team working in unison with industry and other NASA center personnel.

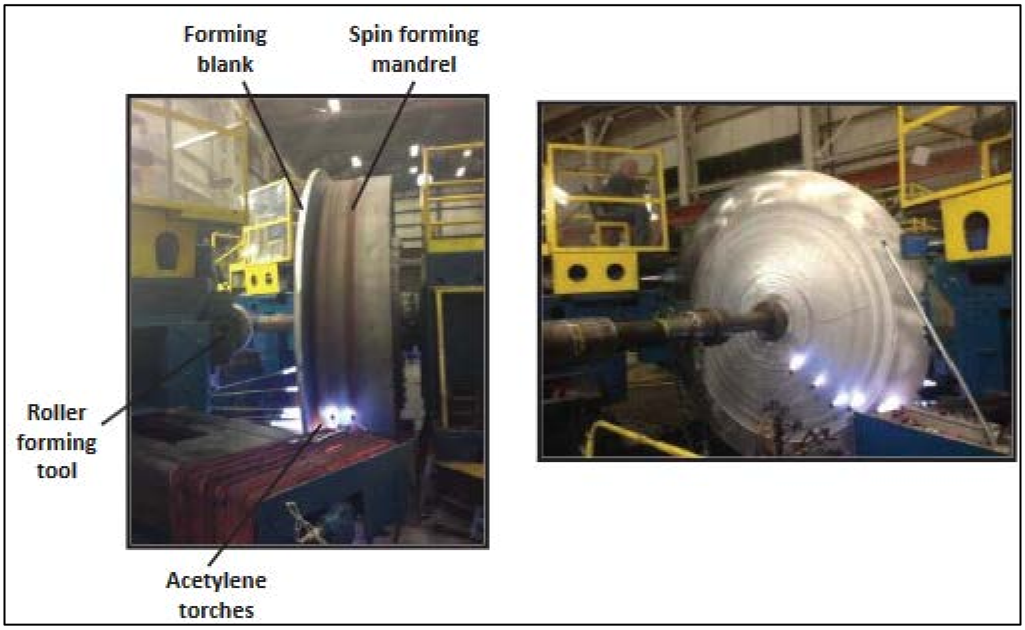


Figure 6.2-9: Spin Forming of the AFT Bulkhead.

Langley, under the leadership of John Wagner and Marcia Domack, has also championed advanced forming processes such as that shown in **Figure 6.2-10**. An example of the type of component that was produced by this process is shown in **Figure 6.2-11**.

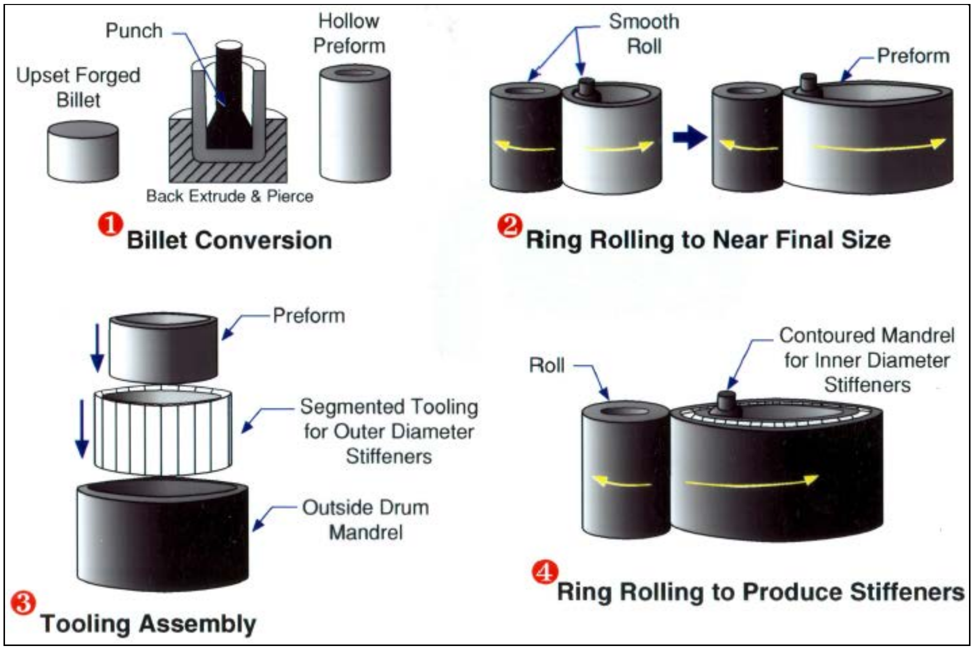


Figure 6.2-10: Near-Net Roll Forging of Al-Li Alloys.

Figure 6.2-11: Roll Forged Component.

6.2.3.1. Integrally Stiffened Cylinder Technology

The team at NASA Langley and the German company Leifeld Metal Spinning are currently collaborating to develop an innovative manufacturing process. Leifeld has been using this technology for the manufacture of net shaped steel parts, such as the commercially produced steel clutch housing, but the Langley program is the first to use this technology for aluminum, in particular the Al-Li alloy 2195. The first Al-Li trial part produced by this process[15] is shown in **Figure 6.2-12**.

Figure 6.2-12: As-Formed, 0.3 m Diameter Al-Li 2195 Alloy Part.[16]

The goal is to apply near net shape integrally stiffened cylinder technology to manufacture launch vehicle cryotanks. The current manufacturing method for launch vehicle structures such as cryogenic propellant tanks (cryotanks) relies on traditional metals fabrication technologies developed in the 1950s. The space shuttle external tank (ET) represents state-of-the-art manufacturing of metallic cryotanks and is the baseline for NASA's Space Launch System (SLS). The ET is machined from 2-inch thick Al-Li alloy plate to form the integrally stiffened skin structure of the cryotank and has in excess of half a mile of welds. New and revolutionary metal forming techniques are being explored to significantly reduce weight and cost and improve the safety and reliability of cryotanks. The basic process for forming an integrally stiffened cylinder (ISC) is illustrated in **Figure 6.2-13**.

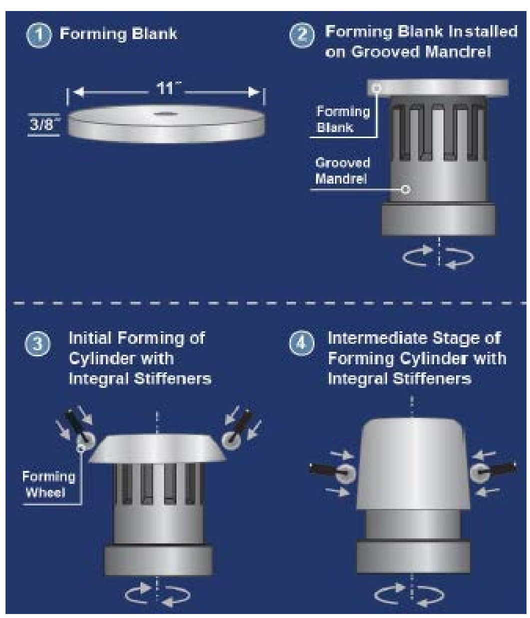


Figure 6.2-13: Spin/Flow forming of Integrally Stiffened Cylinder (ISC).

During this one step process, a rotating circular blank is formed over a cylindrical mandrel which has grooves that correspond to the shape and location of stiffeners in the finished cylinder. As the cylinder takes shape, metal flows into the grooves to concurrently form the stiffeners. An early example of an integrally stiffened cylinder[17] is shown in **Figure 6.2-14**. The goal is to be able to produce a very large cryogenic barrel section like that shown in the lower right of the figure.

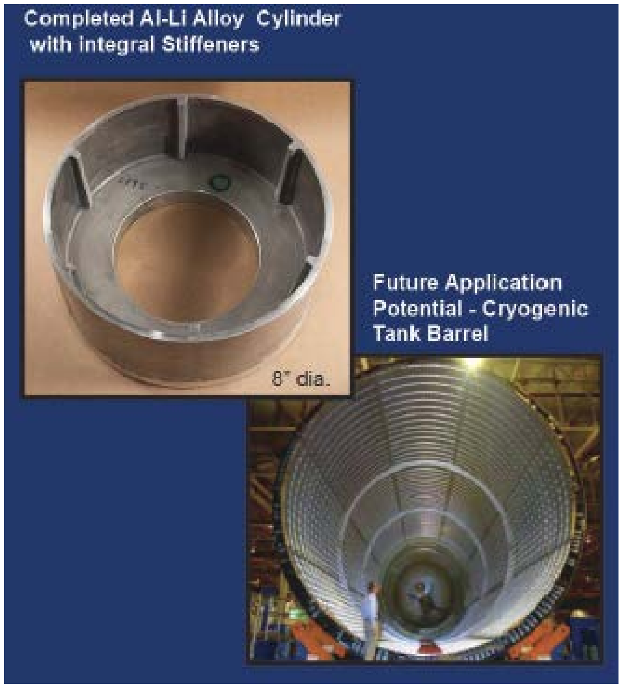


Figure 6.2-14: Completed Al-Li Integral Cylinder with Integral Stiffeners.

NASA is working to optimize and scale up the ISC process to fabricate large, aerospace quality Al-Li alloy cryotanks. The goal is to form net shape cryotank walls (skin) and stiffeners in one forming operation in a process similar to that illustrated in **Figure 6.2-15**. This will eliminate the need for machining and longitudinal welding of the cryotank barrel sections. For an ET size cryotank, raw-material-scrap rate would be reduced from 90% to 5% translating into an ~$8 million savings per tank. Eliminating welds, weld defects, and thick weld lands will increase safety and lower overall cryotank weight. The current team working this technology includes NASA-LaRC, MSFC, OCT, SLS, NESC, MT Aerospace, Leifeld Metal Spinning, International Technologies Inc., and Lockheed Martin. Potential future team players include NASA-JSC, MAF, U.S. Metal Forming Vendors, and Aluminum Producers.

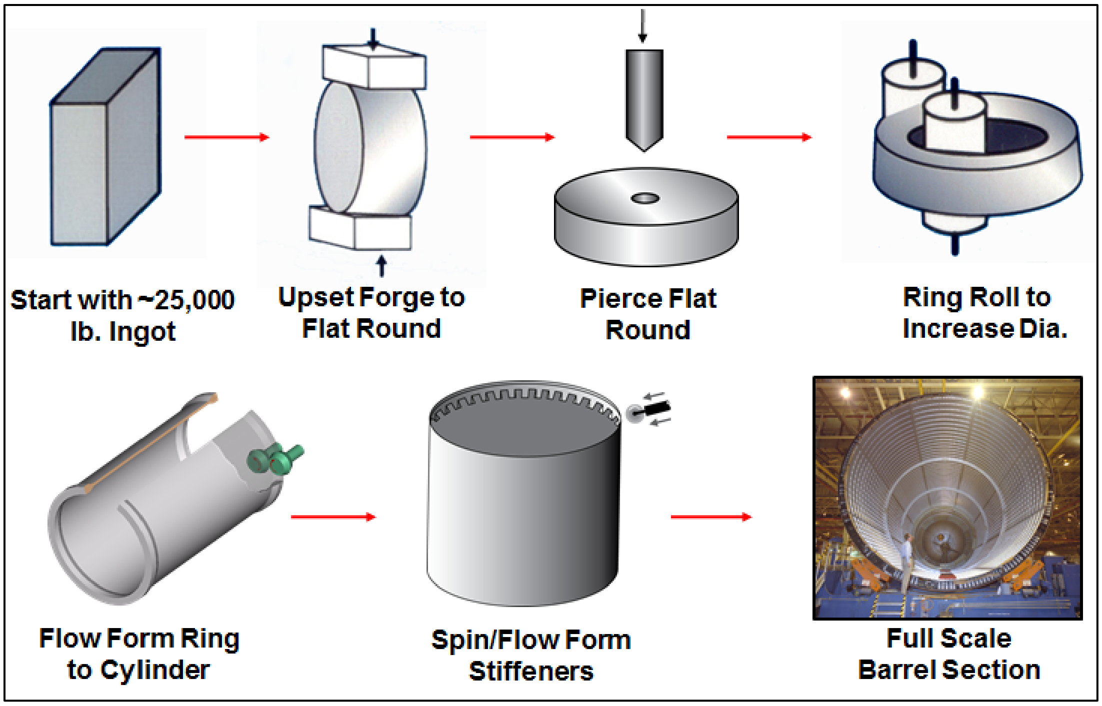


Figure 6.2-15: Scale-Up of Spin/Flow Forming Process.

6.2.3.2. Counter-Roller Technology

A major advancement in the near-net-shape shear forming process is a new counter-roller, low-cost, adaptable tooling process developed by MT Aerospace of Germany. This technology eliminates tooling and has significant manufacturing flexibility, can accelerate schedules by eliminating tool lead-time and can enable designers to fabricate out-of-the-box concepts. The adaptable tooling concept is a modification and optimization of spin forming technology. The adaptable tooling concept employs two opposing rollers, inner and counter rollers, to form the metal. The rollers move outward together to shape a spinning circular metal blank to a contour defined and controlled by a computer program. The adaptable and flexible fabrication method will also enable designers to conduct fabrication trials on innovative high-risk, high-payoff structural concepts that in the past were prohibited in the past, in part, by the cost of tooling. NASA Langley researchers are working closely with the German developers with the long-term objective of producing a highly flexible fabrication method that can be used to manufacture multiple components of varied geometry on a single machine. Schematics and examples of the counter roller spin forming process are shown in **Figure 6.2-16**.[18] Development progress and potential applications are described[19] in **Figure 6.2-17.** NASA and MT Aerospace have been cooperating on the development of this advanced concept for fabricating complex shapes with low tooling approaches.

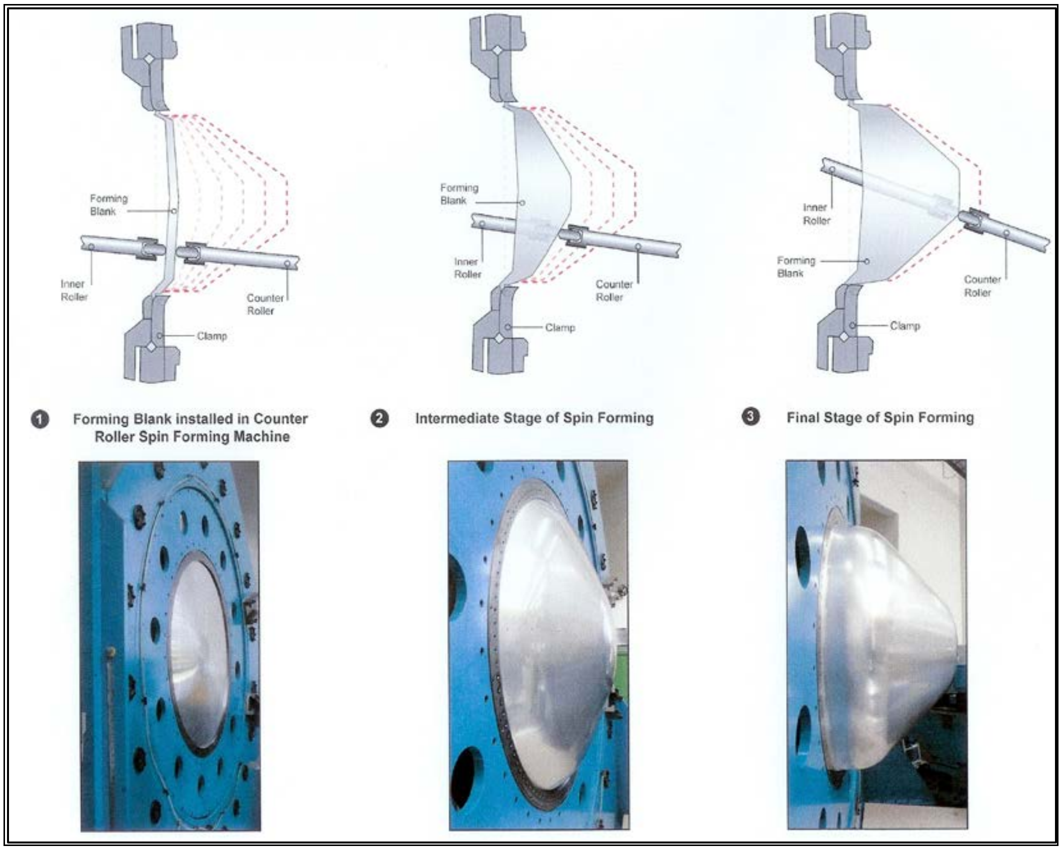


Figure 6.2-16: Example of the Counter Roller Spin Forming Process.[13]

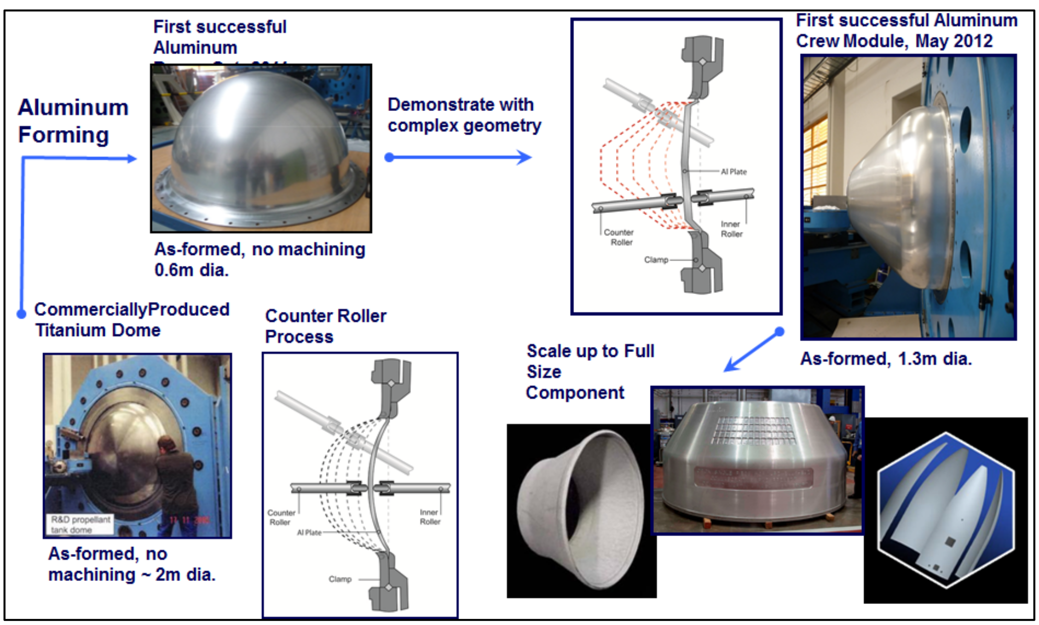


Figure 6.2-17: Adaptable Tooling for Counter Rolling Space Launch Vehicle Components.

References

[1] J. Munroe, K. Wilkins and M. Gruber; "Integral Airframe Structures (IAS), Validated Feasibility Study of Integrally Stiffened Metallic Fuselage Panels for Reducing Manufacturing Costs", NASA/CR-2000-209337, May 2000.

[2] R.G. Pettit, JJ. Wang and C. Toh; "Validated Feasibility Study of Integrally Stiffened Metallic Fuselage Panels for Reducing Manufacturing Costs," NASA/CR-2000-209342.

[3] J.B. Borradaile; "Future Aluminum Technologies and the Application to Aircraft," Paper presented at the RTO A VT Workshop on "New Metallic Materials for the Structure of Aging Aircraft", held in Corfu, Greece, 19–20 April 1999, and published in RTO MP-25

[4] M.J. Birt, M.S. Domack, R.A. Hafley and W.D. Pollock; "Characterization of Al-Cu-Li Alloy 2090 Near Net Shape Extrusion," NASA/TM-1998-207668.

[5] John Wagner and Marcia Domack; "Advanced Manufacturing of Metallic Launch Vehicle Structures," NASA Langley Research Center.

[6] Stephen J. Hales, Robert A. Hafley and Joel A. Alexa; "Catalogue of X-Ray Texture Data for Al-Cu-Li Alloy 1460, 2090, 2096 and 2195 Near-Net-Shape Extrusions, Sheet and Plate," NASA/CR-1998-206924.

[7] M.J. Birt, M.S. Domack, R.A. Hafley and W.D. Pollock; "Characterization of Al-Cu-Li 2090 Near Net Shape Extursion," NASA:TM-1998-207668.

[8] Bird, R.Keith and Dicus, Dennis L.; "Evaluation of Pressurization Fatigue Live of 1441 Al-Li Fuselage Pannel," NASA/TM-1999-209684.

[9] Bird, R.K, Dicus, D.L., Fridlyander, J.N. andSandler, V.S.; "Al-Li Alloy 1441 for Fuselage Applications," http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20040086797_2004090781.pdf.

[10] Troeger, Lillianne P. Marcia S. Domack, and John A. Wagner; "Microstructural and Mechanical Property Characterization of Shear Formed Aerospace Aluminum Alloys", NASA TM-2000-210540.

[11] M. S. Domack, E. K. Hoffman. I. S. Raju, R. S. Piascik; "Spin Forming Aluminum Alloy Crew Module (CM) Metallic Forward Pressure Vessel Bulkhead (FPVBH) – Phase I", February 2014. NASA/TM-2014-218163; NESC-RP-12-00776.

[12] Hoffman, Eric K.; Domack, Marcia S.; Torres, Pablo D.; McGill, Preston B.; Tayon, Wesley A.; Bennett, Jay E.; Murphy, Joseph T.; "Spin Forming Aluminum Crew Module (CM) Metallic Aft Pressure Vessel Bulkhead (APVBH) - Phase II", NASA/TP-2015-218674, NESC-RP-13-00884, L-20647, NF1676L-23225,

[13] Hales, Stephen J., Clayton, Howard Dale and Alexa, Joel A.; "Abnormal Grain Growth Suppression in Aluminum Alloys", Patent No. 9,090,950 B2 issued July 28, 2015.

[14] Hales, Stephen J., Clayton, Howard Dale and Alexa, Joel A.; "Abnormal Grain Growth Suppression in Aluminum Alloys", Patent No. 9,090,950 B2 issued July 28, 2015.

[15] Wagner, John A., Domack, Marcia S. and Bird, R. Keith; "Revolutionizing Metals Forming: Advanced Near Net Shape Technologies for Space Structures," Advanced Manufacturing Technologies Project Review, August 29, 2013.

[16] http://www.nasa.gov/topics/technology/features/spin-forming.html.

[17] Domack, Marcia S., Wagner, John A.; Technical Report NP-2014-11-573-LaRC, NF1676L-20572, 2015.

[18] Wagner, John A. and Domack, Marcia S.; "Game Changing Development Program, Advanced Near Net Shape Technologies for Space Structures", NASA Langley Research Center, September 14, 2012.

[19] Wagner, John A. and Domack, Marcia S.; "Near Net Shape Fabrication of Al-Li Alloys for Launch Vehicles", Advanced Materials & Processing Branch Peer Review NASA Langley Research Center, Hampton, VA, September 18–20, 2012.

6.3. Additive Manufacturing

Karen Taminger and Robert Hafley have championed the development of electron beam free-form fabrication at NASA Langley over the past several years and have published extensively on their work. They acquired one of the first systems produced by Sciaky, Inc., which is the only manufacturer of such equipment in the world, and have continued to modify and improve the capabilities for aerospace applications. Key references to their excellent work will be sited in the following sections after a brief general introduction to additive manufacturing.

The biggest possible game changer in manufacturing of aerospace parts to come along in quite some time is additive manufacturing (AM). Additive Manufacturing is a novel near-net-shape fabrication technique used to produce solid components by consolidating partial or fully melted layers of powder, wires, or ribbons. The materials to be deposited are melted by a focused heat source, such as an electron beam, laser, or plasma as in arc welding. Each layer is a section of a 3-D computer-aided design (CAD) final component model; i.e., the 3-D geometry of the final component is formed by building-up a stack of 2-D profiles layer-by-layer by local melting. The ASTM F-42 committee was formed to standardize AM terminology and develop industry standards. According to their first standard, ASTM F2792-10, AM is defined as "the process of joining materials to make objects from 3-D model data, usually layer upon layer, as opposed to subtractive manufacturing technologies."

Within the last 20 years, AM has evolved from simple 3-D printers used for rapid prototyping in non-structural resins to sophisticated rapid manufacturing that can be used to create parts directly without the use of tooling. Most work to date has been conducted using plastics, but significant effort is now focused on metals.[1] For aerospace, complex AM processes must be developed to meet the industry's stringent requirements and to ensure that products can achieve the robust performance levels established by traditional manufacturing methods. Factors that must be considered for material performance of even the simplest components include specific strengths, fatigue resistance, creep resistance, use temperature, survival temperature, several tests of flammability, smoke release and toxicity, electrical conductivity, multiple chemical sensitivities, radiation sensitivity, appearance, processing sustainability, and costs.[2] Additive manufacturing can be especially useful for small production runs, high-value products, and products with high complexity. Within the aerospace industry, AM can help significantly reduce the high buy-to-fly ratios of cast, forged, and machined components. In these cases, the causes of higher costs are time, high-skilled labor (e.g., mold making), and high levels of scrapped material. AM can reduce and sometimes eliminate the need for tooling, thus helping to accelerate the development of new parts.[3]

Current approaches for fabricating functional metal hardware for aerospace components include forging, casting, and extruding. Material properties and part complexity generally dictate which process is selected. However, these often result in starting with a block of material and machining down to the final part (**Figure 6.3-1**). This leads to significant lead time in ordering large billets of material, long spindle times in machining, and significant material waste in the production of machining chips. Layer-additive technologies can be considered “green manufacturing” in that the amount of energy and material used to develop a final part are considerably less with additive manufacturing as compared to conventional approaches. Layer additive technologies also offer significant reduction in lead time, cost, and waste (in the form of few machining chips and less “toxic waste” from the cutting fluids).[4]

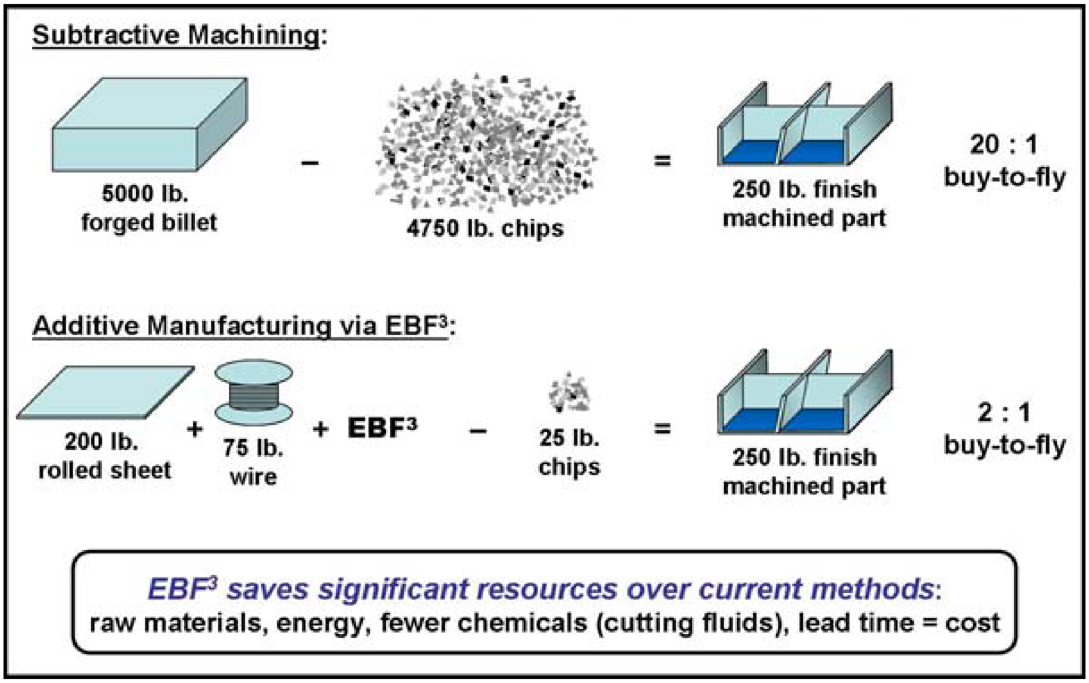


Figure 6.3-1: Comparison of Traditional Machining Versus Additive Manufacturing.[4]

The first use of large-scale metal deposition for aerospace components will occur in non-critical components as a direct replacement of a conventional component. The deposited material will be used to reduce the amount of material machined away by the addition of features (bosses, flanges, ribs, and other asperities) onto a simplified perform. Direct replacement of existing parts will be using existing materials, thus, the material properties of deposited material onto forging/casting must match or exceed specifications for that part. This application will require equivalent chemistry, properties, and no voids. The driving force for the change from conventional to deposited materials is significant reduction in cost and lead time.[4]

As deposited material becomes certified for use in flight hardware, certifying organizations and aircraft designers will become more familiar and more comfortable with additive manufacturing. Gradually, over the next 5–10 years, it can be expected that designers will begin exploring additional uses of metal deposition to build entire parts with additive manufacturing. This will also facilitate designing parts that are not fabricable using traditional methods, taking advantage of the flexibility and complexity of additive manufacturing. This step will require improvements in fabrication process control of the chemistry, properties, and geometry as compared to present day products. The primary driving factor will still be reduction in cost and lead time.[4]

Before the AM process can be routinely used for the manufacture of parts for aerospace, specifications are needed that provide mechanical properties data for available materials,[5] as well as more detail on how parts made from these materials perform.[4] This will require materials characterization as well as materials development and an understanding of the processing-structure-property relationships, areas in which NASA Langley researchers excel.

6.3.1. Langley's Engagement in Additive Manufacturing: Electron Beam Freeform Fabrication (EBF3)

Over the past several years NASA Langley Research Center (LaRC) has been developing electron beam freeform fabrication (EBF^3) for the manufacture of near-net-shape and net-shape metallic components.[6,7,8,9,10,11] EBF^3 offers the potential for efficient, streamlined manufacturing of intricate components due to its ability to directly deposit material to only the regions where it is needed. A wide variety of markets are interested in this direct deposition technology which can improve the materials usage efficiency by eliminating the need for machining large quantities of material from wrought blocks and forgings or the fabrication of highly-detailed molds for castings.

NASA Langley has two EBF^3 systems.[12] The large ground based system is shown in **Figure 6.3-2**, and the primary components of the system are shown in **Figure 6.3-3**. The system uses a high-power electron beam gun in a vacuum environment. The feedstock wire is fed from a spool through the wire feed mechanism. The gun and wire feed are mounted onto a gantry with the capability of translating back and forth along one axis, up and down along the vertical axis, and tilting. The substrate is supported on a table that travels in the transverse direction and has the capability to rotate and tilt. The system is housed within a vacuum chamber with approximate dimensions of 9ft × 7 ft × 9 ft.

The EBF^3 system can be operated manually or via computer code to control the electron beam, wire feed, and translation/rotation parameters to build the desired geometric shapes. During operation, the tip of the wire feed nozzle is brought into close proximity to the substrate. The electron beam forms a small molten pool in the substrate. The wire is fed into the beam and the molten pool, thus depositing material at that location. As the electron beam moves away due to the substrate/gun translation the molten pool rapidly solidifies. Detailed discussions of the EBF^3 process and this particular system can be found in references 6 and 7.

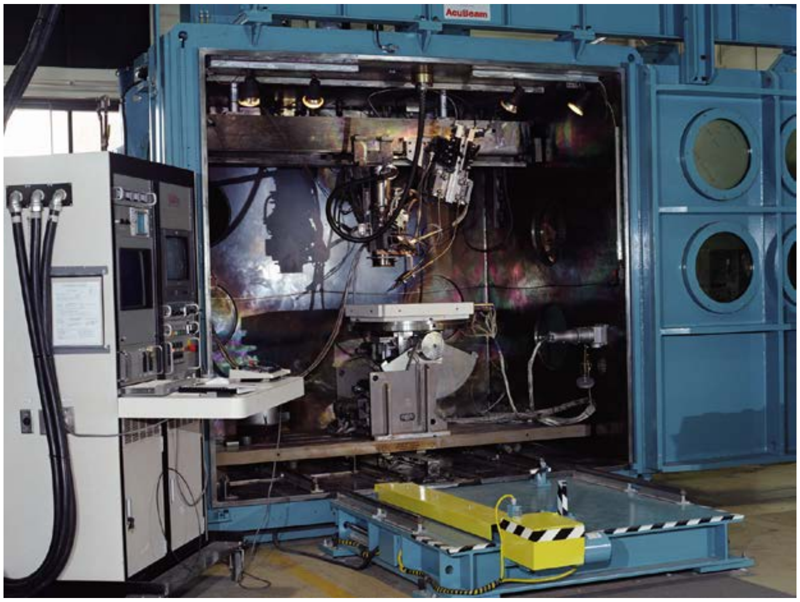


Figure 6.3-2: Ground-Based EBF³ System at NASA Langley Research Center.

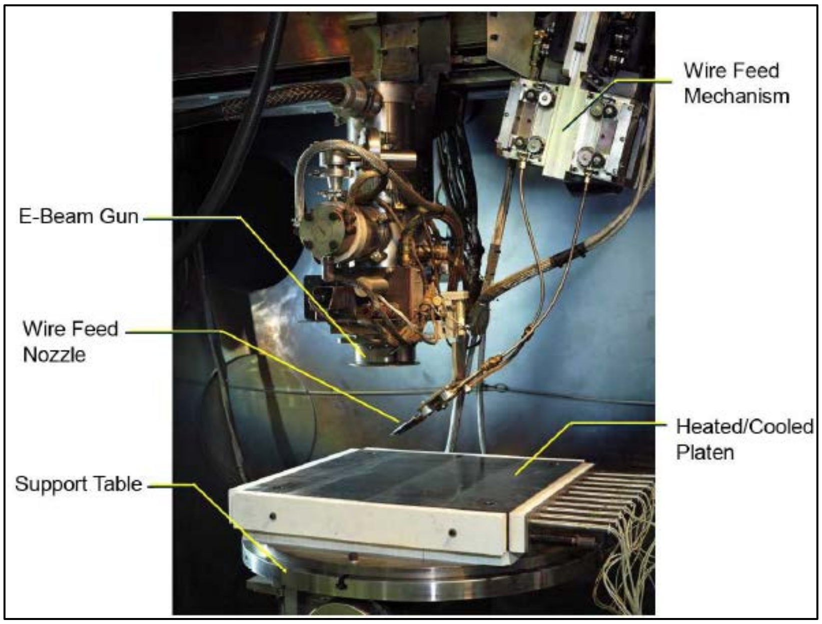


Figure 6.3-3: Electron Beam Freeform Fabrication System.

The EBF³ process offers promise for fabrication of a variety of parts. **Figure 6.3-4** shows photographs of several parts fabricated at NASA Langley using 2219 aluminum and Ti-6-4 that demonstrate the ability to program and control the process, produce parts with complex shape transitions, fabricate parts with unsupported overhangs without tilting the table, and the ability to control the process with varied wire feed angles into the molten pool. The parts include a variety of different nozzle shapes, airfoils, attachment nodes, and a wind tunnel model. All of these parts have been built near-net shape, and require a final machining primarily to achieve the desired surface finish. Examples of some of the parts fabricated using EBF³ have demonstrated acceptable machinability and were machined using the same CAD data to fabricate the component with the EBF^3 process.

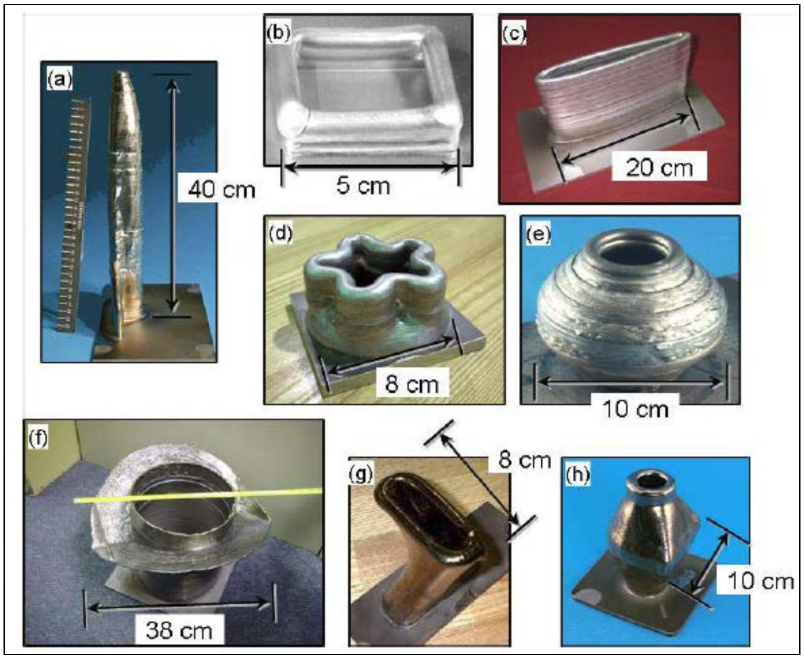


Figure 6.3-4: Examples of parts fabricated at NASA Langley using the EBF3 Process; (a) Ti-6-4 Wind Tunnel Model; (b) 2219 Al Square Box; (c) 2219 Al Airfoil; (d) 2219 Al Mixer Nozzle; (e) 2219 Al Converging Diverging Nozzle; (f) Ti-6-4 Guy Wire Fitting; (g) Ti-6-4 Inlet Duct; (h) Ti-6-4 Truss Node with flat attachment surface.

Langley also built a portable EBF^3 system (**Figure 6.3-5**). This system is comprised of a small vacuum chamber– fixed low-power electron beam gun, four-axis motion control system on the table (X, Y, Z, and rotation), single wire feeder, and data acquisition and control system.[13]

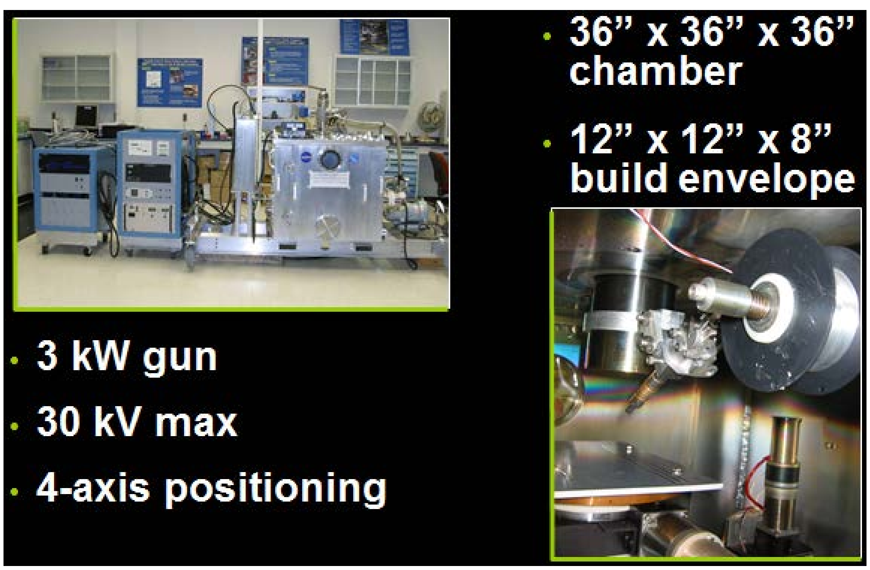


Figure 6.3-5: Portable EBF^3 System at NASA Langley Research Center.

This second EBF^3 system is housed within a 1 m (38 in) cubed vacuum chamber with the ability to fabricate a component 30 cm × 30 cm × 15 cm (12 in × 12 in × 6 in) in size. This system is designed for portability so that it can be used in a variety of different locations. It has been successfully demonstrated in flight on an aircraft as well as on the ground in the laboratory. This system is well-suited for fabrication of smaller parts with intricate details due to the finer wire diameters that can be fed as well as higher precision on the positioning system as compared to the large ground-based system. A prototype of the portable system has been flight tested in a near zero gravity environment, aboard JSC's C-9 aircraft (**Figure 6.3-6** and **Figure** 6.3-7). Although the near zero gravity environment was only 15 to 20 seconds, it was sufficient to collect meaningful data on the process. However, considerable further optimization is required for space-flight hardware.

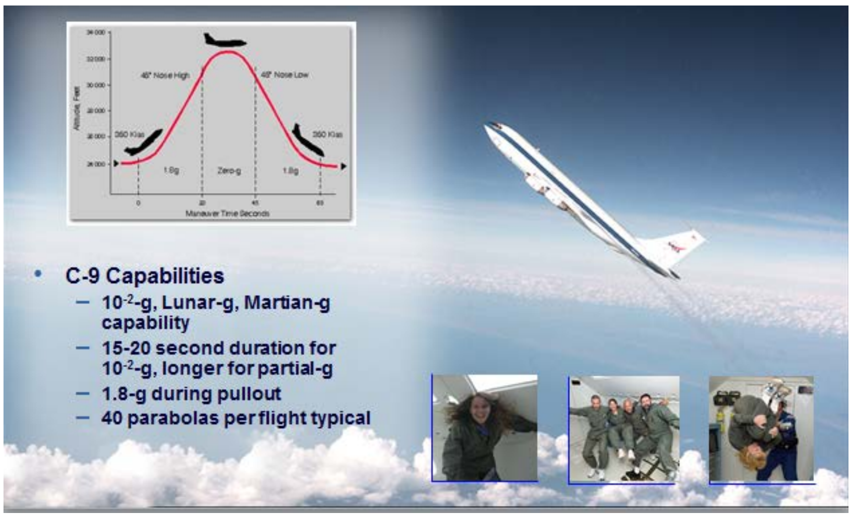


Figure 6.3-6: Microgravity Testing aboard JSC's C-9 Aircraft.

Figure 6.3-7: Testing the EBF^3 Portable System Aboard the NASA JSC C-9 Aircraft.

The possible evolution to a viable space based system has been envisioned by Karen Taminger and her team, and a notional sizing is depicted in **Figure 6.3-8**.

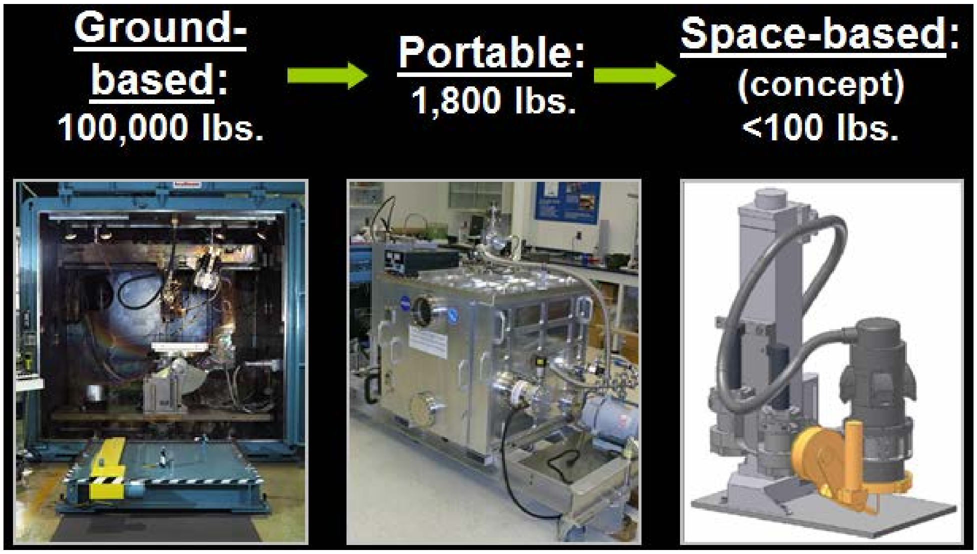


Figure 6.3-8: System Evolution.

Additive manufacturing is a fruitful area of research, and very significant strides are being made to advance this technology to both reduce the cost of space structures and make possible the manufacture of complex parts at a lower cost than machining.

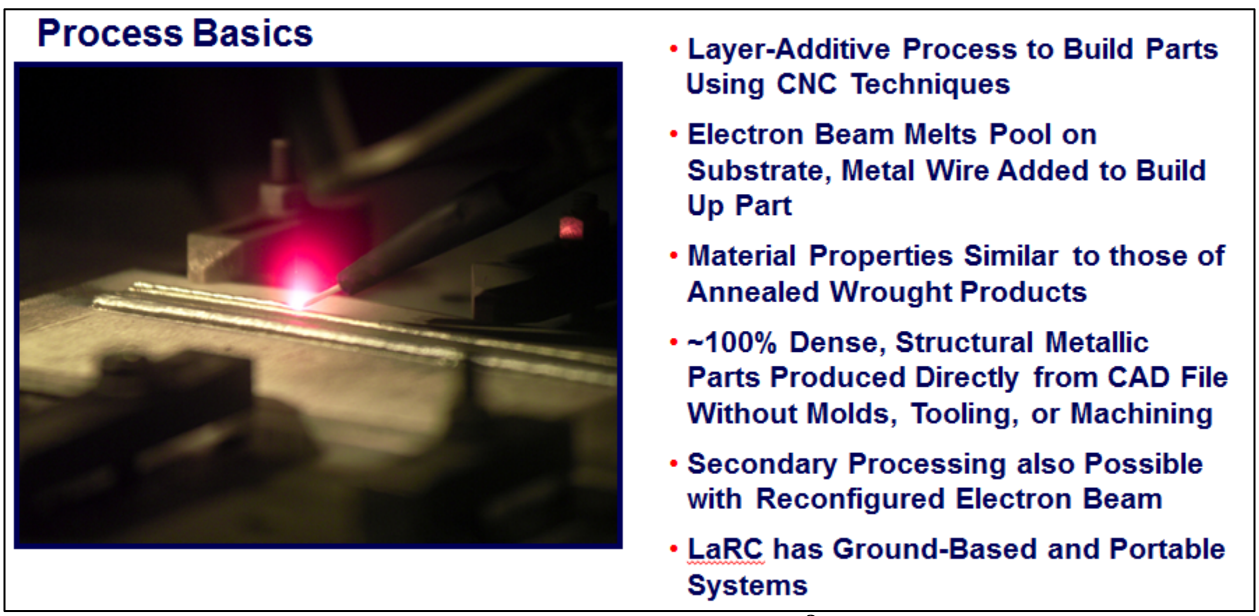


Figure 6.3-9: Electron Beam Freeform Fabrication (EBF^3) Process Developed at NASA Langley

The EBF^3 process basics, attributes, and benefits are shown in **Figure 6.3-9**, and the team at Langley is shown in **Figure 6.3-10**. The Langley team has explored EBF^3 for use with a variety of alloys.

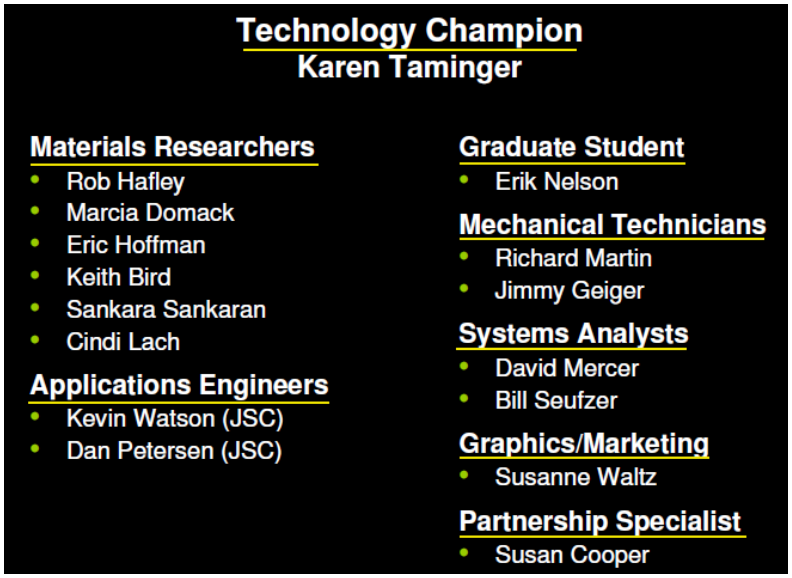


Figure 6.3-10: Electron Beam Freeform Fabrication (EBF^3) In-house Development Team.

EBF deposits of 2219 aluminum and Ti-6Al-4V have exhibited a range of grain morphologies depending upon the deposition parameters. These materials have exhibited excellent tensile properties[14] comparable to typical handbook data for wrought plate product after post-processing heat treatments. **Figure 6.3-11** shows the ultimate tensile strength, 0.2% offset yield strength, and total elongation to failure for EBF^3 2219 Al deposits as compared to typical handbook data for sheet and plate products.[15] The data for the as-deposited 2219 Al were averaged over duplicate tests for seven combinations of beam powers, translation speeds, and wire feed rates. Despite the wide range of processing conditions, the majority of the deposited 2219 Al fell between those for 2219 Al sheet and plate in the annealed (O temper) and solutionized and naturally aged (T4 temper) tempers. This is as expected considering the thermal history the layer additive processes experience. The 2219 Al deposits in the T62 temper also had very little scatter and were equivalent to typical T62 handbook properties for sheet and plate product.[15] As with the 2219 Al, the Ti-6-4 exhibits tensile properties comparable to those of annealed wrought product,[16] as shown in **Figure 6.3-12**.

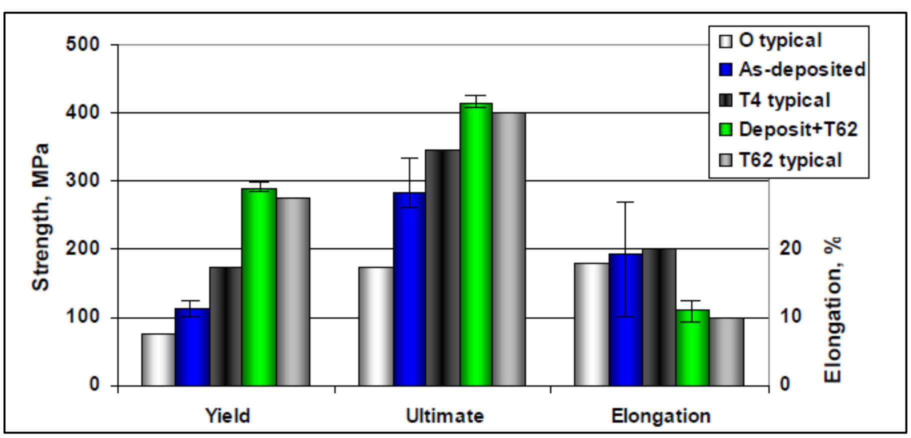


Figure 6.3-11: Tensile Properties at Room Temperature of EBF3 deposited 2219 Al as Compared to Typical Handbook Values for 2219 Al Sheet and Plate.

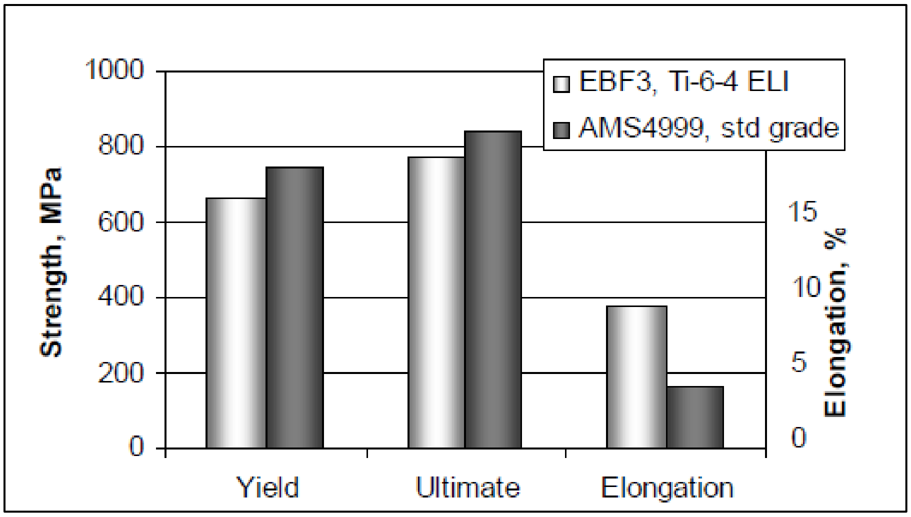


Figure 6.3-12: Tensile properties at room temperature of EBF^3 deposited Ti-6-4 ELI as compared to AMS 4999 Ti-6Al-4V minimum specification (Standard Grade Ti-6-4).

For both the 2219 Al and the Ti-6-4, it has been demonstrated that controlling the heat input through careful selection of the translation speed, wire feed rate, and beam power can influence the microstructure that is developed in the deposited material.[17, 18] Finer grained, equiaxed microstructures are obtained at the lower heat input conditions, which typically correspond to narrower deposits and lower deposition rates. Larger grains, including epitaxial growth from the baseplate in the Ti-6-4 and pervasive dendritic microstructures within the 2219 Al grains and in the interpass regions, develop during builds in which the heat inputs tend to be higher to achieve higher deposition rates. This demonstrates that there is a tradeoff between high deposition rates and fine-grained microstructures. However, examination of the tensile strengths of the EBF^3 deposited materials shows that, for 2219 Al and Ti-6-4, the tensile properties are not statistically affected by the variations within the microstructures obtained during higher versus lower heat input processing conditions. Furthermore, after post-deposition heat treatments, the tensile properties exhibit an even tighter range in the data than observed in the as-deposited condition. Thus, the range in microstructures documented for 2219 Al and Ti-6-4 appears to be small enough that it does not have a significant impact on the bulk tensile properties of the EBF3 deposited materials.

In a more recent study of the metallurgical mechanisms controlling mechanical properties in EBF^3 deposited 2219, Domack and Taminger[19] found that tensile mechanical properties for both as-deposited and T6 temper deposits were in good agreement with published values for wrought products and were constant regardless of deposition parameters. The width of the deposits was controlled by translation speed and the thickness of individual layers by deposition rate. Microstructures of the as-deposited materials were similar for the deposition parameters, exhibiting grains with internal solidification structures with grain refinement at interlayer boundaries. Microstructural refinement occurred during deposition of subsequent layers. Fracture of as-deposited material occurred by low ductility trans-granular fracture along dendrite boundaries and through the refined grains. Heat treatment to T6 temper transformed and refined the dendritic structure and homogenized constituent distribution. Fracture of T6 temper deposits occurred by trans-granular ductile rupture uniformly through the grain structure with limited fracture through refined grains.

The EBF^3 process is capable of bulk metal deposition at deposition rates in excess of 2500 cm^3/hr or finer detail at lower deposition rates, depending upon the desired application. This process offers the potential for rapidly adding structural details to simpler cast or forged structures rather than the conventional approach of machining large volumes of chips to produce a monolithic metallic structure. Selective addition of metal onto simpler blanks of material can have a significant effect on lead time reduction and lower material and machining costs.[14] Examples of parts manufactured by this process at NASA Langley are shown in **Figure 6.3-4.** Even with material test data, the predictive behavior of the types of structures additive manufacturing can build, such as trussed airfoils (**Figure 6.3-13**) is difficult to analyze.[2]

In the future, designs will eventually progress to solid-freeform-fabrication-enabled concepts. New alloys will have to be developed that are specifically designed for additive manufacturing processes. New structures will also be designed that take advantage of the ability to locally-tailor complex shapes, microstructures and chemistries through functional gradients. Additive manufacturing also enables embedded multifunctionality and larger-scale component fabrication (unitized structures). The driving force for these developments will go beyond environmentally friendly, rapid, and lower cost and be driven more by performance enhancements and reduction in weight.[4]

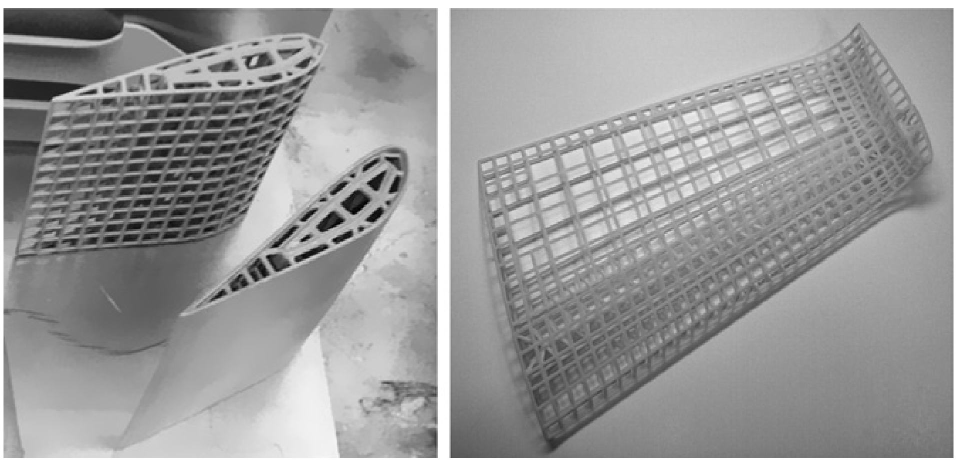


Figure 6.3-13: Two Complex Trusses Suggest the Difficulty of Predictive Analysis.[2]

6.3.2. Additive Manufacturing with Light Alloys

The aerospace industry has a need for high-strength aluminum components that are suitable for lightweight construction and, at the same time, meet the requirements for structural durability and corrosion resistance. The primary objective when qualifying a material for selective laser manufacturing (SLM) is to obtain a component density approaching 100% without any cracks, fusion defects or pores. This involves evaluating the process parameters, especially scanning velocity and laser output power, required to produce components with a density approaching 100 percent.

AlMgScZr (Scalmalloy®) is an innovative new alloy that combines the good corrosion resistance and welding properties of Al-Mg alloys with the increased strength offered by precipitation hardening (Al_3Sc(+Zr) phase). The higher strength of this material is the result of rapid cooling from the molten state. Previous studies demonstrate the viability of melt spinning in this context (cooling rate 104 to 106 K/s). It has been typically applied to extruded parts.

Using SLM with the same range of cooling rates will enable the manufacture of complex 3-D parts with increased strength, a task that was previously not possible.

Recent work has been performed in Europe on Selective Laser Sintering[20] $AlSi_{10}Mg$ and AlSi9Cu3 and with an innovative new alloy (Scalmalloy®) AlMgScZr.[21] Initial results indicate that very high strengths can be achieved (~500 MPa), accompanied by high elongations at rupture (~20 percent). Compared with SLM components made of $AlSi_{10}Mg$, the yield strength Rp 0.2 is ~200% higher and the elongation at rupture ~400% higher. Aerospace components are frequently subjected to dynamic loads, which are currently being tested in an exhaustive series of fatigue tests. Initial results indicate that test specimens made of AlMgScZr possess greater dynamic strength than components made of AlSi10Mg.

6.3.3. SBIR/STTR: H5 Lightweight Structures and Materials

It should be noted that in 2014, the NASA SBIR Phase I Solicitation “H5 Lightweight Spacecraft Materials and Structures” was focused on

- additive manufacturing of lightweight metallic structures;
- deployable structures;.
- advanced fabrication and manufacturing of polymer matrix composite (PMC) structures;
- hot structures.

The H5.01 subtopic was titled “Additive Manufacturing of Lightweight Metallic Structures.” The lead center was LaRC, and participating center(s) were GRC, JSC, and MSFC. The stated objective of this subtopic was to advance technology readiness levels of lightweight metals and manufacturing techniques for launch vehicles and in-space applications resulting in structures having affordable, reliable, and predictable performance with reduced costs. Technologies developed under this subtopic were of interest to NASA programs such as space launch system, multi-purpose crew vehicle, Orion, and commercial launch providers.

One Phase I proposal was awarded under this subtopic H5.01 entitled “New methods of In-Situ Metrology and Process Control for EBF^3 Additive Manufacturing.” There was also a Phase II proposal 14-2 H5.01-9602 that was awarded to COSM Advanced Manufacturing Systems, LLC entitled “New methods of In-Situ Metrology and Process Control for EBF3 Additive Manufacturing.” COSM has a research license on NASA’s EBF^3 technology and is developing a sensor system that can image and measure temperatures in real time, enabling process control and possibly inspection. The initial focus of this effort is an investigation into beam and sensor characteristics for geometric analysis of the deposition. Signals derived from the electron beam-component interaction could offer spatially resolved dimensional information about the deposited material, as it is being deposited. This is important because the ability to monitor a parameter during deposition creates the possibility of controlling that parameter during the deposition process. As a further refinement, the ability to collect and store a spatially resolved pass-by-pass map of the deposition path geometry may have value in on-the-fly adjustments to subsequent build passes. Such mapping would allow working with the layer-by-layer nature of the deposition process to fine tune the deposition geometry. Such spatially resolved, layer-by-layer deposition mapping could also be stored, giving a three dimensional mapping of the as-built deposition path geometry. This could prove valuable for component quality assurance. Great progress is being made on these efforts.

H5 Subtopics were also included in the 2015 solicitation. In 2016, the additive manufacturing of lightweight metallic structures research thrust was moved to Z3.02.

References

[1] Ian D. Harris; “Development and Implementation of Metals Additive Manufacturing,” ewi.org/eto/wp-content/.../Additive-Manufacturing-DOT-Paper-2011.pdf.

[2] Brett Lyons; “Additive Manufacturing in Aerospace – Examples and Research Outlook,” The Bridge, National Academy of Engineering, Spring 2012, pp. 13–19.

[3] Justin Scott, Nayanee Gupta, Christopher Weber, Sherrica Newsome, Terry Wohlers, and Tim Caffrey; “Additive Manufacturing: Status and Opportunities,” IDA, Science and Technology Policy Institute, March 2012.

[4] Karen M. Taminger; “Additive Manufacturing Application in Aerospace Components,” White Paper presented at the Workshop on Roadmap for Additive Manufacturing – Identifying the Future for Freeform Processing, Edited by David L. Bourell, Ming C. Leu and David W. Rosen, University of Texas at Austin, 2009.

[5] April Cooke and John Slotwinski; “Properties of Metal Powders for Additive Manufacturing: A Refiew of the State of the Art of Metal Powder Property Testing”, NISTIR 7873, National Institute of Standards and Technology, July 2012.

[6] Taminger, Karen and Hafley, Robert; “Electron Beam Freeform Fabrication: A Rapid Metal Deposition Process”, Proceedings of the 3rd Annual Automotive Composites Conference, September 9-10, 2003, Troy, MI. Society of Plastics Engineers (2003).

[7] Taminger, Karen and Hafley, Robert; “Electron Beam Freeform Fabrication (EBF 3) for Cost Effective Near-Net Shape Manufacturing”, NASA Technical Memorandum TM-2006-214284, March 2006.

[8] Watson, J. Kevin; Petersen, Daniel D.; Taminger, Karen M.; Hafley, Robert A.; “Portable Electron-Beam Free-Form Fabrication System”, NASA Tech Brief MSC-23518, August 2005.

[9] Taminger, Karen M. B.; Hafley, Robert A.; Dicus, Dennis L.; “Solid Freeform Fabrication: An Enabling Technology for Future Space Missions”, 2002 International Conference on Metal Powder Deposition for Rapid Manufacturing; 8-10 Apr. 2002; San Antonio, TX; United States.

[10] Wallace, Terryl A.; Bey, Kim S.; Taminger, Karen M. B.; Hafley, Robert A.; “A Design of Experiments Approach Defining the Relationships Between Processing and Microstructure for Ti-6Al-4V”, Conference Paper, 15th Solid Freeform Fabrication Symposium; 2-4 Aug. 2004; Austin, TX; United States.

[11] Dorsey, John T.; Doggett, William R.; Hafley, Robert A.; Komendera, Erik; Correll, Nikolaus; King, Bruce; “An Efficient and Versatile Means for Assembling and Manufacturing Systems in Space”, Conference Paper NF1676L-14055, AIAA Space 2012 Conference and Exposition; 11-13 Sep. 2012; Pasadena, CA; United States.

[12] Taminger,Karen M. and Hafley,Robert A.; “Electron Beam Freeform Fabrication for Cost Effective Near-Net Shape Manufacturing”, NATO/RTOAVT-139 Specialist' Meeting on Cost Effective Manufacture via Net Shape Processing, Amsterdam, Netherlands, 2006.

[13] Watson, J.K., Taminger, K.M.B., Hafley, R.A., and Petersen, D.D.; "Development of a Prototype Electron Beam Freeform Fabrication System," Proceedings of 13th SFF Symposium, 458–465, (2002).
[14] Karen M. Taminger and Robert A. Hafley; "Electron Beam Freeform Fabrication for Cost Effective Near-Net Shape Manufacturing", NATO R&T Organization, AVT-139, pp. 16-1–16-10.
[15] Mayer, L.W.; Alcoa Green Letter: Alcoa Aluminium Alloy 2219, Aluminium Company of America, New Kensington, PA, (1967).
[16] McLellan, M.T.; Ti-6Al-4V, Code 3707, Aerospace Structural Metals Handbook, (2002), vol. 4, pp. 1–67.
[17] Taminger, K.M.B. and Hafley, R.A.; "Characterization of 2219 Aluminium Produced by Electron Beam Freeform Fabrication", Proceedings of 13th SFF Symposium, 482–489, (2002).
[18] Taminger, K.M.B., Hafley, R.A., Fahringer, D.T., and Martin, R.E.; "Effect of Surface Treatments on Electron Beam Freeform Fabricated Aluminium Structures", Proceedings of 15th SFF Symposium, (2004).
[19] Domack, M. and Taminger, K.M.; "Metallurgical Mechanisms Controlling Mechanical Properties of Aluminum Alloy 2219 Produced by Electron Beam Freeform Fabrication",
[20] Kempen,K.,Thijs,L.,Yasa,E.,Badrossamay,M.,Verheecke, W., and Kruth, J. P.; "Process Optimization and Microstructural Analyses for Selective Laser Melting of AlSi10Mg", NASA/TM-2006-214316; L-19265. https://lirias.kuleuven.be/bitstream/123456789/314136/1/A22KempenFINAL.pdf.
[21]http://www.generativ.fraunhofer.de/content/dam/rapidprototyping/en/documents/euromold/szenario1/1_slm_aluminum_highstrength_ilt.pdf.

6.4. National Network for Manufacturing Innovation (NNMI)

President Obama has proposed building a National Network for Manufacturing Innovation (NNMI), consisting of regional hubs that will accelerate development and adoption of cutting-edge manufacturing technologies for making new, globally competitive products. Individually and together, these regional hubs—public-private partnerships called Institutes for Manufacturing Innovation (IMI)—will help to strengthen the competitiveness of existing U.S. manufacturers, initiate new ventures, and boost local and state economies. The Federal investment in the NNMI serves to create an effective manufacturing research infrastructure for U.S. industry and academia to solve industry-relevant problems. The NNMI will consist of linked IMIs with common goals, but unique concentrations. In an IMI, industry, academia, and government partners leverage existing resources, collaborate, and co-invest to nurture manufacturing innovation and accelerate commercialization.

As sustainable manufacturing innovation hubs, IMIs will create, showcase, and deploy new capabilities, new products, and new processes that can impact commercial production. They will build workforce skills at all levels and enhance manufacturing capabilities in companies large and small. Institutes will draw together the best talents and capabilities from all the partners to build the proving grounds where innovations flourish and to help advance American domestic manufacturing.

The President unveiled his plan for the National Additive Manufacturing Innovation Institute (NNMII) in March 2012. In his 2013 State of the Union Address, the President renewed his call for creating a full-fledged nationwide network devoted to innovating and scaling up advanced manufacturing technologies and processes. He has asked Congress to authorize a one-time $1 billion investment—to be matched by private and other non-federal funds—to create a network of up to 15 IMIs.[1]

The competitively selected NAMII was launched in August 2012. NAMII was established with an initial federal investment of $30 million, using existing authorities in the Departments of Defense and Energy and other federal agencies. NAMII, a consortium that includes manufacturing firms, universities, community colleges, and non-profit organizations from the Ohio-Pennsylvania-West Virginia "Tech Belt," is led by the non-profit National Center for Defense Manufacturing and Machining. The NAMII partners more than matched the federal investment, contributing almost $40 million in support.

The focus of the National Additive Manufacturing Innovation Institute, as stated in October 2013, was to accelerate additive manufacturing technologies to the U.S. manufacturing sector and increase domestic manufacturing competitiveness.[2] Steps to be taken included

- fostering a highly collaborative infrastructure for the open exchange of additive manufacturing information and research;
- facilitating the development, evaluation, and deployment of efficient and flexible additive manufacturing technologies;
- engaging with educational institutions and companies to supply education and training in additive manufacturing technologies to create an adaptive, leading workforce
- serving as a national institute with regional and national impact on additive manufacturing capabilities
- linking and integrating U.S. companies with existing public, private or not-for-profit industrial and economic development resources, and business incubators, with an emphasis on assisting small- and medium-sized enterprises and early-stage companies (start-ups).

The interagency Advanced Manufacturing National Program Office (AMNPO) conducted a nationwide "crowd sourcing" effort to gather stakeholder ideas and suggestions. The outreach effort consisted of regional workshops for stakeholders and a formal request for information. The AMNPO analyzed the input received from nearly 900 organizations, and individuals distilled their ideas and recommendations into "National Network for Manufacturing Innovation: A Preliminary Design," a report[3] issued by the White House National Science and Technology Council on January 16, 2013.

References

[1] http://www.manufacturing.gov/nnmi.html
[2] http://www.manufacturing.gov/nnmi_pilot_institute.html
[3] http://www.manufacturing.gov/docs/NNMI_prelim_design.pdf.

6.5. Materials Genome Initiative (MGI)

In June 2011, the President launched the Materials Genome Initiative[1] (MGI) alongside the Advanced Manufacturing Partnership to help businesses discover, develop, and deploy new materials twice as fast. The White House released a new white paper describing the initiative, Materials Genome Initiative for Global Competitiveness, produced by the Cabinet-level National Science and Technology Council. MGI aims to capitalize on recent breakthroughs in materials modeling, theory, and data mining to significantly accelerate discovery and deployment of advanced materials while decreasing their cost. At the heart of MGI is the Materials Innovation Infrastructure, a framework of seamlessly integrated advanced modeling, data, and experimental tools that will be used to attain the MGI vision. Going beyond tools and techniques, MGI aims to link together networks of scientists spanning academia, National and Federal laboratories and industry to more effectively share the information that underpins new material discovery and product development, and enables technological leaps.

NASA’s Materials Genome Initiative element is a multi-center effort within the Advanced Manufacturing Technology project, which is funded by the Game Changing Technology Program, managed by NASA Langley Research Center. NASA’s MGI element is consistent with the national Materials Genome Initiative. NASA’s effort is currently focused on developing computational materials tools to reduce the cost and time to develop and certify components manufactured using novel additive manufacturing processes for aerospace vehicles. Additive manufacturing allows for near-net-shape processing to reduce material waste and time and cost of traditional, subtractive, manufacturing.

NASA is developing physics-based computational models to predict the melt pool where powder or wire precursors are heated by a laser to form a solid component, the microstructural evolution, and material behavior. These tools will be used to develop basic understanding to optimize the manufacturing process and to guide the certification process. NASA Langley Research Center is generating a model to include melt pool convection and mixing, and developing in-situ test methods to validate this model. The Langley effort is focused on predicting the deposit shape (layer height and width), 3-D thermal history, residual stress, and distortion. Residual stress distribution maps are being developed for AM component to assist in mechanical testing configuration and component certification. 3-D thermal history results will be applied to commercial microstructural evolution models for microstructure prediction. The objective is to design alternative gradient microstructures that could be utilized to improve component behavior. Available nondestructive evaluation (NDE) methods are being studied to identify melt pool geometry and thermal gradients for selected deposition parameters. Langley’s effort also includes performing mechanical tests on AM material to determine constitutive relationships for microstructural/mechanical response.

References

[1] https://www.whitehouse.gov/sites/default/files/microsites/ostp/NSTC/mgi_strategic_plan_-_dec_2014.pdf

7. FABRICATION AND JOINING TECHNOLOGIES

In this section, we will examine NASA's role in the development and maturation of manufacturing technologies. This has been a focus of metals research at Langley for many years, going back to the early days of NACA, and is expected to remain a key focus for the future.

Langley has been engaged in fabrication of experimental test panels for flight-testing since the early 1920s. The test panel shown in **Figure 6.5-1** was fabricated in the NACA Langley shop in 1940–41. In many cases pioneering work was done in the fabrication of these types of test panels.

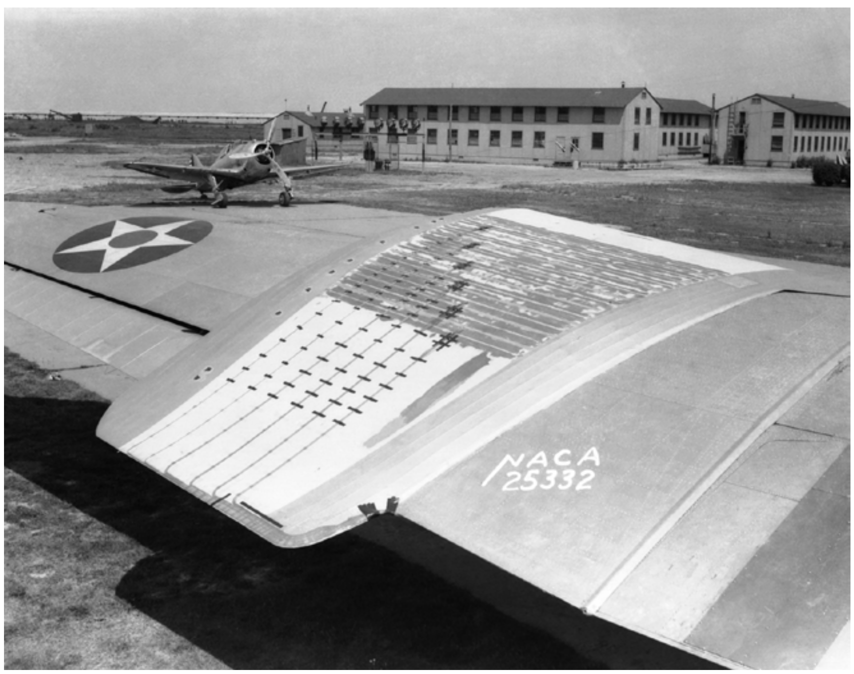


Figure 6.5-1: In the spring of 1941 Langley installed an experimental low-drag test panel on the wing of a Douglas B-18 airplane. The panel was fitted with suction slots and pressure tubes for a free flight investigation of the transition from laminar to turbulent flow in the boundary layer. The pressure at each tube was measured by liquid manometers installed in the fuselage. http://www.archive.org/details/GPN-2000-001244.

A major effort was devoted to the fabrication of lightweight structural panels as part of the Supersonic Cruise Aircraft Research Program. An example of the type of work performed was the fabrication of full-scale Borsic/aluminum-titanium honeycomb-core structural panels,[1] assembled by brazing and designed to meet the design requirements of an upper wing panel for the YF-12 aircraft. Test results obtained on an initial panel met the design requirements for bearing and shear stiffness and carried 93.2% of the design ultimate shear load. A second panel incorporating several design modifications complied with all the ambient temperature design requirements and carried 125% of design ultimate shear load. Additional panels were also fabricated for ground testing following exposure to a simulated supersonic transport environment and for flight service on Mach 3 YF-12 aircraft. The program[2] consisted of laboratory testing and Mach 3 flight service of full-scale structural panels and laboratory testing of representative structural element specimens. Borsic/aluminum honeycomb-core, titanium clad Borsic/aluminum skin-stringer, graphite/PMR-15 polyimide honeycomb-core, and titanium superplastically formed / diffusion bonded panels were designed, fabricated, and successfully tested.

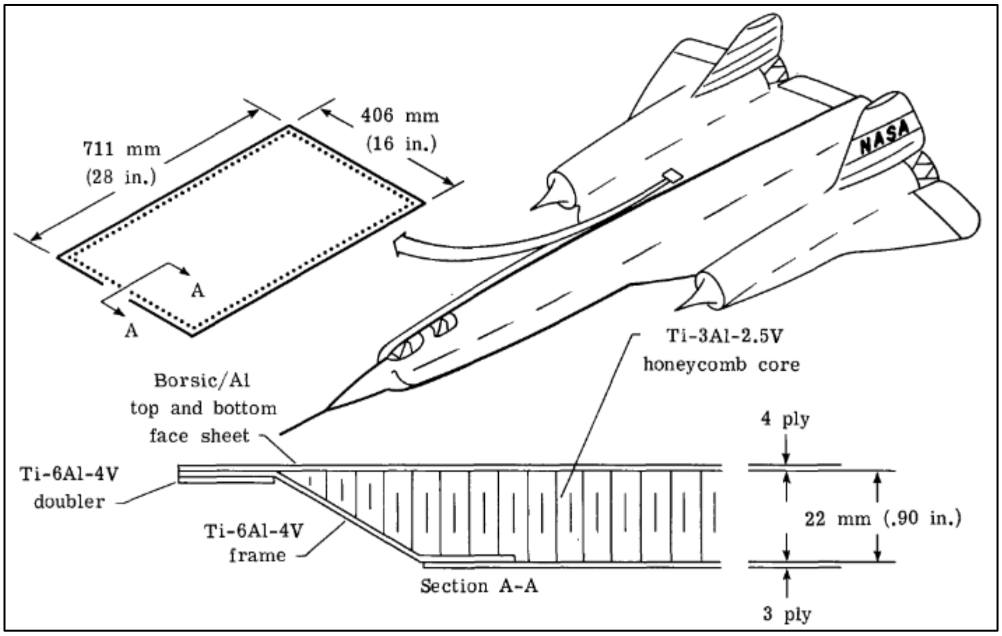


Figure 6.5-2: Bsc/Al-Ti Honeycomb-Core Panel Design for YF-12 Flight Experiment.

References

[1] Bales, T. T.; Wiant, H. R.; Royster, D. M.; “Brazed Borsic/Aluminum Structural Panels”, NASA-TM-X-3432, 1977.

[2] Hoffman, E. L.; Bales, T. T.; Payne, L.; “Fabrication Research for Supersonic Cruise Aircraft. (YF-12 Skin Structures)”, Conference Proceedings, The enigma of the eighties: Environment, economics, energy; Twenty-fourth National Symposium and Exhibition; 24th; May 8-10, 1979; San Francisco, CA, Published Jan. 01, 1979.

7.1. Superplastic Forming / Diffusion Bonding of Ti Alloys

SPF is a hot metal operation capable of making intricate parts in a single operation. Diffusion bonding is often incorporated between the two halves of a die and heating to a pre-determined temperature. Hot argon gas is then pumped into the die at the appropriate pressure to force the titanium to deform superplastically into the shape of the lower die. Superplastic forming requires material with a fine-grained (less than 10 µm, ASTM grain size 10), two-phase structure, typically alpha-beta alloys such as Ti6Al4V.

Superplastic forming gives the following benefits: (1) complex shapes in a single process, (2) reduced weight and cost, (3) shorter production lead times, (4) elimination of machinery operations, and (5) elimination of assembly operations.

Systems trade studies performed to guide development of superplastic forming / diffusion bonding (SPF/DB) research are shown in **Figure 7.1-1**. The baseline for this study was the weight of a typical skin-stiffened panel representative of aircraft structure considered state of the art in 1975. Weight savings projections for SPF/DB Ti sandwich was 25% and 54% reduction for SPF/DB two-sheet Ti core with SCS-2/Al face sheets. Systems trade studies were valuable for identifying the theoretical potential of different structural concepts and fabrication technologies to reduce the weight of advanced aircraft configurations.

7.1.1. Langley Superplastic Forming of Titanium

During the 1970s and 1980s Langley conducted research on superplastic forming of titanium alloys and investigated several different joining approaches. This work was led by Mr. Tom Bales with the help of Dick M. Royster and H. Ross Wiant. Results from the Langley work is documented in several publications.[1,2,3,4]

Research on metals processing was conducted at the Langley Research Center to develop improved forming and joining methods with the potential of reducing the weight and cost of future aerospace structures. The approach followed was to assess the state of the art for fabricating a given structural system, define candidate methods for improving processing, evaluate the merits of each, fabricate, and test subelement components, and then scale up the process to demonstrate validity.

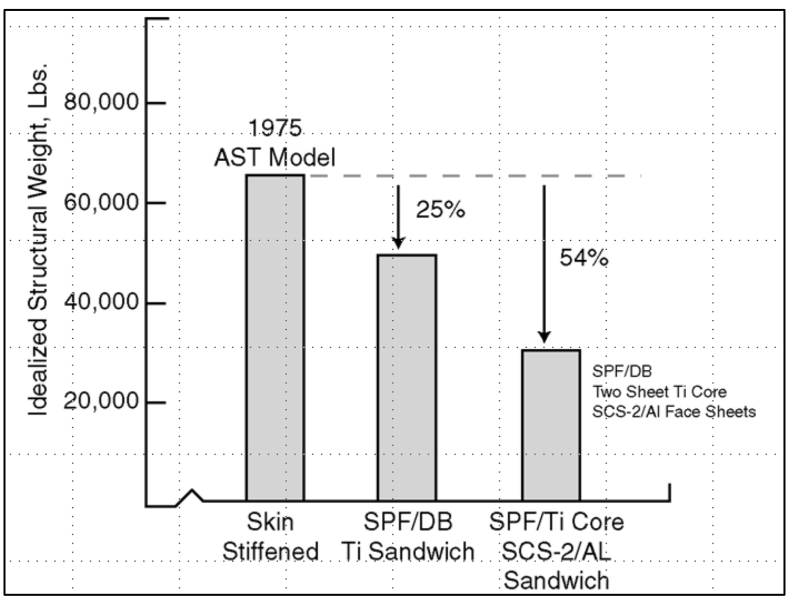


Figure 7.1-1: Idealized Weight Reduction Projected For Sandwich Concepts.

Much of the research was focused on the development of weldbrazing, superplastic forming, superplastic forming and co-diffusion bonding (SPF/DB), and superplastic forming and weldbrazing (SPF/WB) for titanium and the SPF of aluminum. While the technology was developed for aerospace applications, it was also applicable to non-aerospace industries.

Superplastic forming of titanium revolutionized the fabrication of many titanium components. An example of the superplastic behavior exhibited by titanium is depicted in **Figure 7.1-2** which shows a specimen as machined and following superplastic stretching. The as-machined specimen was heated to 1700°F in vacuum, loaded in tension to a stress of 2 ksi, and stretched to a total elongation of over 1000 percent. As shown, the specimen elongated uniformly without experiencing localized necking. Since the flow stress required for stretching is low, the use of gas pressure to blow form or superplastically form the material was developed. Early studies shows that titanium parts could be superplastically formed to exacting tolerances to eliminate the spring back and minimum bend radii problems encountered in conventional forming. Also, the high degree of formability permitted the fabrication of configurations not possible with conventional methods. These features have led to the fabrication of new design concepts having improved structural efficiency. Further work demonstrated that superplastically forming multiple parts in a large tool and a single operation resulted in cost savings of 70% compared to forming by conventional means.

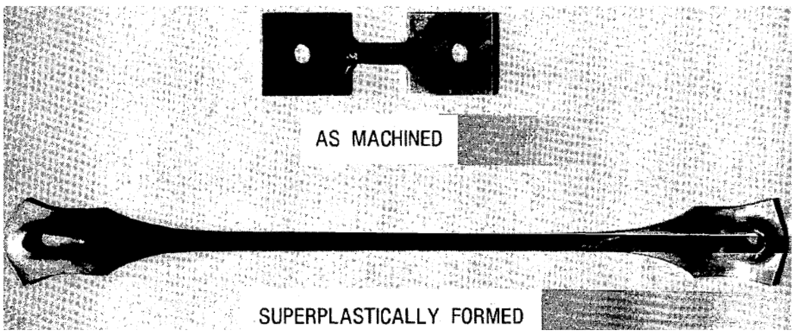


Figure 7.1-2:Titanium Heated to 1700°F, Loaded in Tension to a Stress of 2 ksi, and Stretched to a Total Elongation of Over 1000%.
http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19830003877_1983003877.pdf.

An example of a superplastically forming two sheet panel is illustrated in **Figure 7.1-3**.

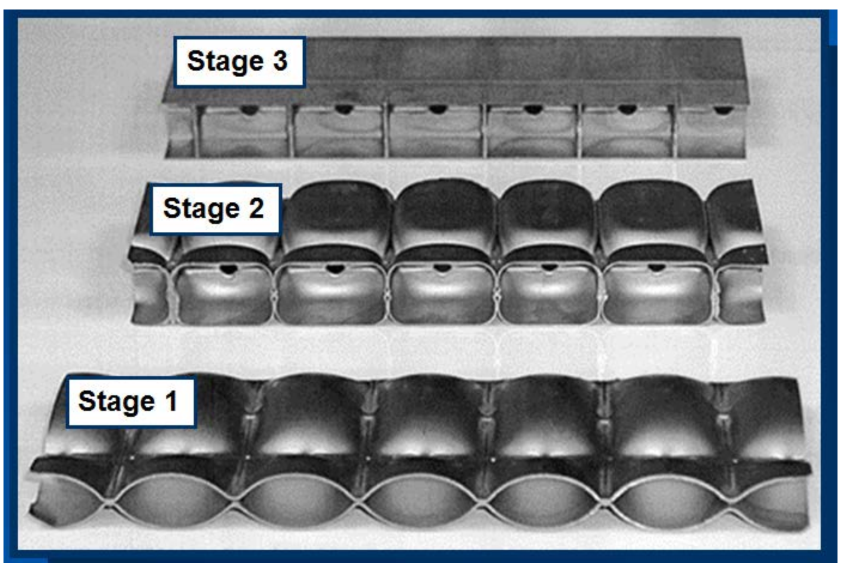


Figure 7.1-3: Three Stages of SPF Two sheet Ti Core.

The method for superplastically forming and co-diffusion bonding titanium sandwich structures using the selective application of stop-off material is schematically represented in **Figure 7.1-4**. In the first step, both sides of the center sheet are selectively coated with a ceramic stop-off material.

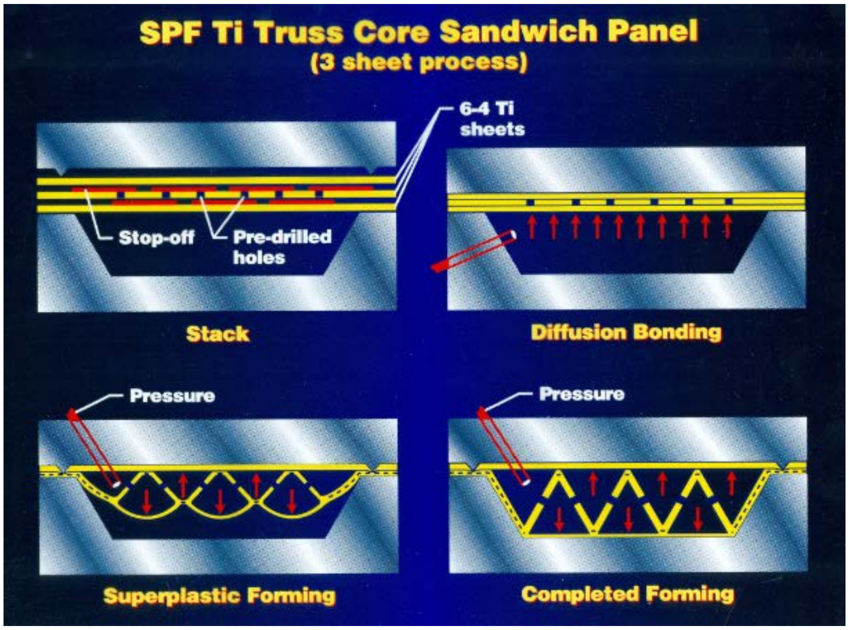


Figure 7.1-4: Ti Truss Core Sandwich Panel Fabrication Process.

The three sheets are then stacked and placed in the tool. The assembly is then positioned between resistance heated ceramic platens that are mounted in a press or loading device. Load is applied and a gas-tight seal is established between the tool and the three titanium sheets due to the pinching action of the projections machined on the upper tool. The cavity of the tool is then purged with argon gas and the assembly heated to 1700°F. Argon gas is then injected into the tool at a pressure of 300 psi to compress the three sheets against the flat side of the tool. Pressure is maintained for three hours to diffusion bond the titanium sheets together in the regions where stop-off was not applied. Gas pressure in the tool cavity is then released and inert gas is injected through the preplaced tubes into the stop-off material between the sheets. Once separation of the sheets occurs, the gas pressure is increased at a programmed rate to a pressure of 100 psi to superplastically form the outer sheets to the contour of the mold cavity. As the face sheets are separated by the gas pressure, the center core sheet is superplastically stretched to form the truss core configuration. Gas pressure is equalized within the sandwich during forming by means of pre-machined holes. Following SPF/DB the panel is chemically milled to remove surface contamination and to obtain the desired skin thicknesses. This process has been patented and has been used to fabricate a wide variety of large components. An example of a three-sheet superplastically formed titanium panel is shown in **Figure 7.1-5**.

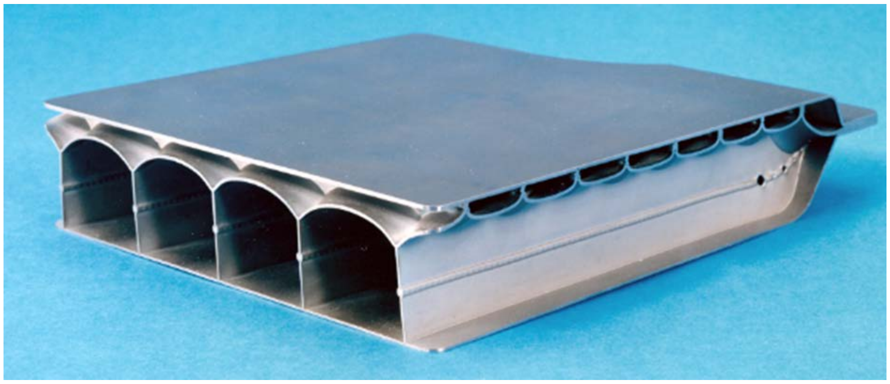


Figure 7.1-5: Three Sheet Super Plastic Forming of Titanium Alloys.

The process used to fabricate a four-sheet panel is illustrated in **Figure 7.1-6**.

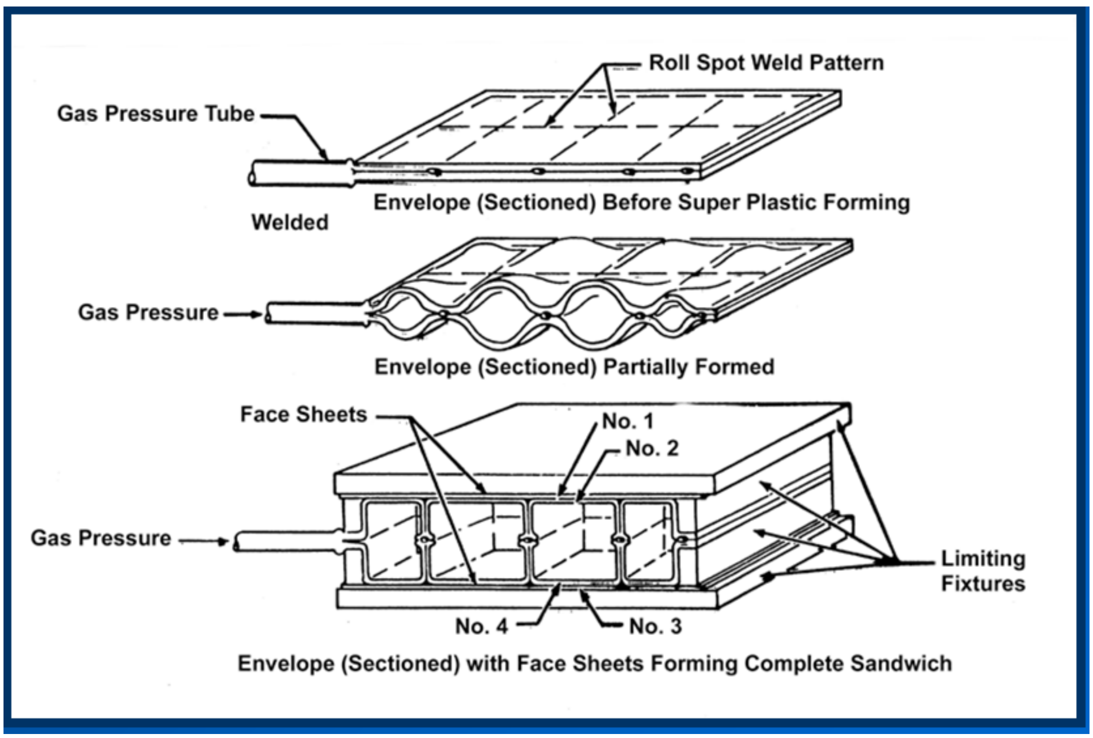


Figure 7.1-6: SPF/DB Titanium 4 Sheet Sandwich Fabrication.

Bales and coworkers also investigated a five-sheet fabrication approach to produce structural panels (**Figure 7.1-7**). High-quality panels were produced and excellent interchange with industry took place during this research program.

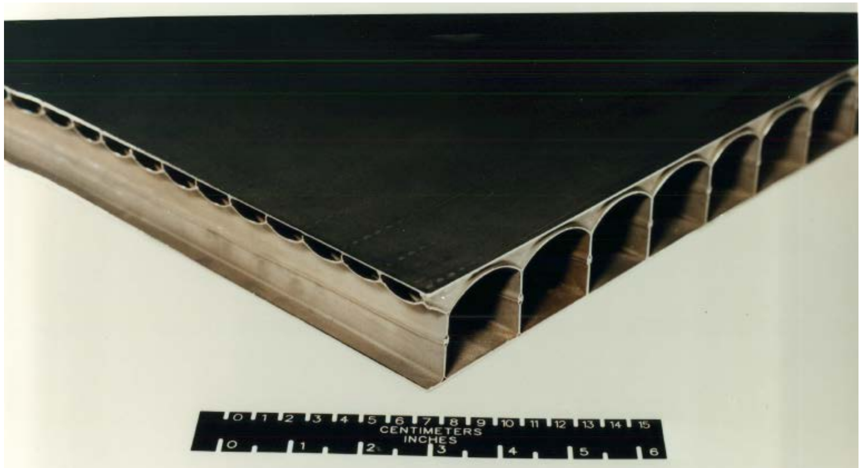


Figure 7.1-7: Core Configuration of Five Sheet SPF/DB Ti-6Al-4V Cross-Web Panel.

Another approach studied at Langley by Bales and coworkers employs spot welding to attach stiffeners to face sheets, as illustrated in **Figure 7.1-8**.

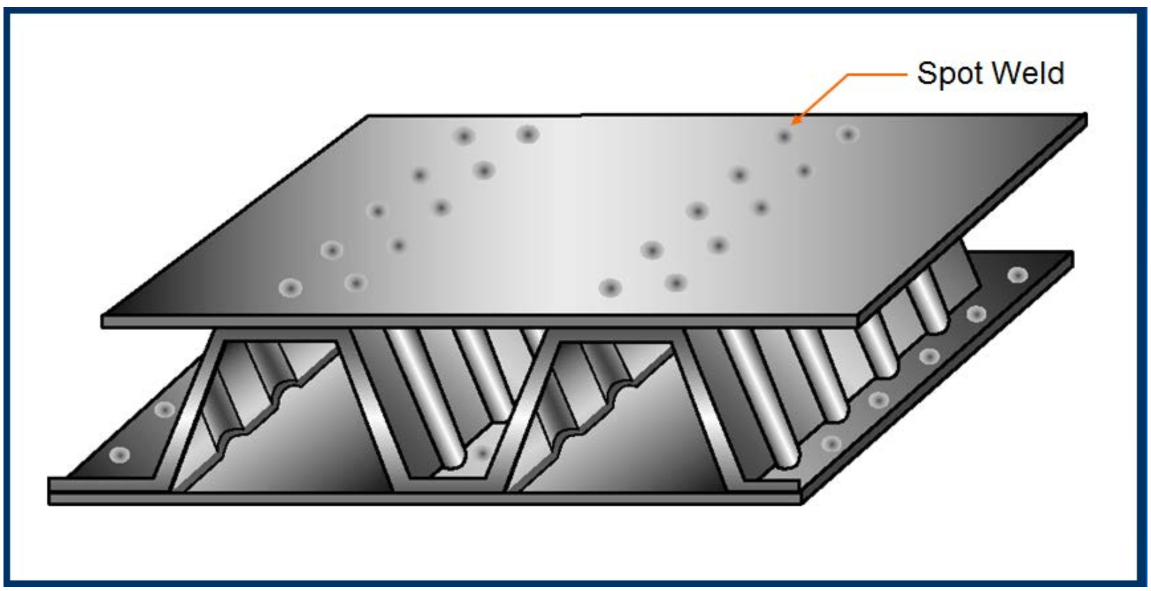


Figure 7.1-8: Weld-Bonded SPF Beaded Web Truss Core Sandwich.

Figure 7.1-9 shows an example of where superplastic forming-diffusion bonding was used to fabricate major sections of the fuselage structure[5] on an F-15E fighter aircraft. SPF/DB Ti-6Al-4V airframe structure has been used as a replacement for built-up assemblies used in earlier models. This has resulted in a dramatic part-count reduction and demonstrated the successful use of unitized construction in service.

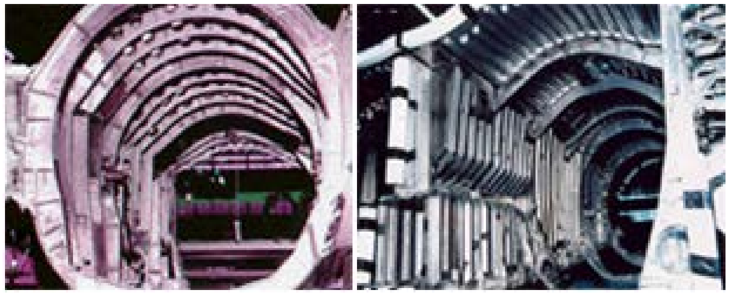


Figure 7.1-9:Superplastic Forming-Diffusion Bonding application on F-15E Fighter Aircraft.

An excellent review article summarizing many recent developments in special forming processes for lightweight components has been recently published by Lang Lihui,[6] et al.

7.1.2. Weld Brazing

Key weld brazing references to the Langley work [7,8,9,10,11,12,13,14]. Because weld brazing was discussed above it will not be covered in this section.

References

[1] Royster, Dick M.; Bales, Thomas T.; and Wiant, H. Ross; "Superplastic Forming/Weld-Brazing of Titanium Skin-Stiffened Compression Panels", Materials Overview for 1982, Volume 27 of National SAMPE Symposium a n d Exhibition, Soc. Advanced Mater. & Process Eng., 1982, pp. 569–582.

[2] Bales, Thomas T.; Royster, Dick M.; and Arnold, Winfrey E., Jr. "Development of the Weld-Braze Joining Process", NASA TN D-7281, 1973.

[3] Giles, Gary L.; "Structural Efficiency of Five Compression Panels with Curved Elements", NASA TN D-6479, 1971.

[4] Royster, Dick M.; Bales, Thomas T., Davis, Randall C.; "Superplastic forming/weld-brazing of Ti-6Al-4V panels for enhanced structural efficiency", International SAMPE Metals and Metals Processing Conference, Cherry Hill, NJ; Aug. 18-20, 1987, Published Jan 01, 1987.

[5] Martin, Rick and Evans, Daniel; "Reducing Costs in Aircraft: The Metals Affordability Initiative Consortium", Journal of Modeling 52, (3) (2000), pp. 24–28.

[6] Lihui, Lang, Kangning, Liu, Cai, Gaoshen, Yang, Xiying, Guo, Chan and Bu, Guoling; "A critical review on special forming processes and associated research for lightweight components based on sheet and tube material", Manufacturing Rev. 2014,1,9, 2014

[7] Royster, D. M.; Bales, T. T.; Davis, R. C.; "Evaluation of superplastic forming and weld-brazing for fabrication of titanium compression panels", In its Welding, Bonding and Fastening, 1984 p 253-270 (SEE N86-11227 02-23) , Sept. 01, 1985.

[8] Bales, T. T.; Royster, D. M.; Arnold, W. E., Jr; "Weld-brazing of titanium", SAMPE Quarterly, vol. 5, Apr. 1974, p. 28-–38.

[9] Bales, T. T.; Royster, D. M.; Arnold, W. E., Jr.; "Weld-brazing of titanium [resistance spot welding combined with brazing]", National Technical Conference; Kiamesha Lake, NY; October 9-11, 1973; 5th, Published Jan 01, 1973.

[10] Bales, T. T.; Royster, D. M.; Arnold, W. E., Jr.; "Weld-brazing - a new joining process [combination resistance spot welding and brazing of titanium alloys]", NASA Tech Brief, Dec 01, 1972.

[11] Royster, D. M.; Davis, R. C.; Shinn, J. M., Jr.; Bales, T. T.; Wiant, H. R.; "Fabrication and evaluation of superplastically formed/weld-brazed corrugated compression panels with beaded webs", NASA-TP-2512; L-15988; NAS 1.60:2512, 1973.

[12] : Royster, D. M.; Bales, T. T.; "Elevated temperature behavior of superplastically formed/weld-brazed titanium compression panels having advanced shaped stiffeners", NASA-TP-2123; L-15547; NAS 1.60:2123, March 01, 1983.

[13] Bales, T. T.; Hoffman, E. K.; Bird, R. K.; "Advanced fabrication technology for high speed aircraft structures", ICAS Congress; Stockholm; Sept. 9-–14, 1990; 17th; Sweden, Jan 01, 1990.

[14] Royster, D. M.; Bales, T. T.; Davis, R. C. and Wiant, H. R.; "Fabrication and evaluation of cold/formed/weldbrazed beta-titanium skin-stiffened compression panels", NASA-TP-2201, L-15634, NAS 1.60:2201, Sep 01, 1983.

7.2. SPF of Al Alloys

7.2.1. Superplastic Forming

Superplastic forming of advanced aluminum alloys has been evaluated at NASA Langley Research Center by Hales[1] and Wagner as an approach for fabricating low-cost, light-weight, cryogenic propellant tanks. Built-up structure concepts (with inherent reduced scrap rate) were investigated to offset the additional raw material expenses incurred by using aluminum-lithium alloys. This approach to fabrication offers the potential for significant improvements in both structural efficiency and overall manufacturing costs. Superplasticity is the ability of especially processed material to sustain–very large-forming strains without failure at elevated temperatures under controlled deformation conditions. It was demonstrated that superplastic forming technology can be used to fabricate complex structural components in a single operation and increase structural efficiency by as much as 60% compared to conventional configurations in skin-stiffened structures. Details involved in the application of this technology to commercial grade superplastic aluminum-lithium material are presented in their paper. Included are identification of optimum forming parameters, development of forming procedures, and assessment of final part quality in terms of cavitation volume and thickness variation.

While typical aluminum alloy sheet can elongate 10%–30% during forming, a superplastic material can achieve ten times these levels or more. While some early observations of exceedingly high elongations at slow strain rates and elevated temperatures were observed for specialized materials in the 1930s, it wasn't until the 1960s that superplasticity started to gain interest as anything more than a laboratory curiosity. Superplastic forming of aluminum alloys has been a niche area for the last few decades, primarily for aerospace and specialty automobiles, and is now receiving increased attention as a result of new developments.

Superplastic forming requires two components: a superplastic alloy as well as a special, high-temperature, relatively low-strain rate forming process for making the desired shape. For aluminum alloys, the primary metallurgical mechanism for achieving high elongations under superplastic forming conditions is grain boundary sliding accommodated by dislocation slip, which points to fine-grain size in the sheet material, typically on the order of 10 microns or so, as the key attribute that's needed. Efforts to produce commercial sheet products with superplastic forming capability have primarily involved specialized alloy compositions and rolling treatments designed to develop and stabilize the fine grains at the elevated temperatures of the superplastic forming process.

The superplastic forming process typically is carried out at temperatures close to the typical alloy solution heat treatment temperatures. Forming rates expressed in terms of strain rate are 10^{-3}–10^{-4} per second, which translates to several minutes to form a moderately complex part shape. Nevertheless, the substantial increase in elongation capability for the aluminum alloys with suitable microstructures under these conditions allows production of substantially more complex formed shapes, which can, in turn, enable part consolidation and elimination of fasteners and joints. These benefits are used to offset the higher costs of the specially prepared sheet material as well as the slow forming rates. Typical alloys available for superplastic forming include 2004 (also known as Supral), 2090, Weldalite, Al-Li, and special-processed 7475. Applications have included specialized aircraft components such as cowlings and auto body components.

Further extension of this process into larger scale use requires reduction in the costs of superplastically formed parts as well as increased forming rates more comparable to conventional stamping processes. One very promising development in this direction is the discovery of what has been termed high-strain-rate superplasticity. It has been found that aluminum-based materials with grain sizes about an order of magnitude smaller than conventional superplastic sheet products, i.e., on the order of 1 micron or so, exhibit superplastic behavior at lower temperatures and significantly higher strain rates of 10^{-2}–10^{1} per second, which could substantially reduce the forming times into the range of conventional warm forming and possibly even stamping. The challenge remaining here is that the aluminum materials showing– these high-strain-rate superplastic characteristics are metal matrix composites or other alloys produced by specialized processes, and so the material cost remains high. Recent work on potentially lower cost processes such as friction stir processing and spray forming to produce the very fine grained alloys should be watched as an indicator for future commercial potential.

An excellent paper[2] showing some of the pioneering work performed at Langley Research Center in manufacturing technology of advanced structural shapes for carrying compression loads in aircraft and spacecraft fuselages was published in 1991 by Davis, Royster, Bales, James, and Shinn. The basic shapes investigated in this study were based on results from an earlier study[3] of structural concepts designed to carry compression loading. The curved-cap corrugation with beaded webs was selected because it offers a very attractive mass-strength efficient wall construction for carrying compression loads (

Figure 7.2-1). One of the unique features of this study was the use of back pressure to control cavitation in the formed part. A basic schematic of the mold is shown in **Figure 7.2-2**. The pressure-time profile used to form specimens by the "back pressure" process is illustrated in

Figure 7.2-3(a) and the post-forming pressure profile is shown in

Figure 7.2-3**(b)**. Examination of the microstructure of the SPF 7475 specimens formed by either the "back-pressure" or the "post forming" process showed significant reduction in cavitation in the part and a much improved ng capability in the final part.

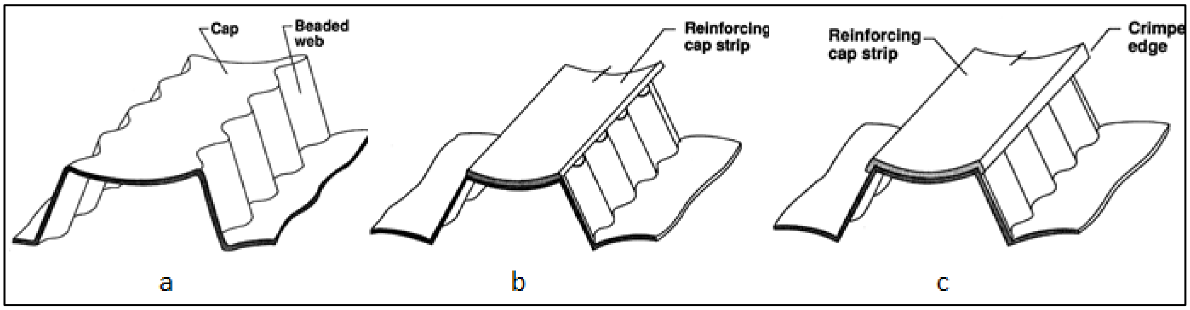


Figure 7.2-1: (a) Single Corrugated Sheet Formed by SPF, (b) Cap Strip Brazed to Center Cap of the SPF Corrugated Sheet, (c) Cap Strip with Crimped Edges Adhesive Bonded to Center Cap of the SPF Corrugated Sheet.

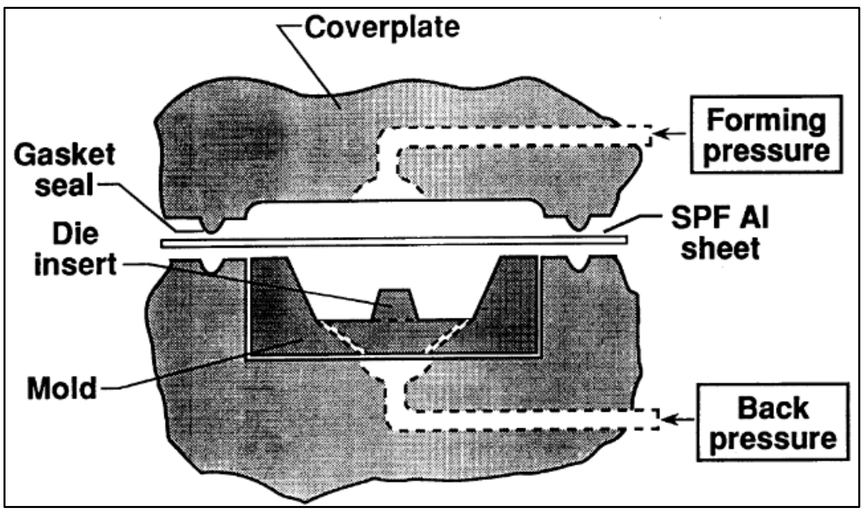


Figure 7.2-2: Schematic of mold, cover plate and die insert.

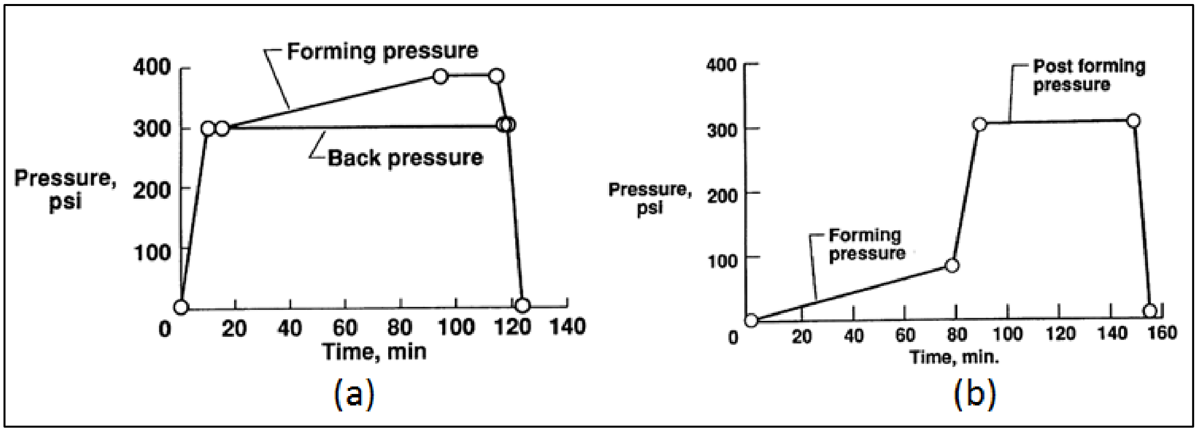


Figure 7.2-3: (a) Pressure-time Profile Used to Form Specimens by "Back Pressure" Process and (b) Pressure-Time Profile for Forming Specimens by the "Post-Forming" Process.

Building on the results of this study, Tom Bales and Steve Hales[4] conducted another study to explore how fast superplastic forming of Al alloys could be done and still achieve useful engineering properties. They experimented with the use of back pressure to suppress cavitation forming during rapid SPF of different shapes potentially useful for structural applications. SPF technology was used to fabricate structural components from the 7475 Al and 8090 Al-Li commercial alloys. Gas-pressurization cycles were established for SPF three-hat stiffener configurations on the basis of uniaxial data and component-geometry considerations. It is established that higher forming rates than the optimum strain rates selected from the uniaxial data for each alloy could be used in the later stages of forming without reducing SPF components' dimensional conformity. Cavitation was precluded through the use of back pressure during forming.

Additional studies conducted at Langley on SPF of Aluminum alloys can be found in papers by Hales,[5] (Wagner, Will, and Cotton[6]), Bales,[7] Hales,[8] and a patent by Troeger[9] and co-inventors.

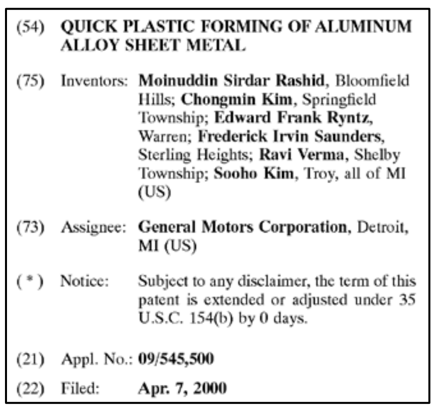
7.2.2. Superplastic Forming of Aluminum for Automotive Applications (SPITFIRE Program)

Over the past couple of decades the auto industry has tried superplastic forming to make aluminum parts for some specialty vehicles. Unlike the aviation sector, the auto industry could not tolerate higher cost and turn-over time. Part of the higher cost is due to the need for application of high-quality grade SP-5083 alloy. The other major barrier for applying SPF technology to automotive applications was the need for optimizing the process for a–lower turn-over time so that the process could handle the larger number of parts required for ordinary passenger vehicles. To help meet this challenge, NASA engaged in a technology transfer program with General Motors Research Laboratory.

In October 1993, a meeting was held at NASA Langley with a team of engineers from General Motors. The purpose of this meeting was to discuss the details of a possible cooperative agreement between NASA Langley and General Motors Corporation. Following this meeting critical experiments were conducted at Langley Research Center by Tom Bales and Steve Hales to explore how fast superplastic forming of Al alloys could be done and still achieve useful engineering properties. They experimented with the use of back pressure to suppress cavitation forming during rapid SPF of different shapes potentially useful for structural applications. SPF technology was used to fabricate structural components from the 7475 Al and 8090 Al-Li commercial alloys. Gas-pressurization cycles were established for SPF three-hat stiffener configurations on the basis of uniaxial data and component-geometry considerations. It is established that higher forming rates than the optimum strain rates selected from the uniaxial data for each alloy could be used in the later stages of forming without reducing SPF components' dimensional conformity. Cavitation was precluded through the use of back pressure during forming.

The results of these experiments were reported to Dr. Rashid and his team at the General Motors Research Laboratory. Dr. Rashid and his team continued development of SPF for automotive applications using the back pressure approach to shorten (compared to the cycle used for aerospace applications) the time required to achieve useful engineering components for automotive applications.

In April 2000, General Motors filed a patent on Quick Plastic Forming of Aluminum Alloy Sheet Metal (**Figure 7.2-4**). A brief Abstract of Patent U.S. 6,253,588 B1 dated July 3, 2001 is given below.


(54) **QUICK PLASTIC FORMING OF ALUMINUM ALLOY SHEET METAL**

(75) Inventors: **Moinuddin Sirdar Rashid**, Bloomfield Hills; **Chongmin Kim**, Springfield Township; **Edward Frank Ryntz**, Warren; **Frederick Irvin Saunders**, Sterling Heights; **Ravi Verma**, Shelby Township; **Sooho Kim**, Troy, all of MI (US)

(73) Assignee: **General Motors Corporation**, Detroit, MI (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/545,500**

(22) Filed: **Apr. 7, 2000**

Figure 7.2-4: GM Patent on Quick Plastic Forming of Aluminum Alloy Sheet Metal.

A method is disclosed for stretching magnesium-containing aluminum alloy sheet stock into intricate shapes such as are required in automotive body panels. The sheet stock, at a temperature in the range of about 400°C to about 510°C, is stretched under the pressure of a working gas into conformance with the surface of a forming tool. The sheet forming pressure is increased continually in a controlled manner from ambient pressure to a final forming level in the range of about 250 psi to about 500 psi or higher. A portion of the sheet can experience strain rates substantially higher than 10^{-3} sec^{-1} and the forming of the sheet can be completed within 12 minutes.

Quick plastic forming (QPF), a patented technology at General Motors, has now reached a state of maturity where it can compete with other limited-volume manufacturing systems in the marketplace. Further developments could enable even higher volume automotive panel production. The goal of the automotive industry has partly been to produce, characterize, and understand superplastic materials suitable for high-volume production. Therefore, there has been a significant amount of work on effects of alloy composition, second-phase particles, and thermomechanical processing parameters that has led to detailed understanding of the alternative deformation mechanisms, elevated temperature fracture behavior as well as surface phenomena. Post-forming mechanical properties has also been studied.

Quick plastic forming is described in U.S. Pat. No. 6,253,588, issued Jul. 3, 2001 to Rashid, et al. For quick plastic forming, a preferred alloy is aluminum alloy 5083 having a typical composition, by weight, of about 4% to 5% magnesium, 0.3% to 1% manganese, a maximum of 0.25% chromium, about 0.1% copper, up to about 0.3% iron, up to about 0.2% silicon, and the balance substantially all aluminum. Generally, the alloy is first hot- and then cold-rolled to a thickness from about 1 to about 4 millimeters.

In the AA5083 alloys, the microstructure is characterized by a principal phase of a solid solution of magnesium in aluminum with well-distributed, finely dispersed particles of intermetallic compounds containing the minor alloying constituents, such as Al-6Mn.

Using QPF, large AA5083-type aluminum-magnesium alloy sheet stock may be formed into a complex three-dimensional shape with high-elongation regions, like an SPF-formed part, at much higher production rates than those achieved by SPF practices. The magnesium-containing, aluminum sheet is heated to a forming temperature in the range of about 400°C to 510°C (750°F. to 950°F). The forming may often be conducted at a temperature of 460°C or lower. The heated sheet is stretched against a forming tool and into conformance with the forming surface of the tool by air or gas pressure against the back surface of the sheet. The fluid pressure is preferably increased continuously or stepwise from 0 psi gage at initial pressurization to a final pressure of about 250–500 psi (gage pressure, i.e., above ambient pressure) or higher. During the first several seconds up to about one minute of increasing pressure application, the sheet accommodates itself on the tool surface. After this initial period of pressurization to initiate stretching of the sheet, the pressure can then be increased at an even faster rate. Depending upon the size and complexity of the panel to be formed, such forming can normally be completed in a period of about two to twelve minutes, considerably faster than realized in superplastic forming. Thus, by working a suitably fine-grained aluminum alloy sheet at significantly lower temperatures and continuously increased, higher gas pressures than typical SPF practices, significantly faster and more practical forming (at least for the automobile industry) times are achieved.

It should be noted the NASA funded work at General Motors in the late 1990s and Langley researchers worked on this process in house at Langley as a cooperative program with General Motors as an aerospace technology spinoff activity.

References

[1] Hales, Stephen J.; Wagner, John A.; “Superplastic forming of Al-Li alloys for lightweight, low-cost structures”, NASA, Washington, D.C.,Technology 2000, Volume 2 p 200-209 (SEE N91-24041 15-99), 1991.

[2] Davis, Randall C.; Royster, Dick M.; Bales, Thomas T.; James, William F.; Shinn, Joseph M., Jr.; “Test of superplastically formed corrugated aluminum compression specimens with beaded webs”, NASA-TM-104119, NAS 1.15:104119, 1991.

[3] Davis, Randall C.; Mills, Charles T.; Prabhakaran, R.; and Jackson, L. Robert; “Structural Efficiency Studies of Corrugated Compression Panels With Curved Caps and Beaded Webs”, NASA TP 2272, 1984.

[4] Hales, S. J.; Bales, T. T.; Shinn, J. M.; James, W. F.; “Fabrication of structural components from commercial aluminum alloys using superplastic forming”, Conference Paper A91-48901, Superplasticity in Aerospace II, Edited by McNelley, T.R., and Heikkenen, H.C., The Metallurgical Society of AIME, 1990.

[5] Hales, S. J.; Bales, T. T.; Shinn, J. M.; James, W. F.; “Fabrication of structural components from commercial aluminum alloys using superplastic forming”, Superplasticity in aerospace II; Proceedings of the Symposium, 119th Annual Meeting of the Metallurgical Society, Anaheim, CA, Feb. 19-22, 1990 (A91-48901 21-26). Warrendale, PA, Minerals, Metals, and Materials Society, 1990, pp. 167–185.

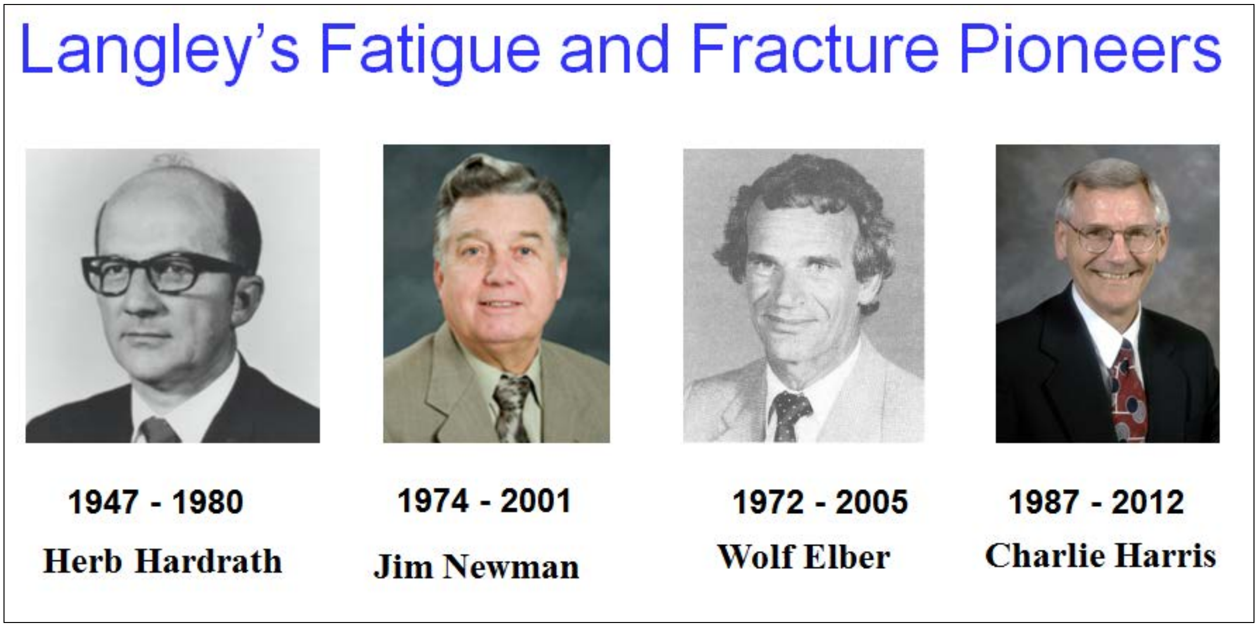
[6] Wagner, John A.(Technical Monitor) ; Will, Jeff D.; Cotton, James D.; “Superplastic Forming/Adhesive Bonding of Aluminum (SPF/AB) Multi-Sheet Structures”, NASA/CR-2003-212400, NAS 1.26:212400, 2003.

[7] Bales, Thomas T.; Shinn, Joseph M., Jr.; Hales, Stephen J.; James, William F; “Fabricating Structural Stiffeners By Superplastic Forming”, NASA Tech Brief LAR-14549, 1994.

[8] Hales, Stephen J.; Wagner, John A.; “Superplastic forming of Al-Li alloys for lightweight, low-cost structures”, http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19910014752.pdf.

[9] Troeger, Lillianne P. (Inventor); Starke, Jr., Edgar A. (Inventor); Crooks, Roy (Inventor); “Method of producing superplastic alloys and superplastic alloys produced by the method”, US-PATENT 6,350,329, US-PATENT-APPL-SN-332736, 2002.

8. FATIGUE AND FRACTURE



Langley has a rich history of major contributions to safety of air vehicles for many decades. The research staff is world class. Although, outstanding contributions have been made by many different researchers including Buddy Poe, Dick Everett, Walter Illg, Dr. Robert S. Piascik, Dr. Ivatury Raju, and many others, four are cited here as deserving special recognition. Herb Hardrath, former Branch Head of the Fatigue and Fracture Branch, is considered by most to be the father of materials durability within NACA and NASA. Dr. Jim Newman's contributions are too numerous to mention, but he is regarded by most researchers in this field to be the world leading expert in crack growth and fracture of metals. Wolf Elber, former Branch Head, made a major discovery on the crack closure mechanism of fatigue crack growth which is discussed in detail below. Dr. Charlie Harris, former Branch Head, made many outstanding contributions including leading the National Aging Aircraft Program, which resulted in new methodologies and inspection procedures to prevent future fuselage failures in older aircraft.

8.1. Background

The major research thrusts in fatigue and fracture performed for different classes of vehicles are shown in **Figure 8.1-1**. All of the research areas have been worked at Langley over the past several decades. The volume of this work is beyond the scope of this publication and only selected examples will be highlighted to illustrate the many significant contributions made to safety of flight of air vehicles.

Vehicle Class	Fatigue and Fracture				
Research Activity	Fatigue	Fracture	Test Methods and Standards	Codes and Analyses	Failure Case Studies
Launch Vehicles	High Cycle Fatigue	Cryogenic Fracture Toughness	Man Rated Standards	NASTRAN STAGS	NESC Apollo Tank Failures
Hypersonic Aircraft	Thermal Cycling	Brittle Fracture Behavior	High temp. Test Methods	Thermal Stress Analyses	
Supersonic Aircraft	Time-Temp-Stress Cycling	Temp. Dependant Fracture	Combined Envs. Test Methods	Multidisciplinary Design Analyses	
Subsonic Aircraft	Crack Closure Small Crack Growth	Critical Crack Criteria Env. Assisted Cracking	Test Methods Fracture Mech. Testing	FASTRAN, NASTRAN, Zip 3D, FRANC 2D & 3D	Aging Aircraft F-111 Wing Failure
Major Contribution	Crack Closure Metodology	Fail Safe Methodology	Validated Test Standards	Stress Intensity Factors	Improved Safety

Figure 8.1-1: Fatigue and Fracture Research Thrusts for Different Vehicle Classes.

Durability and damage tolerance issues have been a prominent consideration in aircraft design since several fatal accidents of De Havilland Comets during the 1950s. Accidents and incidents resulting from fatigue and fracture continue to be an issue for the fleet and are a design consideration for future aircraft. Of the accidents investigated by NTSB, those attributed to airframe structural failure are among the most catastrophic and potentially fatal. The unfortunate consequences of structural failure are well illustrated by several recent accidents investigated by the NTSB and are shown in **Figure 8.1-2**.

Figure 8.1-2(a) shows the forward fuselage section of an Aloha Airlines Boeing 737 shortly after separation of eighteen feet of fuselage above the passenger floor line and immediately aft of the cabin entrance door. Although the airframe had only 35,496 flight hours, the number of ground-air-ground cycles was much larger than might be expected because of the short duration of many of the aircraft's flights between the various Hawaiian Islands. The cause of the Aloha Airlines accident was attributed to the linking of fatigue cracks emanating from fastener holes (multi-site fatigue damage). **Figure 8.1-2(b)** shows the vertical tail of American Airlines flight 587, an Airbus A300, as it was recovered from Jamaica Bay in New York. The cause of the American Airlines accident was determined to be the in-flight separation of the vertical tail as the result of loads beyond ultimate that were created by the first officer's unnecessary and excessive rudder pedal inputs. Analyses at NASA Langley Research Center showed that of the six attachment lugs that join the vertical tail and fuselage, the right rear lug failed first at a load of almost two times the design limit load. **Figure 8.1-2(c)** shows the right engine of a Delta Airlines flight 1288, a McDonnell Douglas MD-88, after the front compressor hub of the #1 engine shattered and penetrated the left aft fuselage. The cause of the accident was final fracture of a fatigue crack growing from a manufacturing defect at a tie rod hole in the compressor hub. **Figure 8.1-2(d)** shows one of several tankers operated by the U.S. Forest Service that recently suffered catastrophic structural failures. In the case shown, both wings of a C-130A detached from the fuselage at their respective center wing box-to-fuselage attachment locations after the aircraft dropped its payload and began to arrest its decent and level out. Examination of the center wing box lower skin revealed that failure was caused by fast fracture of a 12-inch-long fatigue crack that had not been detected during regular inspections.

(a) Forward fuselage after Aloha Airlines accident (1 person killed)

(b) Recovery of Vertical Tail after American Airlines Flight 587 accident (265 people killed)

(c) Engine after Delta Flight 1288 accident (2 people killed)

(d) U.S. Forest Service C-130 on June 17, 2002 near Walker, CA (3 people killed)

Figure 8.1-2: Notable Aircraft Accidents.

These aircraft accidents have driven fatigue and fracture research for many years. Two are discussed in more detail in the following sections. The first of these is the Comet failures, and the second is the Aloha Airlines Flight 243 failure.

8.1.1. Comet Failures

On January 10, 1954, British Overseas Airways Corporation Flight 781, a de Havilland DH.106 Comet 1 registered *G-ALYP*, took off from Ciampino Airport in Rome, Italy, en route to Heathrow Airport in London, England, on the final leg of its flight from Singapore. At about 10:00 GMT, the aircraft suffered an explosive decompression at altitude and crashed into the Mediterranean Sea, with the loss of all 35 on board.[1] After several crash events and extensive testing fatigue cracking was found in the fuselage that originated from the aft lower corner of the forward escape hatch and also from the right-hand aft corner of the square windows. Both of these locations featured sharp right hand corners which caused local areas of high stress-concentration that provided very benign conditions for crack initiation and propagation under fatigue loading. The stress concentration around the escape hatch and window cutouts was exacerbated by countersunk bolt holes creating a "knife-edge" in both the primary skin and doubler reinforcement. Cracks that grew across a bay from one cutout to the next could not be tolerable and resulted in ultimate failure of the structure.

The most notable lesson learned from the Comet disaster is that viewing windows are no longer designed square but with rounded edges to reduce any stress concentrations. Another immediate lesson was that crack-stoppers should be placed between frame-cutouts that take the shape of circumferential stiffeners that break-up the fuselage into multiple sections and thus prevent the crack from propagating from one window to the next. Most importantly however, before and during the Comet era the aircraft design philosophy was predominantly Safe-Life, which means that the structure was designed to sustain the required fatigue life with no initial damage and no accumulation of damage during service, e.g., cracking. The Comet accidents showed that around stress concentration, cracks would initiate and propagate much earlier than expected, such that safety could not be universally guaranteed in the Safe-Life approach without uneconomically short aircraft service lives.

For this reason the Fail-Safe design philosophy was developed in the late 1950s. All materials are assumed to contain a finite initial defect size before entering service that may grow due to fatigue loading in-service. The aircraft structure is thus designed to sustain structural damage without compromising safety up to a critical damage size that can be easily detected by visual inspection between flights. All inspections are coupled with crack propagation calculations that guarantee that an observed crack is not susceptible to grow to the critical size between two inspection cycles, in which case adequate repair is performed. Furthermore, the structure is designed to be damage tolerant with multiple load paths and built-in redundancies that impart residual strength to the aircraft in case the primary structure is compromised in-service.

The failure of the Comet transport jet aircraft from fatigue cracks gave rise to treatments of crack propagation using notch-root parameters and the stress-intensity factor concept of Irwin[2] and Paris et al.[3,4]

8.1.2. Aloha Aircraft Failure

Aloha Airlines Flight 243 (AQ 243, AAH 243) was a scheduled Aloha Airlines flight between Hilo and Honolulu in Hawaii. On April 28, 1988, a Boeing 737-200 serving the flight suffered extensive damage after an explosive decompression in flight, but was able to land safely at Kahului Airport on Maui. The only fatality was flight attendant C.B. Lansing who was blown out of the airplane. Another 65 passengers and crew were injured. The safe landing of the aircraft, despite the substantial damage inflicted by the decompression, established Aloha Airlines Flight 243 as a significant event in the history of aviation (**Figure 8.1-2(a)**), with far-reaching effects on aviation safety policies and procedures. The explosive decompression was a result of what became known as "widespread fatigue damage (WFD)."

This WFD phenomenon may have been at work in two non-fatal incidents that have occurred since 2009. One involved a Southwest Airlines Boeing 737-300 on July 13, 2009 during a Baltimore-Nashville flight that had to divert to Charleston, West Virginia after the aircraft's cabin depressurized when a 1 ft × 2ft hole appeared in its upper fuselage near its vertical stabilizer (commonly known as the tail). The incident caused no serious injuries.

Subsequently, the U.S. National Transportation Safety Board (NTSB) found that the hole was caused by longitudinal cracking of the fuselage skin caused by metal fatigue. According to the NTSB's report on the incident, highly magnified inspections of the longitudinal crack revealed continuous fatigue thumbnail cracks propagating outward (through the thickness of the aircraft's skin) from multiple origins at the inner surface of the skin.

The second incident happened on October 26, 2010, when an American Airlines Boeing 757 flying from Miami to Boston had to return to Miami when it, too, depressurized after a 1 ft× 1 ft hole opened in the upper part of the fuselage near a cabin door toward the front of the plane. There were no serious injuries in this second incident. The Aloha Airlines 737-200 was about 19 years old, the Southwest Airlines 737-300 was about 15 years old, and the American 757 20 years old at the times of the incidents. The Aloha 737-200 had accumulated 89,680 take-off and landing cycles and 35,496 hours of flight time; the Southwest 737-300 had accumulated 42,500 take-off and landing cycles and 50,500 hours of flight time; and the American Boeing 757 had accumulated some 22,000 take-offs and landings. (American did not provide the amount of flight hours the Boeing 757 had accumulated, but Boeing 757s tend to operate longer flights than do 737-300s as they are larger and offer much longer range.)

The FAA's 2006 WFD regulation applies to airliners with a takeoff weight of 75,000 lbs and heavier. It also applies to all transport designs certificated in the future. According to the FAA, the affected models include a total of 4198 U.S.-registered aircraft. They include all in-service Airbus, Boeing, and McDonnell Douglas jets, as well as the Lockheed TriStar and Hercules, the Embraer 170 and 190, the Bombardier CRJ900, and the Fokker 100. The Boeing 787, 747-8 and Airbus A350 XWB are not covered by the current FAA rule, as they are not yet in service, but the FAA will require that these aircraft be covered by the rule too when they begin commercial operations.

The FAA is working closely with the European Aviation Safety Agency (EASA) and other national authorities to harmonize this rule with their regulations as much as possible. EASA is now developing rulemaking to address WFD, and the FAA is participating in that process.

All aerospace vehicles must be designed to be durable and damage tolerant. This design imperative is dramatically illustrated in **Figure 8.1-2(a)**. The fuselage failure of the Aloha Airlines Boeing-737 aircraft in 1988 and in the more recent events cited above illustrates the need to design primary structures that are both durable and damage tolerant. Each failure was precipitated by the accumulation of undetectable fatigue damage that occurs when the structure is subjected to repeated loads, such as the pressurization and depressurization that occurs with every flight of an airplane. Over time this fatigue damage results in cracks in the structure, and the cracks may begin to grow together. Widespread fatigue damage is the simultaneous presence of fatigue cracks at multiple structural locations that are of sufficient size and density that the structure will no longer meet the residual strength requirements of Federal Aviation Regulations FAR 25.571 (Damage Tolerance and Fatigue Evaluation of Structure) § 25.571(b).1.[5]

Structural fatigue characteristics of airplanes are understood only up to the point where analyses and testing of the structure are valid. There are concerns about operating an airplane beyond that point. One reason is that WFD is increasingly likely as the airplane ages, and is almost certain if the airplane is operated long enough. Another is that existing inspection methods do not reliably detect WFD because cracks are initially so small and may link up and grow so rapidly that the affected structure fails before an inspection can be performed to detect the cracks. To preclude WFD related incidents in existing transport category airplanes, this final rule requires holders of design approvals for those airplanes subject to the rule to perform the following actions: (1) establish a limit of validity of the engineering data that supports the structural maintenance program (LOV); (2) demonstrate that WFD will not occur in the airplane prior to reaching the LOV; and (3) establish or revise the Airworthiness Limitations section in the Instructions for Continued Airworthiness to include the LOV.

Durability is typically viewed as an economic life-cycle design consideration whereas damage tolerance is an attribute of the structure that is directly related to the vehicle safety. However, both durability and damage tolerance design methodologies must address the deleterious effects of changes in material properties and the initiation and growth of microstructural (undetectable) damage due to fatigue that may occur during the service lifetime of the vehicle.

References

[1] I. Cohen, B., Farren, W., Duncan, W. and Wheeler, A.; “Report of the Court of Inquiry into the Accidents to Comet G-ALYP on 10 January 1954 and Comet G-ALYY on 8 April 1954,” HMSO, London, 1955.

[2] Irwin, G. IL; Journal of Applied Mechanics, Vol. 24, 1957, pp 361–364.

[3] Paris, P., Gomez, M. and Anderson, W.; “The Trend in Engineering”, Vol. 13, 1961, p 9.

[4] Paris, P. C. and Erdogan, F., Journal of Basic Engineering, Vol. 85, 1963, p 528.

[5] http://www.faa.gov/documentLibrary/media/Advisory_Circular/AC%2025.571-1D%20.pdf.

8.2. Historical Background and the Early Years

The research studies on metallic materials began almost as soon as the airplane industry began to go away from the original “composite” materials, wood and cloth, to metals. In the past few decades, however, the aircraft industry has slowly begun to bring composite materials back into aircraft structural components. NASA LaRC has made very significant contributions.[1] However, the introduction of metallic materials to an airframe structure brought with it the old phenomenon called “fatigue.” After World War II, the Materials Branch in the Structures Research Division at NACA Langley was headed by Paul Kuhn, and within this branch was the Fatigue Section that was headed by Herb Hardrath. The Fatigue Section was formed to study and understand the fatigue and fracture behavior of metals used in airplane construction, mainly the aluminum alloys. This group made many important contributions to the study of fatigue and fracture behavior of metallic materials, but only a few will be briefly reviewed here: in particular, the fatigue studies and stress analyses of notched coupons by H. Hardrath and his colleagues, the early fatigue-crack-propagation tests and analyses made by A. J. McEvily and W. Illg, and the fracture testing and analyses of notched and cracked coupons made by P. Kuhn and W. Figge. These early tests and analyses involved studying fatigue and fracture behavior of holes, notches and cracks to simulate stress concentrations and damaged parts in airplane structures. Some of the fatigue results and design charts for the aluminum alloys and steels are still used by aircraft designers today. These studies paralleled the earlier works of Inglis,[2] Neuber,[3] and Griffith[4] in using an elliptical hole to approximate the stresses and strains around a very sharp notch or crack. This work centered on a field called “notch analysis.” By the early 1960s, the newly developing field of “fracture mechanics” began to rapidly displace the notch analysis methods for characterization of fatigue-crack-growth and fracture. Fracture mechanics research in the Fatigue Branch was initiated by W. Anderson, who was one of the founding pioneers of the field of fracture mechanics, along with George Irwin and Paul Paris.

Herbert F. Hardrath (**Figure 8.2-1**) contributed greatly to the success of fatigue and fracture research in both metallic and composite materials in the United States and world-wide. He was instrumental in the success of ASTM Committee E-9 on fatigue. He was a member of the ASTM E-9 Committee from 1958 until his death on September 25, 1985, and was the Chairman of Committee E-9 from 1966 to 1971. Herb grew up in Manitowoc, WI, and joined the Navy during World War II. He received a Bachelor of Science and a Master of Science degree in civil engineering at Tulane University and the Case Institute in Cleveland, Ohio. In 1947, he joined the National Advisory Committee on Aeronautics (NACA) as a Structural Engineer to forge a fatigue research effort. In 1952, he became the Head of the embryonic Fatigue Section. Under his leadership, the Fatigue Section became a Branch at the National Aeronautics and Space Administration (NASA) Langley Research Center in 1958. In 1970, he was elevated to Assistant Division Chief of the Materials Division. Also in 1970, he received a Special Achievement Award for his amassed contributions. Herb retired from NASA in 1980.

Figure 8.2-1: Herbert F. Hardrath.

Herb was very active in ASTM Committee E-9 on fatigue. He received the ASTM Award of Merit in 1970 for his many contributions to fatigue research and for the development of fatigue standards. He was invited, in 1970, to present the AIAA Structures Design Lecture. In 1972, he presented the ASTM Gillett Memorial Lecture, and, in 1974, he presented the AIM Armstrong Research Lecture. Because of his expertise in fatigue and fracture mechanics, Herb was chosen to be part of a select group to visit technical centers in the U.S.S.R. in 1976. Herb was the United States delegate to the International Committee on Aeronautical Fatigue (ICAF) from 1965 to

1980. In 1971, he hosted an international meeting of ICAF in Miami, FL. He presented the Sixth Plantema Memorial Lecture to open the 1977 ICAF meeting in the Federal Republic of Germany. As an eminent fatigue expert, he was chosen to participate in many investigations of fatigue problems in military and commercial aircraft, such as the B-47, F-111, C-5, and the DC-10. Herb is remembered for more than his technical accomplishments; he was a model for personal integrity and dedication.

The Fatigue Section became the Fatigue Branch in 1960 and has been led by those listed in **Table 8.2-1**. The branch has changed names over the years and was led by very talented leaders. They helped to build the world-class fatigue and fracture laboratory, as shown in **Figure 8.2-2.**

Table 8.2-1: Chronological Listing of Branch Heads and Names over the Past 50 Years.

Branch Head	Name	Period
Herb Hardrath	Fatigue Branch	1960–1971
Jack Davidson	Structural Integrity Branch	1971–1981
Jack Davidson	Fatigue and Fracture Branch	1981–1984
Wolf Elber	Fatigue and Fracture Branch	1984–1986
John Crews (acting)	Fatigue and Fracture Branch	1986–1987
Charles Harris	Fatigue and Fracture Branch	1987–1988
Charles Harris	Mechanics of Materials	1989–1994
Ivatury Raju	Mechanics of Materials	1994–1999
Damodar Ambur	Mechanics and Durability Branch	1999–2003
Tom Gates	Mechanics of Structures and Materials Branch	2003–2006
Jonathan Ransom	Durability, Damage Tolerance and Reliability Branch	2006–present

Figure 8.2-2:Fatigue and Fracture Laboratory in Building 1205 at NASA LaRC.

8.2.1. Fatigue Behavior of Notched Coupons

In the early 1950s, both Kuhn and Hardrath were involved in an investigation that was aimed at understanding why the notch fatigue stress-concentration factor, K_F, was less than that predicted by the theoretical notch stress-concentration factor, K_T. In this regard, the theoretical and experimental work of Neuber was of considerable interest. Neuber had developed a method for the calculation of K_T for notches, but when he attempted to verify his predictions experimentally he found that the experimental values of K_T were less than the theoretical values. In order to reconcile these findings, Neuber proposed that materials could not support the steep stress gradients at the roots of notches, and that over a distance ρ' at the root of a notch of radius ρ, the stress remained constant. He expressed the relationship between K_F and K_T as

$$K_F = 1 + \frac{K_T - 1}{1 + \sqrt{\dfrac{\rho'}{\rho}}} \tag{1}$$

Kuhn and Hardrath analyzed a large volume of data on K_F for steels and developed a design chart for ρ' as a function of tensile strength, and this chart is still used by designers today.[5] As will be shown, the Neuber approach was later incorporated into the analysis of fatigue crack propagation by McEvily and Illg.[6,7]

8.2.2. Fatigue-Crack-Propagation Testing and Analyses

In this same time period, Hardrath acquired a bank of sub-resonant axial-loaded fatigue test machines, and they were being used by Illg to acquire stress-life (S-N) data. Then in 1954–55, the catastrophic fuselage failures of the Comet jet aircraft occurred, and these crashes were directly related to fatigue crack propagation at nearly-square windows. As a result, John Duberg, a structural engineer involved with administrative matters at Langley, suggested that the Fatigue Section carryout experimental work on fatigue crack propagation. Illg immediately started such an experimental test program involving sheet specimens made of the aluminum alloys 2024-T3 and 7075-T6. As data were obtained, McEvily set out to provide a method to correlate the fatigue-crack-propagation rates and a method to use in aircraft design. At that time, the state of knowledge concerning fatigue crack propagation was meager. Research had shown that fatigue striations were formed during the fatigue-crack-growth process, but it was not yet known whether these markings were formed on a cycle-by-cycle basis or intermittently. It was known that plastic deformation occurred at the tip of a fatigue crack; thus, the initial approach employed by McEvily was to incorporate plastic deformation in a model of fatigue crack growth, using procedures developed at Langley by Hardrath and Ohman,[8] but these attempts were not fruitful. A parametric analysis using the Neuber ideas was then tried. In this analysis, it was tacitly assumed that whatever events occurred at the tip of a fatigue crack were in response to the elastic stress range at the crack tip, given by $K_T S$, where S is the applied stress range at $R = S_{min}/S_{max} = 0.05$. However, in order to assign a stress-concentration factor, K_N, to a fatigue crack, it was necessary to assign an effective crack-tip radius, ρ_e, which had to be determined empirically. K_N for a fatigue crack was given as

$$K_N = 1 + \frac{K_T - 1}{1 + \sqrt{\frac{\rho'}{\rho_e}}} \tag{2}$$

As a simplification, it was assumed that the tip radius, ρ_e was equal to ρ', and therefore

$$K_N = 1 + \frac{1}{2}(K_T - 1) = \frac{1}{2}(K_T + 1) \tag{3}$$

K_T values were obtained from the literature for finite-width specimens. Since the Neuber K_T values were based upon net-section stresses, the controlling parameter was expressed as $K_N S_{net}$. An example of the results of the analysis is shown in **Figure 8.2-3** for crack propagation in a 7075-T6 aluminum alloy.[6,7]

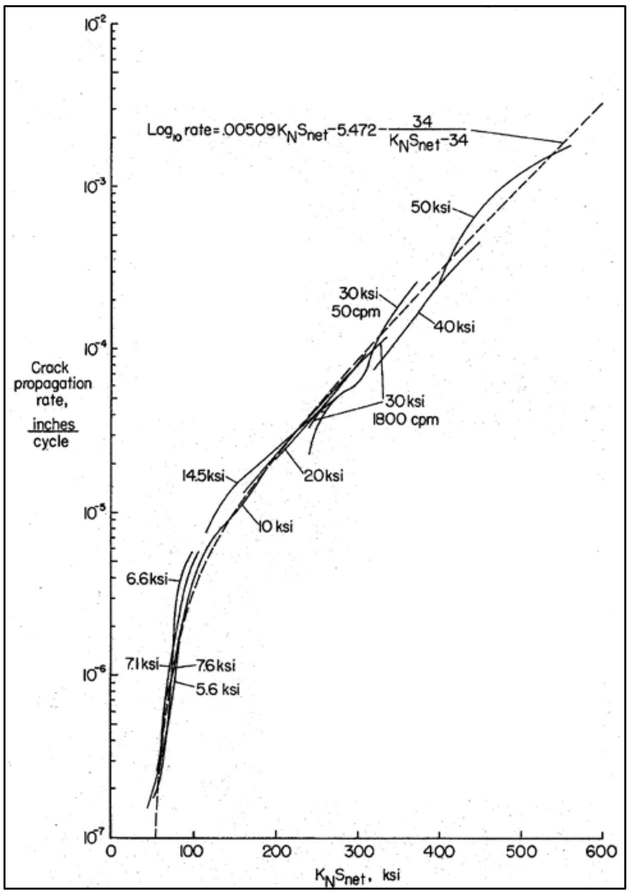


Figure 8.2-3:Rates of Fatigue Crack Propagation in 7075-T6 Aluminum Alloy Sheet Specimens (Stresses are Initial Net-Section Stresses).

This type correlation of fatigue crack propagation was published in NACA Technical Notes from 1958 to 1959, several years before the fracture mechanics approach of Paris, Gomez, and Anderson[9] using the stress-intensity-factor range (ΔK) was published. Years later, it was shown that $K_N S_{net}$ was related to the maximum stress-intensity factor (K_{max}) for a crack. Thus, the work of McEvily and Illg was actually an early analysis of crack propagation that would revolutionize how fatigue crack propagation data is analyzed and used in fatigue and damage-tolerance analyses for aircraft structures.

8.2.3. Notch-Strength Analysis

In the 1950s, NACA Langley was engaged in research aimed at improving the fatigue design methods for aircraft. One result of this work was a method for predicting the fatigue factors for notches. Somewhat later, it became necessary to consider the effect of fatigue cracks on the static (residual) strength of cracked structural components. In view of the conditions characteristic of aircraft design, it was clear that it was highly desirable to develop a capability for structural analysis rather than a method for ranking materials.

In the initial Langley studies of cracked structural components residual strength, transitional temperature, Charpy tests and other test methods were immediately found to be either inapplicable or inadequate. The newly developing field of fracture mechanics was considered, but was judged to have insufficient accuracy as a design method. Finally, it was found that the previously developed method for predicting fatigue factors could be extended to handle the static-residual strength problem for notches, as well as cracks as a limiting case. The resulting method of notch-strength analysis[10,11,12] was found to be accurate for sheet-metal parts, but could not deal with the static-residual strength in thick parts.

As pointed out by Kuhn,[11] linear-elastic fracture mechanics was based on the proposition that "unity" in the stress-concentration equation for an elliptical hole in an infinite plate under remote uniform stress could be neglected. The exact stress-concentration factor is

$$K_T = 1 + 2\sqrt{(a/\rho)} \qquad (4)$$

where a is the semi-major axis of the notch and ρ is the root radius. For a very sharp notch or crack, the root radius would be very small and, thus, unity could be neglected. The stress-intensity factor, K, was then given by

$$K = S\sqrt{a} \qquad (5)$$

This was the same quantity that Griffith[4] had used on the strength of glass. (Note that K should not be confused with the stress-concentration factor, K_T.) The stress-concentration for small cracks in glass was of the order of 100, and equation (5) was appropriate. Thus, the fracture toughness given by equation (5) was only appropriate for very brittle materials, like glass, and this formed the original concept of the "plane-strain fracture toughness, K_{Ic}" pioneered by Brown and Srawley[13] at NASA Glenn.

Based on notch-strength analysis, in 1970, Kuhn was the first to propose a "two-parameter" fracture criterion to analyze fracture of metallic materials.[12] The net-section stress (S_N) was given as

$$S'_N = \sigma'_u / K'_u \qquad \text{'(6)}$$

where K'_u is the local tensile strength at the crack tip (like the fracture strength) and K'_u is the associated stress-concentration factor as

$$\text{'}K'_u = 1 + C'_m\, kw\sqrt{a} \qquad \text{'(7)}$$

where C'_m was a material constant, and kw was a geometrical boundary-correction factor. Because of notch-strengthening and constraint effects around a crack front, the second material (or geometric) parameter was $K'u$.

In the application of Kuhn's notch-strength analysis method, the fracture criterion has worked very well on thin-ductile materials, like those used in many aerospace applications, but did not perform well on thicker higher-strength (brittle) materials. The latter was handled very well with linear-elastic fracture mechanics, like KIc. In 1973, Jim Newman, using notch-strength analyses and Neuber's equation,[14] derived a two-parameter fracture criterion[15] quite similar to Kuhn's method, but was able to correlate fracture behavior on both thin-ductile and thick-brittle materials.

References

[1] Tenney, D. R.; "Structural Framework for Flight: NASA's Role in Development of Advanced Composite Materials for Aircraft and Space Structures", 2010.

[2] Inglis, C. E.; "Stresses in a Plate Due to the Presence of Cracks and Sharp Corners", Transactions of the Institute of Naval Architects, Vol. 55, 1913, pp. 219–241.

[3] Neuber, H.; "Theory of Notch Stresses", 1937 (English, Edwards, Ann Arbor, 1946).

[4] Griffith, A. A.; "The Phenomena of Rupture and Flow in Solids", Philosophical Transactions, Series A, Vol. 221, 1920, pp. 163–198.

[5] Kuhn, P. and Hardrath, H. F.; "An Engineering Method for Estimating Notch-Size Effect in Fatigue Tests on Steel", NACA TN-2805, October 1952.

[6] McEvily, A. J. and Illg, W.; "The Rate of Fatigue-Crack Propagation in Two Aluminum Alloys", NACA TN-4394, September 1958.

[7] Illg, W. and McEvily, A. J.; "The Rate of Fatigue-Crack Propagation in Two Aluminum Alloys under Completely Reversed Loading", NASA TN-52, October 1959.

[8] Hardrath, H. F. and Ohman, L., "A Study of Elastic and Plastic Stress Concentration Factors due to Notches and Fillets in Flat Plates", NACA TN-2566, December 1951.

[9] Paris, P, C., Gomez, M. P. and Anderson, W.; "A Rational Analytic Theory of Fatigue", The Trend in Engineering, Vol. 13, 1961, pp. 9–14.

[10] Kuhn, P. and Figge, I. E.; "Unified Notch-Strength Analysis for Wrought Aluminum Alloys", NASA TN-1259, May 1962.

[11] Kuhn, P.; "A Comparison of Fracture Mechanics and Notch Analysis", NASA TM-X-56206, 1965.

[12] . Kuhn, P.; "Residual Tensile Strength in the Presence of Through Cracks or Surface Cracks", NASA TN D-5432, March 1970.

[13] Plane Strain Crack Toughness Testing of High Strength Metallic Materials, ASTM STP-410, W. Brown and J. Srawley, eds., American Society of Testing and Materials, 1966.

[14] Neuber, H.; "Theory of Stress Concentration for Shear-Strained Prismatic Bodies with Arbitrary Nonlinear Stress-Strain Law", Transactions of ASME, Series E, J. Applied Mechanics, Vol. 28, 1961, pp. 544–550.

[15] Newman, J. C., Jr.; "Fracture Analysis of Surface- and Through-Cracked Sheets and Plates", Engineering Fracture Mechanics, Vol. 5, 1973, pp. 667–689.

8.3. Stress Intensity Factor Solutions

In the late 1950s, Irwin's "stress-intensity factor" concept [1] initiated an era in the rational engineering treatment of fatigue-crack-growth and fracture behavior in metallic materials. The stress-intensity factor, *K*, is the strength of the square-foot singularity at a crack tip (not to be confused with the stress-concentration factor, K_T). During the next few decades, the calculation of crack-tip stress and strain fields under tensile and shear loading by Irwin and many others, and the applications of the concept to fatigue crack propagation and brittle fracture provided the naval, nuclear, and aerospace industries with the analytical tools required to manage the life and strength of damaged structures. These *K* solutions are tabulated in several handbooks.[2,3]

NASA LaRC researchers have generated a very large number of stress-intensity factor (*K*) solutions from simple laboratory coupons to complex structural configurations. Newman[4] used complex-variable theory of elasticity to determine the *K* solution for the standard compact specimen with pin-loaded holes (**Figure 8.3-1**). Previous solutions did not include the influence of the pin-loaded holes, which had a significant effect for crack-length-to-width (c/w) ratios less than 0.4. Srawley,[5] at NASA Glenn, fitted a wide-range equation (0.2≤ c/w <1) to Newman's results and the equation is used in several ASTM test standards.

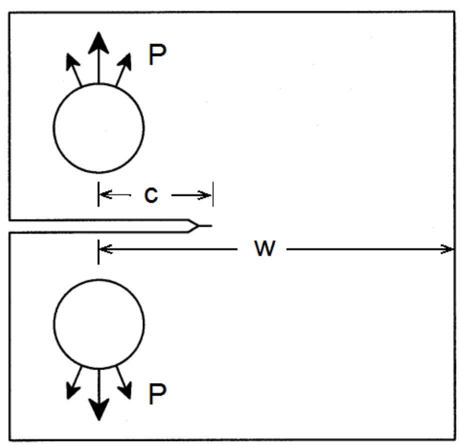


Figure 8.3-1: Standard Compact Specimen for Fatigue-Crack-Growth and Fracture Testing.

By the late 1970's, the stress-intensity-factor solutions for 3-D crack configurations, like the surface crack in a plate or corner crack at a fastener hole, were not well established. For example, published literature *K* solutions for the surface-crack configuration varied as much as a factor of 2 for some crack configurations, which made life calculations very unreliable.[6] Ivatury Raju and Jim Newman, using a 3-D finite-element code developed at NASA LaRC, set out to provide accurate *K* solutions for the surface crack in a plate[7] and for the corner crack at a hole[8] under tension and bending loads, as shown in **Figure 8.3-2**. They were able to generate *K* solutions and equations [9] for many 3-D crack configurations over a wide range in crack-configuration parameters (a/c, a/t, c/r, c/b, and ϕ, the angular location along the crack front) that are classic solutions today.

These *K* solutions, provided by NASA LaRC, are used in many industries world-wide to conduct fatigue-crack-growth and fracture analyses of damaged structural components. Many of the *K* solutions for the laboratory coupons, such as the compact and surface-crack specimens, are used in various ASTM fatigue-crack-growth and fracture standards.

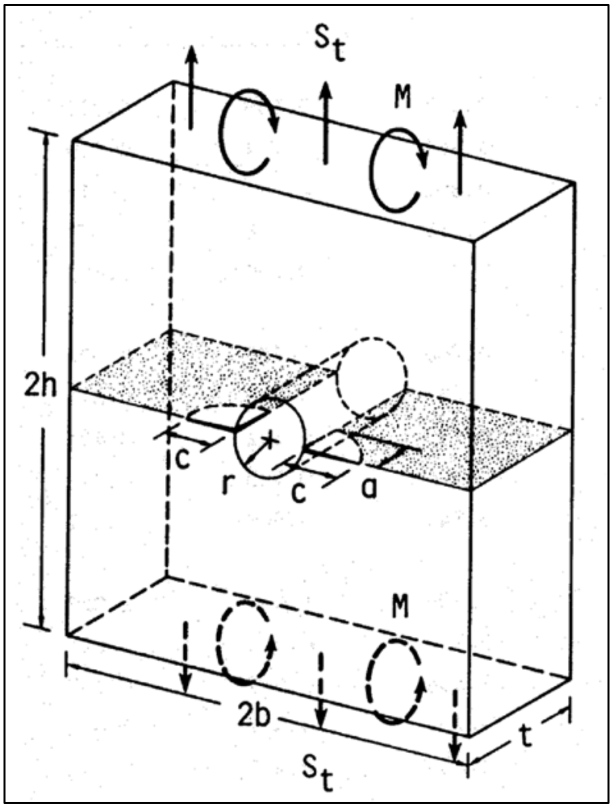
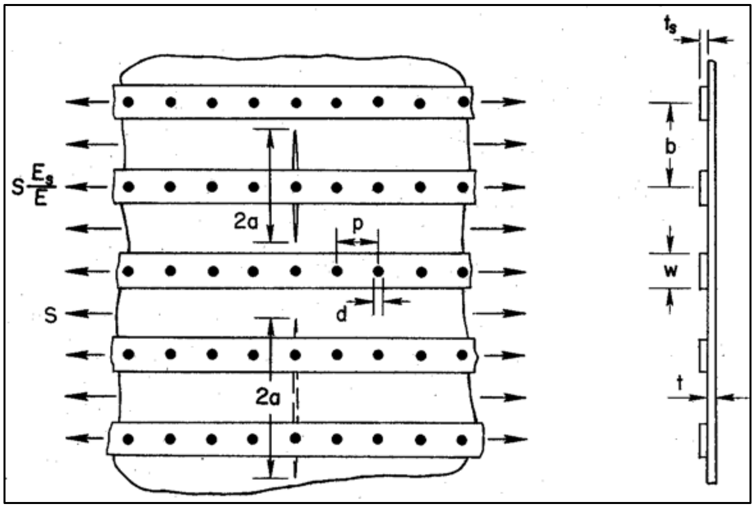


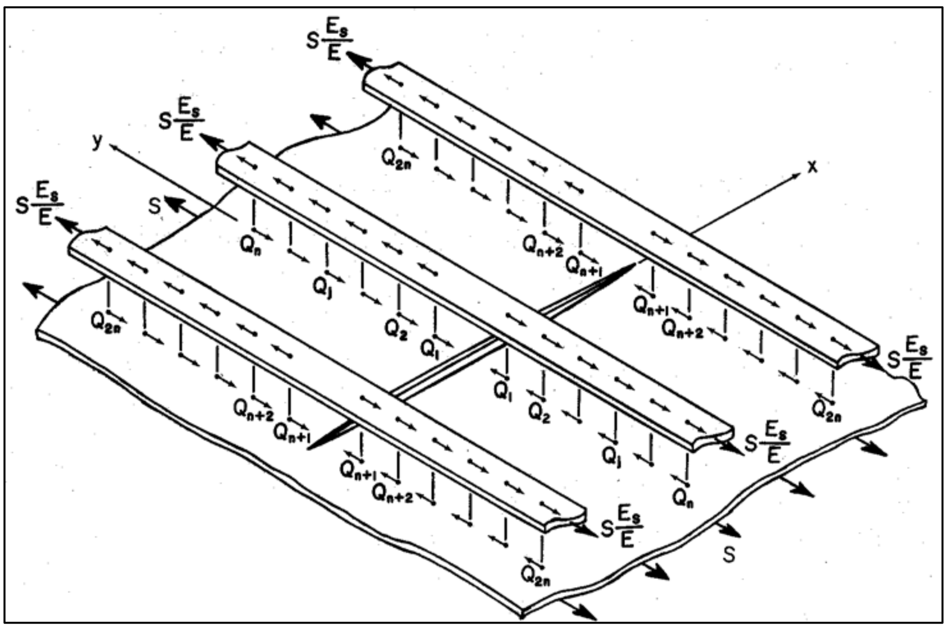
Figure 8.3-2: Corner Crack at an Open-Hole Subject to Remote Tension and Bending Loads.

8.4. Stiffened Panel Analyses

For his 1971 work, C. C. Poe, Jr. received the first H.J.E. Reid Award for his classical stress analysis of cracks in panels with riveted and uniformly spaced stringers to simulate the stress state in aircraft structures.[10] He used existing stress and displacement solutions for a crack in a large body under remote tensile stress and rivet forces to use the displacement-compatibility method to generate the stress-intensity factor solutions for a vast array of crack and stringer configurations. An example cracked-stringer configuration is shown in **Figure 8.4-1(a)** and **(b)** for a crack in a large riveted and stiffened panel under remote uniform stress.



(a)



(b)

Figure 8.4-1: Crack in Large Riveted and Stiffened Panel under Remote Uniform Stress.

The panel shown in **Figure 8.4-1** was stiffened by stringers of uniform size and spacing with equally spaced rivets and the sheet and stringers were subjected to uniaxial stress, *S*, and $S\,E_s/E$, respectively, which produced equal strains at a large distance from the crack. The rivet forces were determined by displacement-compatibility analysis assuming a rigid connection. The crack stress-intensity factors were calculated for varying stringer stiffness, stringer spacing, rivet spacing, and crack length, and the results were presented in the form of design graphs. Some typical results are shown in **Figure 8.4-2**.

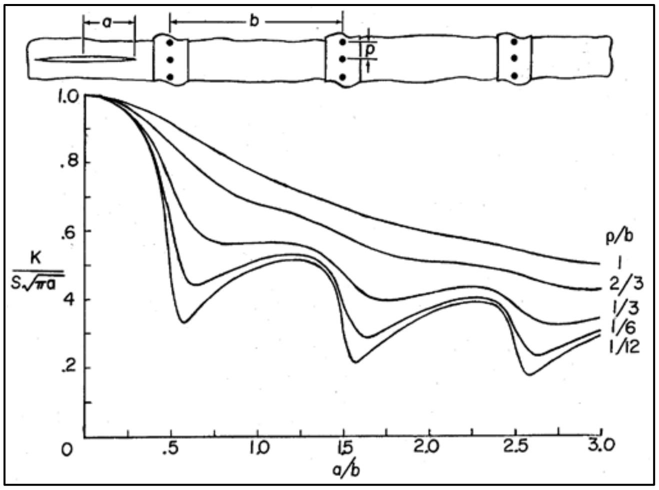


Figure 8.4-2: Effect of Rivet Spacing on Relationship Between Stress-Intensity Factor and Crack Length (Ratio of Stringer Stiffness to Total Stiffness = 0.5).

The normalized stress-intensity factor is plotted against the crack length, *a*, to stringer spacing, *b*, for various normalized rivet spacing, ρ/b. Smaller rivet spacing caused larger reduction in the stress-intensity factors as the crack grew under a stiffener. These design graphs are useful in selecting stringer spacing and stiffness to improve the damage-tolerance life of aircraft structures. Future work should model rivet flexibility, like the rivet models of Swift,[11] which should increase the normalized stress-intensity factors due to lower rivet loads near the crack.

References

[1] Irwin, G. R.; “Analysis of Stresses and Strains near the End of a Crack Traversing a Plate”, Journal of Applied Mechanics, Vol. 24, 1957, pp. 361–364.

[2] The Stress Analysis of Cracks Handbook, H. Tada, P. C. Paris, and G. R. Irwin, Eds., Del Research Corporation, Bethlehem, PA, 1985.

[3] Stress Intensity Factors Handbook, Y. Murakami, Ed., Pergamon Press, Tokyo, Japan, 1987

[4] Newman, J. C., Jr.; “Stress Analysis of the Compact Specimen Including the Effects of Pin Loading”, Fracture Analysis, ASTM STP 560, 1974, pp. 105–121.

[5] Srawley, J. E.; “Wide Range Stress Intensity Factor Expressions for ASTM Method E 399 Standard Fracture Toughness Specimens”, International Journal of Fracture, Vol. 12, June 1976, pp. 475–476.

[6] Newman, J. C., Jr.; “A Review and Assessment of the Stress-Intensity Factors for Surface Cracks”, Part-Through Crack Fatigue Life Prediction, ASTM STP 687, 1979, pp. 16–42.

[7] Raju, I. S. and Newman, J. C., Jr.; “Stress-intensity Factors for a Wide Range of Semi-Elliptical Surface Cracks in Finite-Thickness Plates”, Engineering Fracture Mechanics, Vol. 11, No. 4, 1979, pp. 817–829.

[8] Raju, I. S. and Newman, J. C., Jr.; “Stress-Intensity Factors for Two Symmetric Corner Cracks”, Fracture Mechanics, ASTM STP 677, 1979, pp. 411–430.

[9] Newman, J. C., Jr. and Raju, I. S.; "Stress-intensity Factor Equations for Cracks in Three-Dimensional Finite Bodies", Fracture Mechanics, Fourteenth Symposium—Volume 1, Theory and Analysis, ASTM STP 791, 1983, pp. I-238–I-265.

[10] Poe, C. C., Jr.; "Stress-Intensity Factor for a Cracked Sheet with Riveted and Uniformly Spaced Stringers", NASA TR R-358, May 1971.

[11] Swift, T.; "Repairs to Damage Tolerant Aircraft", FAA-AIR-90-01, International Symposium on Structural Integrity of Aging Airplanes, Atlanta, GA, March 1990.

8.5. ASTM Test Standards

NACA and NASA Langley scientists and engineers have contributed greatly to the American Society for Testing and Materials. Herb Hardrath was the Chairman of Committee E-09 on fatigue for many years, and C. Michael Hudson was the Chairman of Committee E-24 on fracture. Hudson was Chairman when it was decided to combine E-09 and E-24 into one Committee, E-08 on fatigue and fracture. Others from NACA and NASA LaRC have been very active on Subcommittees and Task Groups to standardize fatigue, fatigue crack growth and fracture testing. Surprisingly, more than one-half of the crack stress-intensity-factor (K) solutions for fatigue-crack-growth (E-647) and fracture (E-399, E-740, E-1820, and E-2472) standards were generated at NASA LaRC. These two former committees and E-08 have sponsored many symposia and conferences over the years, and many papers by Langley researchers have appeared in many Special Technical Publications (STP). Unfortunately, ASTM STPs have been considered conference proceedings by the public and government libraries, even though the papers had been peer reviewed by two or three reviewers. A large portion of the fatigue and fracture mechanics technology developed over the past 50 years has been published in these STPs and, sadly, these publications may not exist in the future.

8.6. Fatigue Crack Propagation Testing

The classic paper by Paris, Gomez, and Anderson[1] that characterized the growth of fatigue cracks using the linear-elastic stress-intensity factor range, ΔK, revolutionized how crack growth in aircraft structural components could be analyzed. There was a strong effort made by many industry and government organizations to generate these types of data on metallic materials. C. Michael Hudson[2] was one of the first to generate crack-growth-rate data over a wide range in rates and over a wide range in mean-stress levels for two aluminum alloys (2024-T3 and 7075-T6), similar to McEvily and Illg's work on the same alloys 10 years earlier. These data are considered classical examples of how these types of data should be generated. Later, Ed Phillips[3] generated fatigue-crack-growth-rate data at extremely low rates in establishing the threshold behavior on these same two materials. Robert Dubensky,[4] University of Akron, under contract with NASA LaRC, generated fatigue-crack-growth-rate data at extremely high applied-stress levels approaching and exceeding the yield stress of the same two materials. These ΔK-rate data for the 2024-T3 alloy are shown in **Figure 8.6-1**.

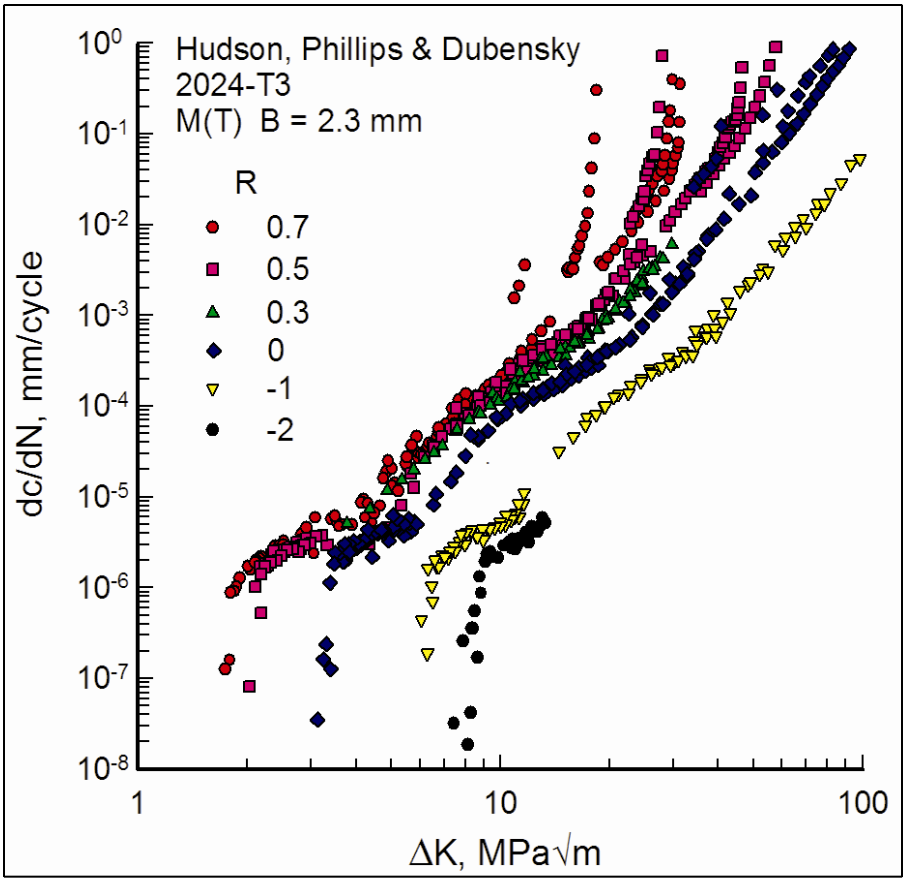


Figure 8.6-1: Fatigue-Crack-Growth-Rate Data on 2024-T3 Aluminum Alloy.

These data were generated on middle-crack-tension, *M*(*T*), specimens (50 to 300 mm wide) over 8 orders of magnitude in rates for stress ratios ($R = S_{min}/S_{max}$) ranging from 0.7 to –2. The negative *R* tests used anti-buckling guides to prevent out-of-plane buckling. These are the types of ΔK-rate data that need to be generated on any material and thickness of interest to conduct a damage-tolerance analysis. Surprisingly, the number of test specimens required to generate these type of data are small due to the computer-controlled test hardware/software available today.

References

[1] Paris, P, C., Gomez, M. P. and Anderson, W.; "A Rational Analytic Theory of Fatigue", The Trend in Engineering, Vol. 13, 1961, pp. 9–14.

[2] Hudson, C. M.; "Effect of Stress Ratio on Fatigue-Crack Growth in 7075-T6 and 2024-T3 Aluminum Alloy Specimens", NASA TN D-5390, 1969.

[3] Phillips, E. P.; "The Influence of Crack Closure on Fatigue Crack Growth Thresholds in 2024-T3 Aluminum Alloy", ASTM STP 982, J. C. Newman, Jr. and W. Elber, eds., American Society for Testing and Materials, Philadelphia, PA, 1988, pp. 505–515.

[4] Dubensky, R. G.; "Fatigue Crack Propagation in 2024-T3 and 7075-T6 Aluminum Alloys at High Stress", NASA CR-1732, March 1971.

8.7. Plasticity-Induced Crack Closure

In 1968, Wolf Elber[1] made a major discovery on the mechanism of fatigue crack growth, and by 1970, he was at NASA LaRC, in large part, due to the efforts of Herb Hardrath. Elber had observed that fatigue crack surfaces contact each other even during tension-tension cyclic loading. This contact was due to residual plastic deformations that are left in the wake of an advancing crack, as illustrated in **Figure 8.7-1(a)**. This deformed material contacts during unloading is called plasticity-induced crack closure (PICC). It is surprising that this observation appeared so many years after crack growth was first studied. This simple observation and the explanation of the crack-closure mechanism (or more properly crack-opening load and the effective stress-intensity factor range) began to explain many crack-growth characteristics almost immediately.[2] Since the discovery of PICC, several other closure or crack-shielding mechanisms, such as roughness- and oxide/corrosion/fretting-product-induced closure, have been identified. The roughness mechanism, discovered by Walker and Beevers,[3] appears to be most prevalent in the near-threshold regime of large-crack growth where the maximum plastic-zone sizes are typically less than the grain size. At these low stress levels, crack extension is primarily along a single slip system resulting in a Stage I-like mechanism and a serrated or zig-zag ($\pm\theta$ deg.) crack-growth path, as shown in **Figure 8.7-1(b)**. These cracks will have mixed-mode (Modes I and II) crack-surface deformations, which provide the mechanism with contact between the surfaces during cyclic loading roughness-induced crack closure (RICC). Cracks growing along a non-planar path, such as during overloads in aluminum alloys, will develop surface contact and create debris due to fretting and the growth of oxides from the newly created crack surfaces (**Figure 8.7-1(c)**). This debris will cause premature contact, as discussed by Paris et al.[4] and is referred to as debris-induced crack closure (DICC). These new closure mechanisms, and the influence of the plastic wake on local crack-tip strain field, have greatly advanced the understanding of the fatigue crack growth process.

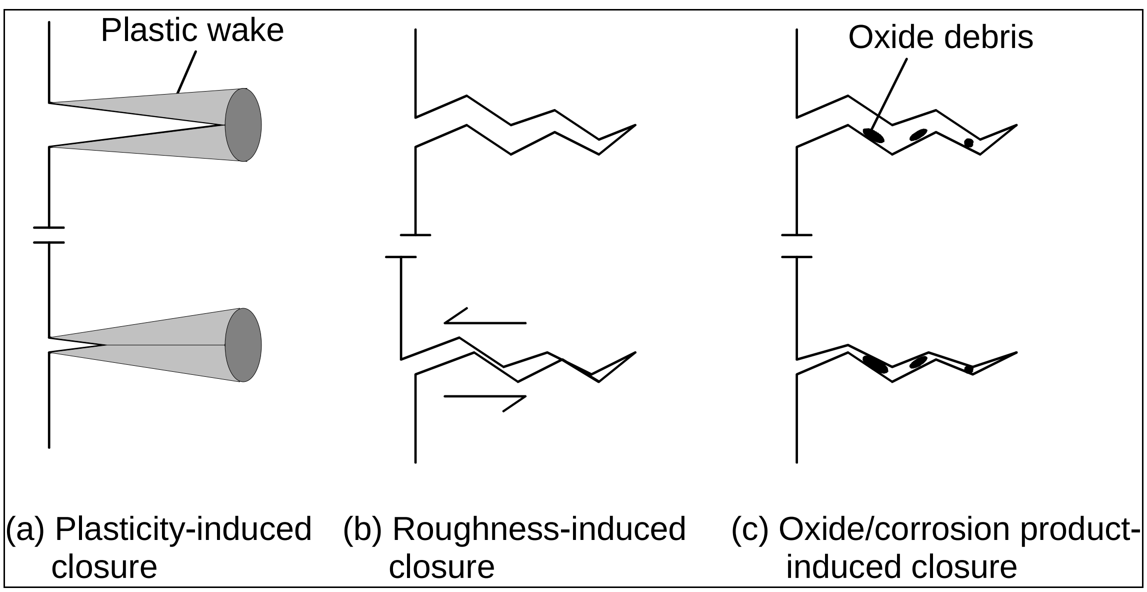


Figure 8.7-1: Dominant Fatigue-Crack-Closure (or Crack-Shielding) Mechanisms.

In the ASTM E-24 Committee, Ed Phillips[5] led a task group activity to standardize the measurement of crack-opening loads. The appendix is part of E-647 on the standard method to determine fatigue-crack-growth rates in metallic materials. This method was developed for constant-amplitude loading, but it has been applied to the load-shedding test to generate near-threshold data, which is a variable-load test, and some difficulties have arisen. Efforts are currently under way to develop constant-amplitude methods to generate threshold and near-threshold data, which will make Elber's and Phillips' method to measure crack-opening loads more reliable.

Shortly after Elber arrived at Langley, Jim Newman[6] began to develop analyses to simulate crack growth and closure. His finite-element analysis was the first major simulation of the crack-growth and closure process, which agreed well with Elber's measurements on 2024-T3. Also, Newman[7] develop a PICC model using the strip-yield concept that is called "FASTRAN"; see the model at maximum and minimum applied remote stresses in **Figure 8.7-2**. The model uses a constraint factor, α, which accounts for the 3-D stress state around a crack front. The constraint factor is very important in modeling crack-closure behavior, especially under variable-amplitude loading. NASGRO,[8] developed at NASA Johnson Space Center by Royce Forman, has a very similar strip-yield model, STRIPY, which uses the FASTRAN logic.

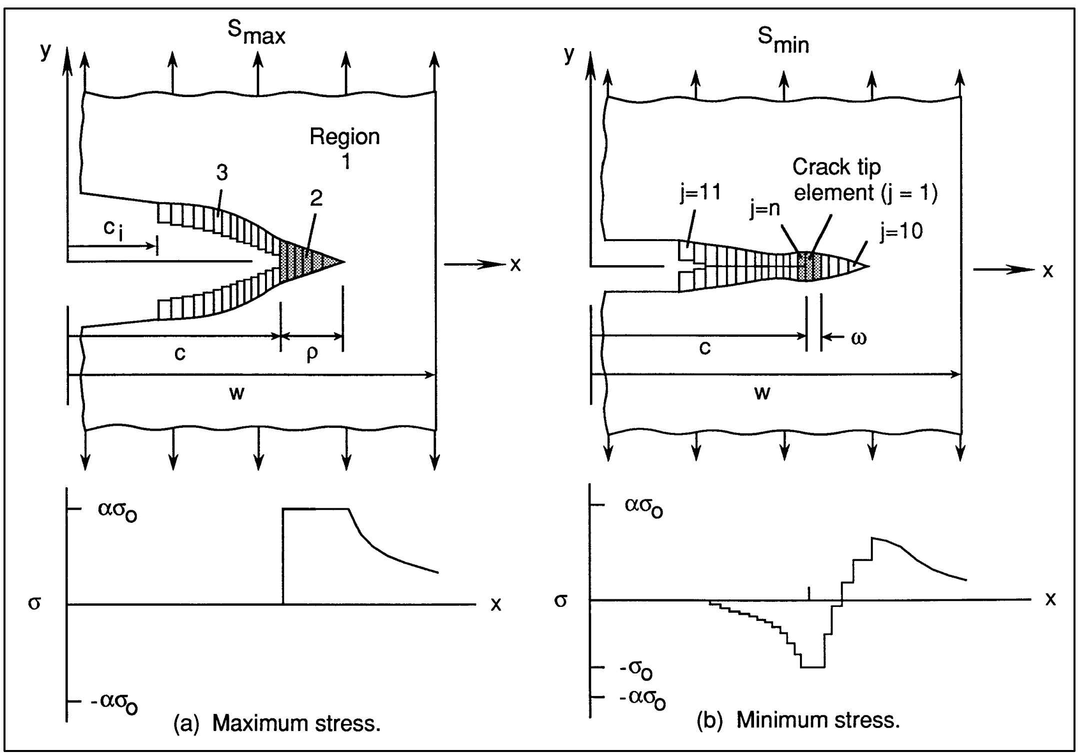


Figure 8.7-2: Fatigue-Crack Growth and Closure Model, FASTRAN, Based PICC.

FASTRAN is an advanced non-linear fracture mechanics model that is able to correlate fatigue-crack-growth-rate data over a wide range in rates and stress ratios (R). The classic fatigue-crack-growth-rate data generated by Hudson, Phillips, and Dubensky has been correlated with the model, as shown in **Figure 8.7-3**. The chart shows Elber's ΔK_{eff} plotted against rate for data over

8 orders-of-magnitude that collapsed the data into a tight band, except in the threshold and fracture regimes. In the fracture regime, it was found that a large portion of Dubensky's data was like an interrupted fracture test (stable-crack growth). The vertical dashed lines are predicted failure values using Newman's two-parameter fracture criterion (like Kuhn's notch-strength analysis). The constraint-loss regime is associated with the flat-to-slant (plane-strain to plane-stress) crack-growth behavior. In the threshold regime, some large differences have been observed between small- and large-crack growth behaviors. This low-rate regime is still a very active area of research that involves PICC, RICC, and DICC mechanisms.

Andy Newman[9] has made a very nice advancement in modeling the three major mechanisms. In the future, these three mechanisms need to be incorporated into a model like FASTRAN. One of the major advantages of the FASTRAN model is its ability to predict crack growth under aircraft spectrum loading. Again, some areas of difficulty involve the three crack-growth mechanisms.

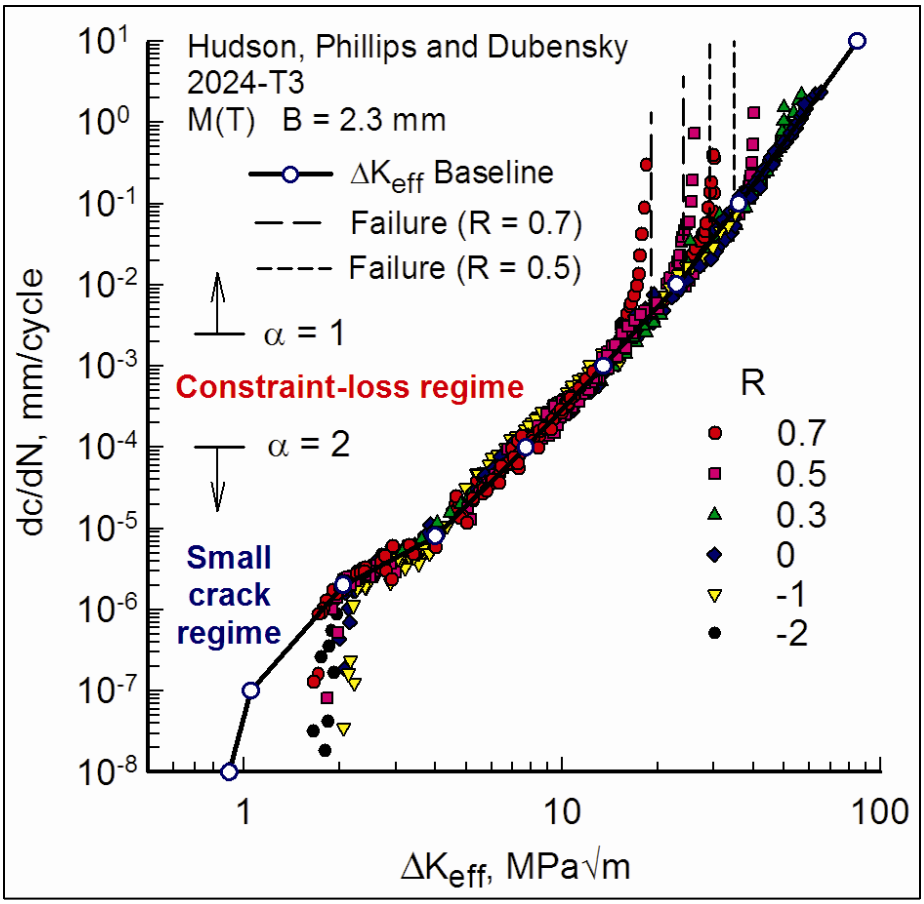


Figure 8.7-3: Correlation of Fatigue-Crack-Growth-Rates Against ΔK_{eff} Using the FASTRAN Model.

References

[1] Elber, W.; "Fatigue Crack Propagation", Ph.D. Thesis, University of New South Wales, 1968.
[2] Elber, W., "The Significance of Fatigue Crack Closure," Damage Tolerance in Aircraft Structures, ASTM STP 486, 1971, pp. 230–242.
[3] Walker, N. and Beevers, C. J.; "A Fatigue Crack Closure Mechanism in Titanium", Fatigue of Engineering Materials and Structures, Vol. 1, No. 1, 1979, pp. 135–148.
[4] Paris, P. C., Bucci, R. J., Wessel, E. T., Clark, W. G. and Mager, T. R.; "Extensive Study of Low Fatigue Crack Growth Rates in A533 and A508 Steels", ASTM STP 513, 1972, pp. 141–176.
[5] Phillips, E. P.; "Results of the Round Robin on Opening-Load Measurement", NASA TM 101601, May 1989.
[6] Newman, J. C., Jr.; "Finite-Element Analysis of Fatigue Crack Propagation Including the Effects of Crack Closure", Virginia Polytechnic Institute and State University, 1974.
[7] Newman, J. C., Jr.; "A Crack-Closure Model for Predicting Fatigue Crack Growth under Aircraft Spectrum Loading", ASTM STP 748, American Society for Testing and Materials, Philadelphia, PA, 1981, pp. 53–84.
[8] NASGRO Reference Manual Version 5.2, Southwest Research Institute and NASA Johnson Space Center, 2008.
[9] Newman, J. A.; "The Effects of Load Ratio on Threshold Fatigue Crack Growth of Aluminum Alloys", Ph.D. Thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA, 2000.

8.8. Small Crack Growth

Dr. Jim Newman presented the seventh annual Jerry L. Swedlow Memorial Lecture at the 1997 ASTM Committee E08 on fatigue and fracture annual meeting. The paper published was entitled "Merging of Fatigue and Fracture Mechanics Concepts: A Historical Perspective."[1] In this paper Dr. Newman give an excellent history of fatigue and fracture. The brief section from that paper related to small crack growth is presented below.

In the mid-1970s, Pearson[2] and Kitagawa[3] showed that short cracks (less than about 0.5 mm in length) grew much faster than long cracks when correlated against the stress-intensity factor range. During the next two decades, short- or small-crack research formed the final link between fatigue and fracture mechanics. These studies, conducted by many world-wide organizations[4,5] including the AGARD Structures and Materials Panel[6,7,8] ASTM Committees E9 and E24,[9] NASA, and the CAE[10] provided experimental databases and analysis methods to perform fatigue analyses on notch components using "crack propagation" theories. The small-crack theory (treatment of fatigue as the growth of microcracks, 1–20 micrometers in length) has been applied to many engineering materials with reasonable success. The local notch-root stresses and strains from classical fatigue analyses are the driving forces behind the initiation and growth of small cracks at material discontinuities or manufacturing defects. The merging of fatigue and fracture mechanics concepts has provided industries with a unified approach to life prediction. Small-crack theory can now be used to assess the influence of material defects and manufacturing or service-induced damage on fatigue life behavior. This approach has improved the reliability and economic usefulness of many structures.

References

[1] Newman, J. C., Jr.; "The Merging of Fatigue and Fracture Mechanics Concepts: A Historical Perspective", Fatigue and Fracture Mechanics: 28th Volume, ASTM STP 1321., J. H. Underwood, B. D. MacDonald, and M. R. Mitchell, Eds., American Society for Testing and Materials, Philadelphia, PA, 1997

[2] Pearson, S.; Engineering Fracture Mechanics, Vol. 7, No. 2, 1975, pp 235–247.

[3] Kitagawa, H. and Takahashi, S.; Proceedings of 2ndInternational Conference on Mechanical Behavior of Materials, Boston, MA, 1976, pp 627–631.

[4] Ritchie, R. O. and Lankford, J., eds.; Small Fatigue Cracks, The Metallurgical Society, Inc., Warrendale, PA, 1986.

[5] Miller, K. J. and de los Rios, E. R., eds.; The Behavior of Short Fatigue Cracks, European Group on Fracture, Publication No. 1, 1986.

[6] Zocher, H., ed., AGARD CP-328, 1983.

[7] Newman, J. C., Jr. and Edwards, P. R.; AGARD Report No. 732, 1988.

[8] Edwards, P. R. and Newman, J. C., Jr., eds.; AGARD Report No. 767, 1990.

[9] Larsen, J. M. and Allison, J. E., eds.; ASTM STP 1149, 1992.

[10] Newman, J. C., Jr.; Wu, X. R.; Venneri, S. L and Li, C. G.; NASA RP-1309, 1994

8.9. Structural Integrity Analyses Methods

8.9.1. Structural Analysis Code

It is interesting to note that one of NASA's most significant and lasting technical contributions in the field of structures and materials[1] was a direct result of a collaborative effort among all the NASA Field Centers. In January 1964, key personnel from all NASA Field Centers gathered at Headquarters in Washington, D.C. to discuss efforts underway to improve structural analysis methods, particularly as it applied to the shell configurations commonly used in aerospace structure. Each representative described how his group had written special-purpose computer programs to analyze particular shell configurations. After this meeting, NASA Headquarters commissioned an ad hoc committee, with a representative from each NASA Center, to investigate the state of analysis methods in the aerospace industry. The first action taken by the committee was to visit the aircraft companies that were doing prominent work in developing computer–based, advanced structural analysis methods. The committee's visits to the aircraft companies revealed that no single computer program incorporated enough of the best analysis features desired by NASA. Therefore, the committee recommended to Headquarters that NASA sponsors the development of its own computer program as a means to upgrade the analytical capability of the whole aerospace industry. Headquarters endorsed the recommendation and selected Goddard Space Flight Center (GSFC) to manage the development of the computer program. Under the leadership of GSFC, the ad hoc committee developed a visionary and thorough technical specification for the computer program and released a Request for Proposals in July 1965. Much of the eventual success of the project was directly attributed to the initial work of the NASA committee in developing the thorough specification for the computer program.[2] In December 1965, NASA awarded two Phase I contracts for preparation of a Technical Evaluation Report: one to a team led by the MacNeal-Schwendler Corporation (MSC) and one to the team led by Douglas Aircraft Company. After an evaluation of the two competing Phase I reports and the associated Phase II proposals, MSC was selected as the recipient of the Phase II contract and began development of the computer program in July 1966. Shortly thereafter, NASA designated the name of the computer program to be the NAsA STructural ANalysis (NASTRAN) Computer Program. The contracting team completed the computer program in 1969 and delivered it to all the NASA Field Centers. In February 1970, the Program Office at Goddard was disbanded. Later that year, NASA Headquarters established the NASTRAN Systems Management Office (NSMO) at Langley Research Center. The NSMO had the dual mission of maintaining NASTRAN and developing new capabilities for the program. A NASTRAN Advisory Group was set up to provide guidance to the NSMO. This Advisory Group consisted of members from each of the NASA Centers and was, in effect, a continuation of the ad hoc committee which drafted the initial NASTRAN specification in 1964. In November 1970, NASTRAN was released to the public through the COSMIC Distribution Center at the University of Georgia for the price of $1750. Less than a year later in September, the first NASTRAN Users Conference held at Langley Research Center was attended by about 200 representatives of the rapidly growing user community. Thus were the origins of the most successful finite element structural analysis computer code used throughout the world and in virtually all industrial sectors.

References

[1] Harris, Charles E.; "Implementation Plan for the NASA Center of Excellence for Structures and Materials", NASA/TM-1998-208714.

[2] The MacNeal-Schwendler Corporation; The First Twenty Five Years , by Dr. Richard H. MacNeal, The MacNeal-Schwendler Corporation, Major Aerospace and Defense Accounts, 1000 Howard Blvd., Suite 105, Mount Laurel, NJ 08054, 1988

8.10. Residual Strength Analyses Methodology

An excellent review paper entitled "Advances in Structural Integrity Analysis Methods for Aging Metallic Airframe Structures with Local Damage" by James H. Starnes, Jr., James C. Newman, Jr., Charles E. Harris, Robert S. Piascik, Richard D. Young, and Cheryl A. Rose was presented at the RTO AVT Specialists' Meeting on "Life Management Techniques for Ageing Air Vehicles," held in Manchester, United Kingdom, October 8–11, 2001, and published in RTO-MP-079(II). This paper gives a comprehensive description of the fatigue crack growth analysis and the residual strength analysis methodology developed at NASA Langley Research Center. The fatigue crack growth analysis methodology is based on small-crack theory and a plasticity induced crack-closure mode.[1] The residual strength analysis methodology is based on elastic-plastic fracture mechanics and nonlinear structural analyses[2] and is general enough to include the effects of multiple-site damage. This methodology includes a critical crack-tip opening-angle (CTOA) fracture criterion[3,4] and the Structural Analysis of General Shells (STAGS) nonlinear shell analysis code.[5] This analysis methodology accounts for both material and geometric nonlinear behavioral characteristics of the materials and structures of interest. The following sections describe the CTOA fracture criterion, and the geometric and material nonlinear, finite-element shell analysis code STAGS used in the residual strength analysis methodology.

8.10.1. CTOA Fracture Criterion and Plane-Strain-Core Height

One of the objectives of the NASA Airframe Structural Integrity Program[2] was to develop the methodology to predict the residual strength of fuselage structures with large two-bay cracks in the presence of multiple-site damage (MSD) cracking at adjacent rivet holes. The prediction of the residual strength of a complex built-up shell structure, such as a fuselage with frames, tear-straps, and lap-splice joints, required the integration of a ductile fracture criterion and a detailed nonlinear stress analysis of the cracked structure. The critical crack-tip opening-angle fracture criterion has been experimentally verified to be a valid fracture criterion for mode I stress states in thin and moderately thick (13 mm or less) aluminum alloys. The CTOA criterion has been demonstrated to be valid for predicting the link-up of a large lead crack with small fatigue cracks ahead of the advancing lead crack. This fracture criterion has been implemented into the STAGS geometric and material nonlinear finite-element-based shell analysis code[6,5] to provide an integrated structural-integrity analysis methodology.

The CTOA/CTOD fracture criterion is one of the oldest fracture criteria applied to the failure of metallic materials with cracks.[7] The use of elastic-plastic finite-element analyses to simulate fracture of laboratory specimens and structural components using the CTOA fracture criterion has expanded rapidly.[8] The early finite-element applications were restricted to two-dimensional analyses, assuming either plane-stress or plane-strain behavior around the crack-front region, which lead to generally non-constant values of CTOA, especially in the early stages of crack extension. Later, the non-constant CTOA values were traced to inappropriate state-of-stress (or constraint) assumptions in the crack-front region, blunting of the crack tip, and severe crack tunneling in thin-sheet materials. To account for the high-constraint around the crack front, the concept of the "plane-strain core" was developed.[9] This concept was implemented into ZIP2D (a two-dimensional finite-element code) and STAGS.[5,6] The plane-strain core allowed for more accurate fracture simulations on laboratory specimens and some simple structural cracked configurations. More recently, the CTOA fracture criterion has been used with three-dimensional finite-element analyses (ZIP3D[10]) to study constraint effects, crack tunneling, and the fracture process. The constant CTOA criterion (from crack initiation to failure) has been successfully applied to numerous structural applications, such as aircraft fuselages[11] and pipelines.[8] (The critical CTOA fracture parameter is used in an ASTM fracture standard E-2472.[12])

A high-resolution photographic camera with a video system was used to measure the critical CTOA values during stable crack growth in a thin-sheet 2024-T3 aluminum alloy, as shown in **Figure 8.10-1**. The critical CTOA values were nearly constant after a small amount of tearing.

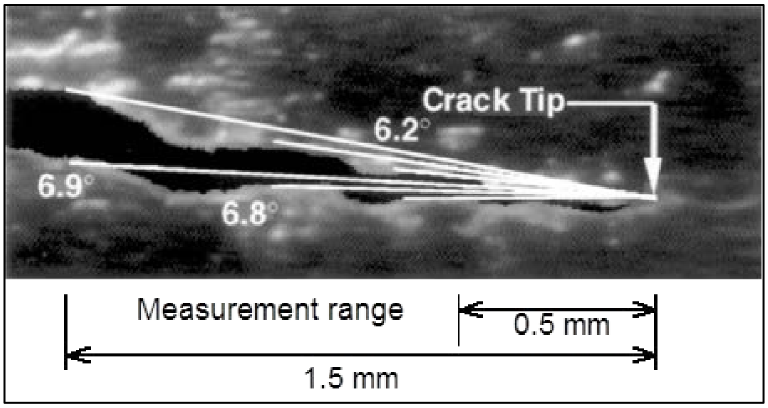


Figure 8.10-1: Photograph of Tearing Crack and Measurement of Critical Crack-Tip Opening Angle (CTOA) in 2024-T3 Aluminum Alloy.

The values measured on the aluminum alloy for both middle-crack tension M(T) and compact C(T) specimens are shown in **Figure 8.10-2** as a function of surface measured crack extension, Δc_S. The C(T) specimen is primarily a bend specimen and the results show that both tension and bend specimens produce nearly the same critical CTOA after a small amount of crack extension. This validates that the critical CTOA fracture criterion can be used for complex cracked structural components under combined loading conditions. The non-constant CTOA region (measured at the free surface) has been shown to be associated with crack-tip blunting and severe tunneling during the initiation of stable tearing. In addition to the high-resolution photographic method, a digital-imaging correlation method was used to measure the surface CTOA values. These two methods gave very similar CTOA values for the thin-sheet aluminum alloys.

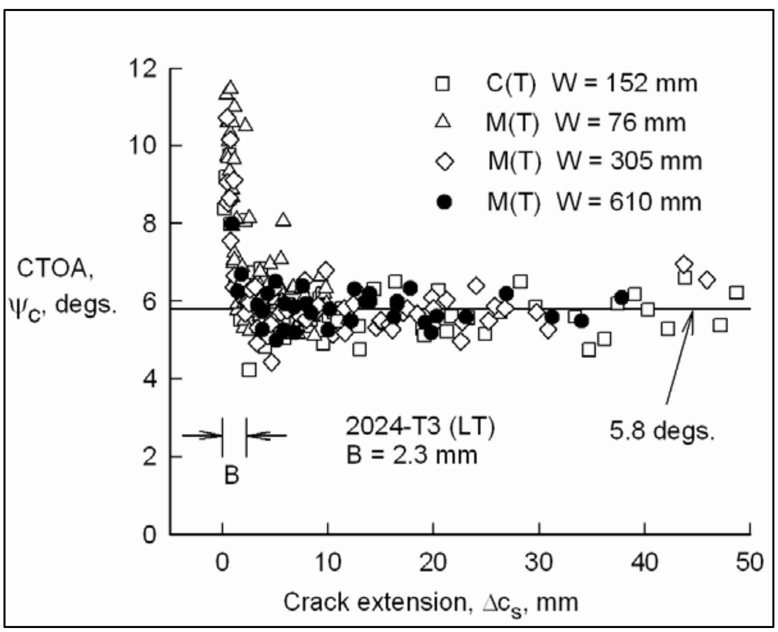


Figure 8.10-2: Measured Critical CTOA Values for Compact and Middle-Crack Tension Specimens on 2024-T3 (LT).

The CTOA criterion assumes that crack extension will occur when the CTOA reaches a critical value, CTOAcr, and that the CTOAcr will remain constant as the crack extends. The critical CTOA value can be obtained experimentally using a photographic technique, but significant scatter is usually present in the measurements. A better method of determining the critical CTOA value is to simulate the fracture behavior of a laboratory specimen with a three dimensional elastic-plastic finite element analysis and determine the angle that best describes the experimentally observed fracture behavior.

An example demonstrating the use of a three-dimensional, elastic-plastic finite element analysis to determine the critical CTOA for three different thicknesses of 2024-T3 aluminum alloy is shown in **Figure 8.10-3**, where the critical value of CTOA for each thickness is represented by the symbol Ψ_c. Results of compact tension (C(T)) laboratory tests are shown in **Figure 8.10-3** for 2024-T3 aluminum-alloy sheets with the cracks parallel to the sheet rolling direction.

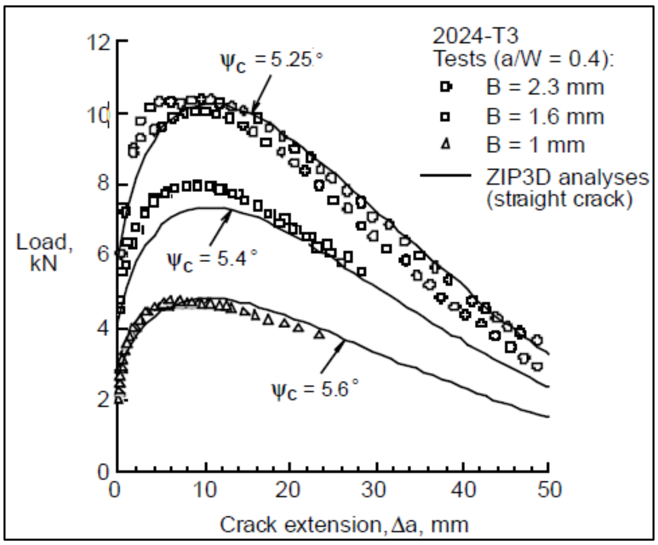


Figure 8.10-3: Experimental Fracture Measurements and ZIP3D Finite Element Predictions for 152 mm wide C(T) specimens of 2024-T3 aluminum alloy with an initial crack length of a/W = 0.4 and three specimen thicknesses.

The compact-tension test specimens are 152 mm wide with an initial crack length a = 61 mm. Data for three different sheet thicknesses are shown on the figure. Analytical results from the geometrically linear elastic-plastic three-dimensional finite element code ZIP3D 12 are also shown on the figures, and the critical CTOA values represent the best fit with the test data. A three-dimensional finite element analysis code, such as ZIP3D, requires only the critical CTOA to predict the fracture behavior of thin ductile materials, since three dimensional constraint effects that develop at the local crack tip are explicitly accounted for in the model. In a finite-element shell analysis code, which typically uses two-dimensional plane-stress elements, a modeling approximation is required to simulate the actual state of stress near the crack tip. The modeling approximation used in the present methodology is to introduce a thin strip of plane-strain elements in a region on each side of the crack line. The width of the plane-strain region on each side of the crack line is commonly referred to as the plane-strain-core height, h_c, and is approximately equal to the thickness of the specimen. This strip of plane-strain elements has plane-strain conditions, while the remainder of the model has plane-stress conditions, as illustrated in **Figure 8.10-4**.

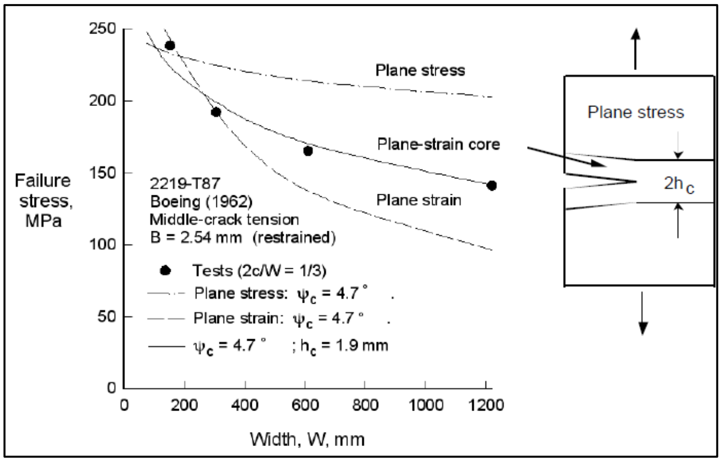


Figure 8.10-4: ZIP2D Finite Element Predictions for C(T) specimens to determine plane-strain core height, h_c.

The plane-strain-core height, h_c, is determined from analyses using the two-dimensional ZIP2D code, and the critical angle determined from the ZIP3D analysis is used to determine the value of h_c that makes the ZIP2D analysis results consistent with the ZIP3D results, as shown in **Figure 8.10-3**.

8.10.1.1. Laboratory Specimens With and Without Anti-Buckling Guides

The STAGS shell code[5,6] and the critical CTOA fracture criterion were used to study the behavior of cracked panels that were either restrained from buckling or allowed to buckle.[13] It has been found that the same CTOA can be used to predict the effects of buckling on stable tearing. An illustration of the STAGS/CTOA capability is shown in **Figure 8.10-5**. Two middle-crack tension panels (W = 610 mm wide) were tested with anti-buckling guides, and these results are shown as the uppermost symbols. Then, two identical crack panels were tested without the guides, and these results are shown as the lower symbols. Buckling had a large influence (about 25%) on the residual strength. The critical CTOA (Ψ_c) of 5 degrees was determined from a ZIP3D fracture analysis and the plane-strain core height (h_c) of 1 mm was determined from a ZIP2D fracture analysis (to fit the ZIP3D results) from 152 mm wide compact tension specimen tests.[14] The Ψ_c and h_c values were then used in the STAGS code (with the plane-strain core option[5]) to predict stable tearing on the panel restrained from buckling (dashed curve) and the panel allowed to buckle (solid curve). The predicted results agreed quite well with the test data and demonstrate that the fracture methodology can account for severe out-of-plane deformations. This methodology has also been successful used to predict stable tearing and residual strength in large curved pressured fuselage test articles within about 10%.

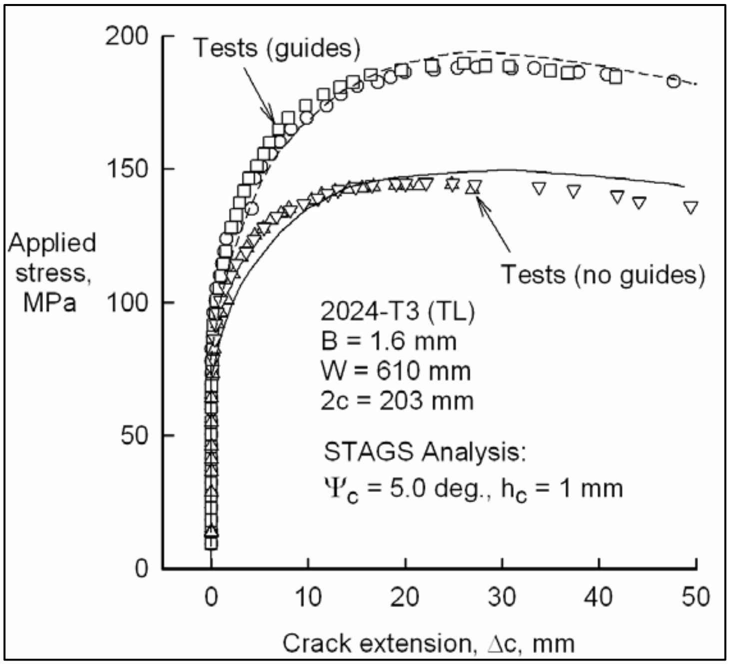


Figure 8.10-5: Measured and Predicted Stable Tearing Using STAGS in Buckling-Restrained and Buckling Panels.

References

[1] Newman, J. C., Jr.; "FASTRAN-lI -A Fatigue Crack Growth Structural Analysis Program", NASA TM 104159, 1992.

[2] Harris, C. E., Newman, J. C., Jr., Piascik, R. S., and Starnes, J. H., Jr.; "Analytical Methodology for predicting the Onset of Widespread Fatigue Damage in Fuselage Structure", Journal of Aircraft, Vol. 35, No. 2, 1998, pp. 307–317.

[3] Newman, J.C., Jr.; "An Elastic-Plastic Finite Element Analysis of Crack Initiation, Stable Crack Growth, and Instability", ASTM STP 833, 1984, pp. 93–117.

[4] Dawicke, D. S., Sutton, M. A., Newman, J. C., Jr., and Bigelow, C. A.; "Measurement and Analysis of Critical CTOA for an Aluminum Alloy Sheet", NASA TM-109024, September 1993.

[5] Rankin, C. C., Brogan, F. A., Loden, W. A., and Cabiness, H. D.; "STAGS User Manual, Version 3.0", Lockheed Martin Missiles and Space Co., Inc., Advanced Technology Center, Report LMMS P032594, June 1998

[6] Almroth, B.; Brogan, F. and Stanley, G.; "User's Manual for STAGS", NASA CR 165670, 1978.

[7] de Koning, A. U.; "A Contribution to the Analysis of Slow Stable Crack Growth", National Aerospace Laboratory Report NLR MP 75035U, 1975.

[8] Newman, J. C., Jr. and Zerbst, U. (editors), "Fundamentals and Applications of the Crack Tip Opening Angle (CTOA)", Engineering Fracture Mechanics, Vol. 70, No. 3-4, 2003.

[9] Newman, J. C., Jr.; Bigelow, C. A. and Dawicke, D. S.; "Finite-Element Analyses and Fracture Simulation in Thin-Sheet Aluminum Alloy", Durability of Metal Aircraft Structures, S. N. Atluri et al, eds., W. H. Wolfe Associates, Alpharetta, GA., 1992, pp. 167–186.
[10] Shivakumar, K. N., and Newman, J. C., Jr.; "ZIP3D - An Elastic-Plastic Finite-Element Analysis Program for Cracked Bodies", NASA TM-102753, 1990.
[11] Hsu, C.; James, L.; Yu, J.; Lee, X. and Tan, P.; "Residual Strength Analysis using CTOA Criteria for Fuselage Structures containing Multiple Site Damage", Engineering Fracture Mechanics, Vol. 70, No. 3-4, 2003, pp. 525–545.
[12] Standard Test Method for Determination of Resistance to Stable Crack Extension under Low-Constraint Conditions, E-2472, Volume 3.01 – Metals Test Methods and Analytical Procedure, 2006.
[13] Seshadri, B. R. and Newman, J. C., Jr.; "Analysis of Buckling and Stable Tearing in Thin-Sheet Materials", Fatigue and Fracture Mechanics: 29th Volume, ASTM STP 1332, American Society for Testing and Materials, 1998, pp. 114–134.
[14] Young, R. D.; Rouse, M.; Ambur, D. R.; and Starnes, J. H.; "Residual Strength Pressure Tests and Nonlinear Analyses of Stringer- and Frame-Stiffened Aluminum Fuselage Panels with Longitudinal Cracks", The Second Joint NASA/FAA/DoD Conference on Aging Aircraft, C. E. Harris, ed., NASA CP-208982, 1999, pp. 408–426.

8.11. Crack-tip-Opening-Angle (CTOA) Fracture Criterion and the STAGS Nonlinear Finite Element Shell Analysis Code

8.11.1. Nonlinear Structural Analysis Code

The STAGS nonlinear shell analysis code[1] is used in the residual strength analysis methodology to predict the response and residual strength of unstiffened aluminum shells and stiffened aluminum fuselage panels with longitudinal cracks.–STAGS is a finite-element code for analyzing general shells and includes the effects of geometric and material nonlinearities in the analysis. STAGS can perform crack-propagation analyses, and can represent the effects of crack growth on nonlinear shell response. A nodal release method and a load relaxation technique are used to extend a crack while the shell is in a nonlinear equilibrium state. The changes in the stiffness matrix and the internal load distribution that occur during crack growth are accounted for in the analysis, and the nonlinear coupling between internal forces and in- and out-of-plane displacement gradients that occurs in a shell are properly represented.

8.11.2. Stiffened Panels with Single and Multi-site Damage

NASA and the FAA jointly designed and conducted fracture tests on 1016 mm wide sheets made of 1.6 mm thick 2024-T3 aluminum alloy with and without stiffeners.[2] Some of the specimens had five 7075-T6 aluminum alloy stiffeners (2.2 mm thick) riveted on each side of the sheet, as shown in **Figure 8.11-1**. The central stiffeners were cut along the crack line. Open holes were machined into the sheet at the required rivet spacing along the crack line, but rivets were not installed. Five different crack configurations were tested: a single center crack, a single center crack with an array of 12 holes on either side of the lead crack, and a single center crack with three different equal MSD cracks (0.25, 0.76, and 1.3 mm) at the edge of each hole.[2] For each crack configuration, identical specimens were tested with and without riveted stringers. All tests were conducted under stroke control. Measurements were made of load against crack extension. A photograph of one of the stiffened panels is shown in a high-load capacity test machine at NASA LaRC in **Figure 8.11-2**.

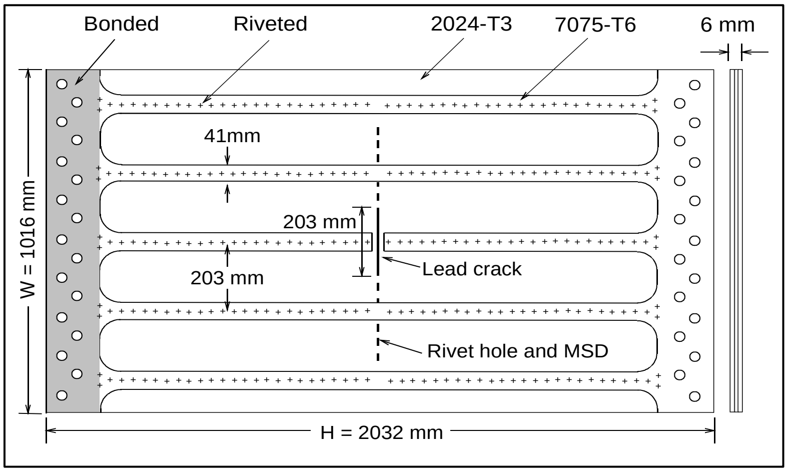


Figure 8.11-1: Wide Stiffened Panel With Single Lead Crack and Multiple-Site Damage.

Figure 8.11-2: Wide Stiffened Panel in Test Frame at NASA LaRC.

Comparisons of measured and predicted load against crack extension for a stiffened panel test with a single crack and a test with a single crack and MSD are shown in **Figure 8.11-3** and **Figure** 8.11-4, respectively. The CTOA (Ψ_c = 5.4 deg.) was determined from laboratory specimens restrained from buckling.[2] The stiffened panels were allowed to buckle. The STAGS analyses with the plane-strain core (h_c = 2 mm) compared well with the test data (symbols). These results demonstrate that the residual-strength analysis method can predict stable crack growth and failure loads for complex structure.

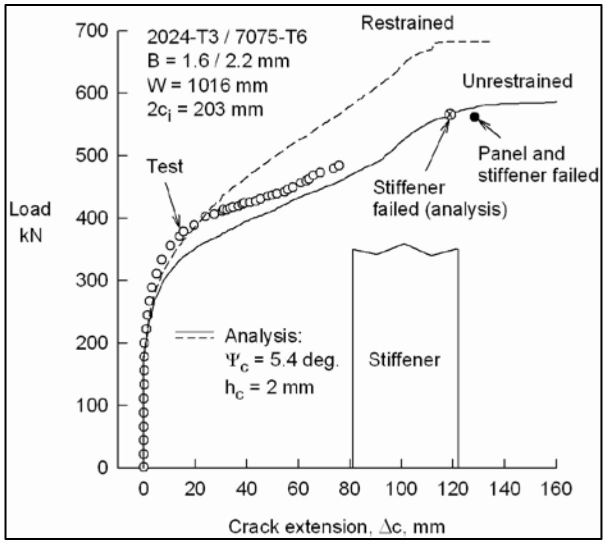


Figure 8.11-3: Measured and Predicted Load-Against-Crack Extension for Stiffened Panel with a Single Crack.

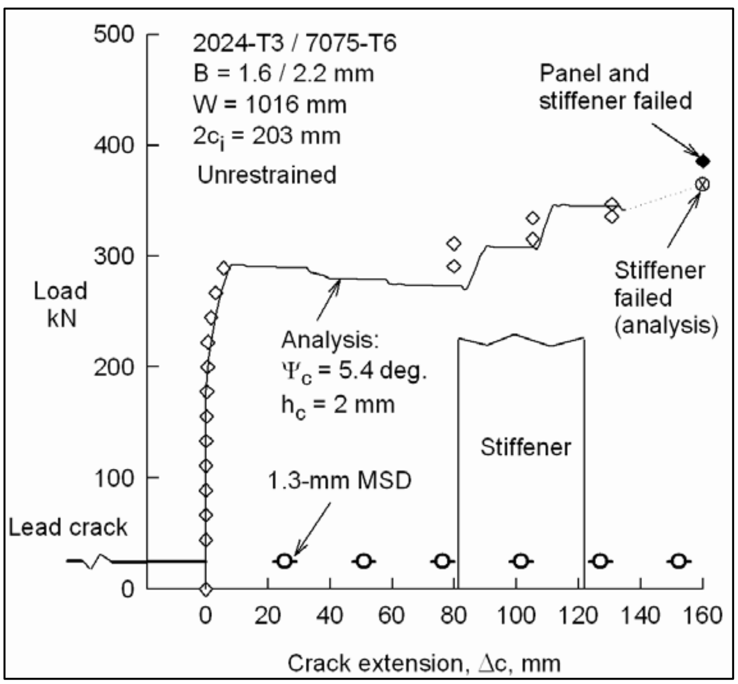


Figure 8.11-4: Measured and predicted Load-Against-Crack Extension for Stiffened Panel with a Single Crack and MSD.

The measured and predicted load-against-crack extension for stiffened panel with a single crack and MSD are shown in **Figure 8.11-4**.

8.11.2.1. DC-9 Aft-Bulk Head with Large Lead Crack and MSD

An extensive experimental program was conducted by the Boeing Company under the funding of the Federal Aviation Administration (FAA), NASA, and the United States Air Force Research Laboratory (AFRL) to investigate the effects of multiple-site damage on the residual strength of typical fuselage splice joints.[3] The experimental results were used to validate the analytical prediction using various methodologies, including STAGS (a generalized shell finite-element code) with the crack-tip opening angle and T* (generalized path independent J-integral related to material energy-release rate) fracture criteria. The test specimens consisted of large flat panels, curved panels, and an aft pressure bulkhead. The flat panel specimens included three types of longitudinal splice joints and one type of circumferential splice joint. For each type, one panel contained only a lead crack and the other two panels contained MSD 1.3 and 2.5 mm in size, respectively, at the fastener holes ahead of the lead crack. The curved panels were tested under simulated loads of combined cabin pressure and fuselage down bending. Two skin splice types were tested. For each splice type, one panel contained a lead crack only and the other had a lead crack with various sizes of MSD. A section of a DC-9 aft fuselage, as shown in **Figure 8.11-5**, containing a large lead crack and MSD in the pressure dome was also tested to demonstrate the capabilities of the methodologies in analyzing actual aircraft structures.

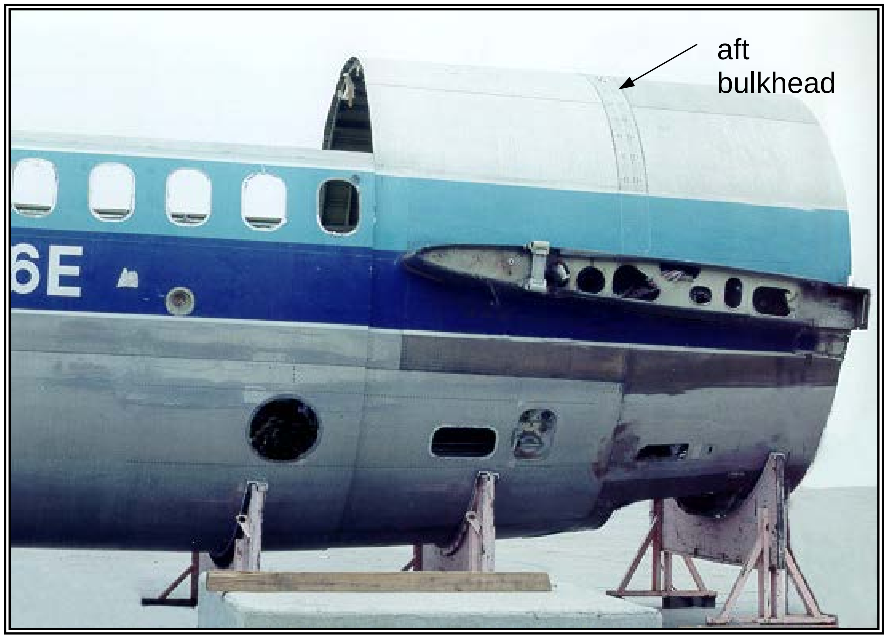


Figure 8.11-5: DC-9 Aft Fuselage and Bulkhead Used in the Residual-Strength Demonstration.

The structural configuration was fabricated from a salvaged DC-9 Series 30 aft fuselage barrel with 57,757 landings and 60,583 flight hours. The aft pressure dome web was made of 2014-T3 aluminum alloy with a nominal thickness of 1.0 mm, which was attached to an outer ring via two rows of 4.0 mm diameter aluminum rivets 19 mm apart. The cross section of the joint is shown in **Figure 8.11-6**. A simulated primary damage 279 mm in length was introduced to the web at the first fastener row. Simulated MSD approximately 1.27 mm in size were introduced to the fastener holes in the projected path of the primary damage. The overall area with MSD and lead crack was approximately 914 mm long, located on the left side of the fuselage, 1016 mm above the cabin floor. The test specimen was mounted to a strongback and pressurized using regulated plant air to 53.8 KPa several times for an initial strain survey. Following the strain survey, the specimen was then pressurized in small increments until failure occurred at approximately 62

KPa at the aft pressure dome web. The critical areas were continuously monitored by remotely controlled video cameras during the test.

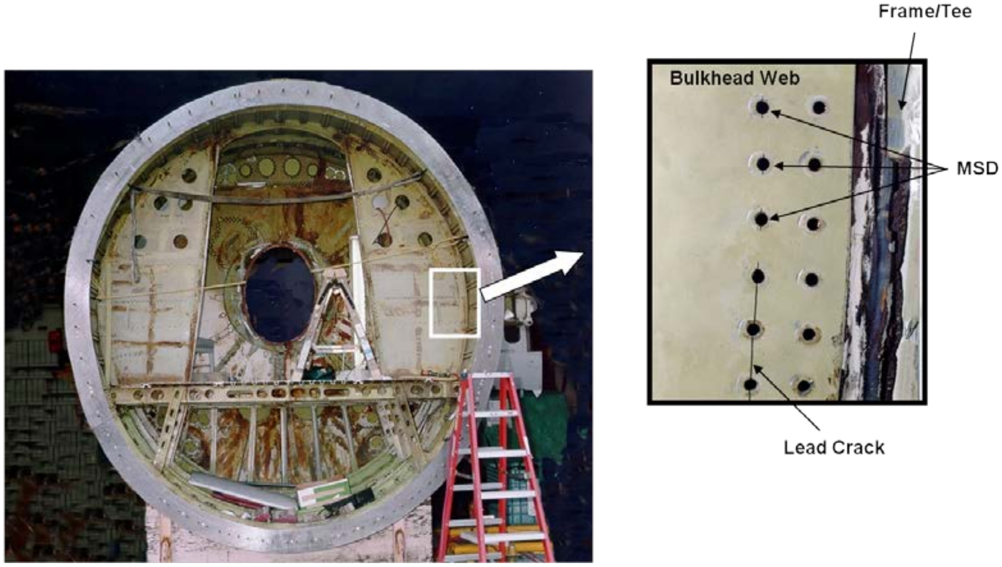
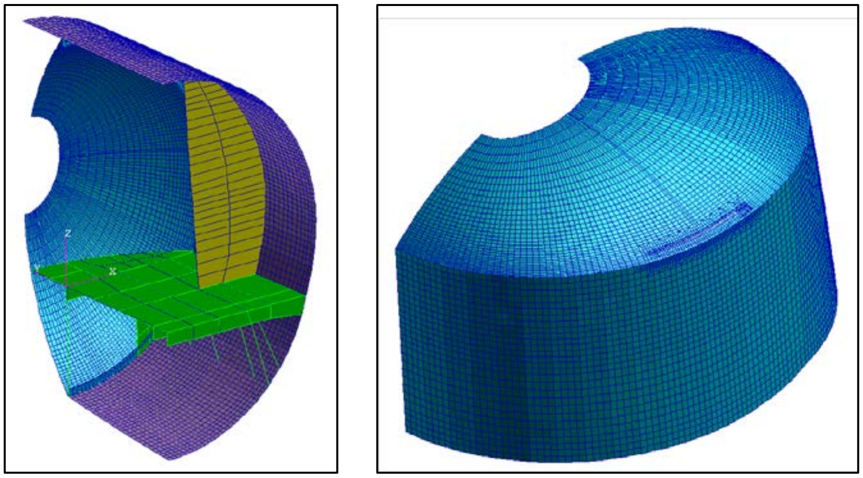


Figure 8.11-6: Inside View of DC-9 Aft Bulkhead with Large Lead Crack and MSD.

The STAGS finite-element model for the test article includes a section of aft fuselage shell approximately 2.5 m in length, the passenger floor, the under-floor struts, the pylon bulkhead, and the aft-pressure bulkhead. Beam elements were used to model the longerons, frames, and local reinforcements such as the radial stiffeners and doorjamb in the pressure dome. Quadrilateral shell elements were used to model the fuselage skin, the dome web, the floor, and the pylon bulkhead. To take advantage of symmetry, only the left hand side of the test article was modeled. The overall view of the finite-element model is shown in **Figure 8.11-7**. Bar elements with specified shear stiffness were used to represent the fasteners in the joint. The shear stiffness of the fasteners was calculated based on the fastener stiffness equation derived by Swift.[4] The mirror image boundary conditions are applied to the symmetry plane of the model. A series of rigid constraints were used to prevent relative out-of-plane displacement for each pair of the coincident nodes along the cracked surfaces in the dome web (**Figure 8.11-8)**. The reason for the additional constraints is to simulate the dome web being pressed against the T-ring forcing the two sides of the crack surface to remain planar.



(a) STAGS model of aft-bulkhead and fuselage **(b) STAGS model of aft-bulkhead dome with damage**

Figure 8.11-7: Overall View of STAGS Model for Aft-Pressure Bulkhead.

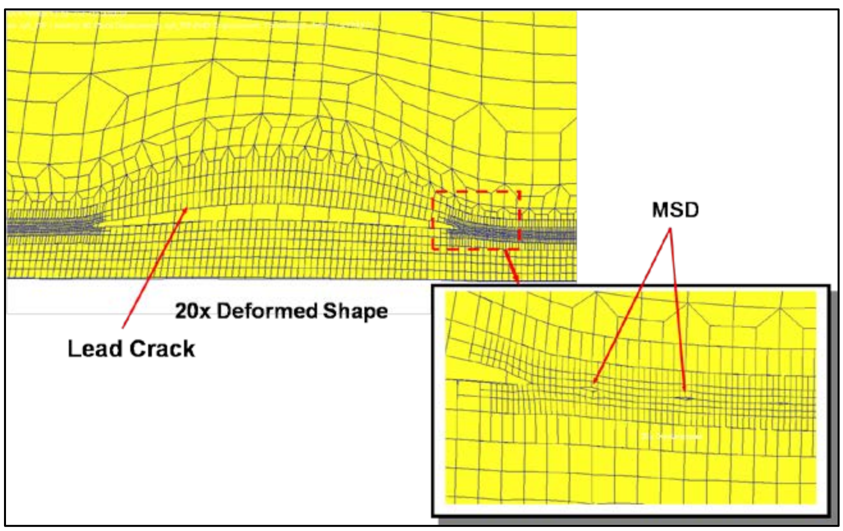


Figure 8.11-8: Local View of Damage (Lead Crack and MSD) in Aft-Bulkhead.

Stable tearing of the lead crack was analyzed using the STAGS code and a critical tearing angle Ψ_c of 3.4 degrees for the 2014-T3 aluminum alloy. The pressure loading was incrementally increased starting from 0.3 KPa. The stable-tearing prediction of applied cabin pressure against crack-tip location is shown in **Figure 8.11-9**, the upper tip being shown on the left hand side and the lower tip on the right hand side. The STAGS prediction indicated that the lead crack started to propagate at a cabin pressure level of approximately 56.5 Kpa, linking up with the MSD in the first adjacent fastener hole at 64 KPa. The lead crack became unstable immediately after the first link-up. No indication of propagation for the MSD cracks was predicted. The predicted failure pressure correlates well with the experimental result of 62 KPa. The difference in the test and predicted failure pressure was within 5%.

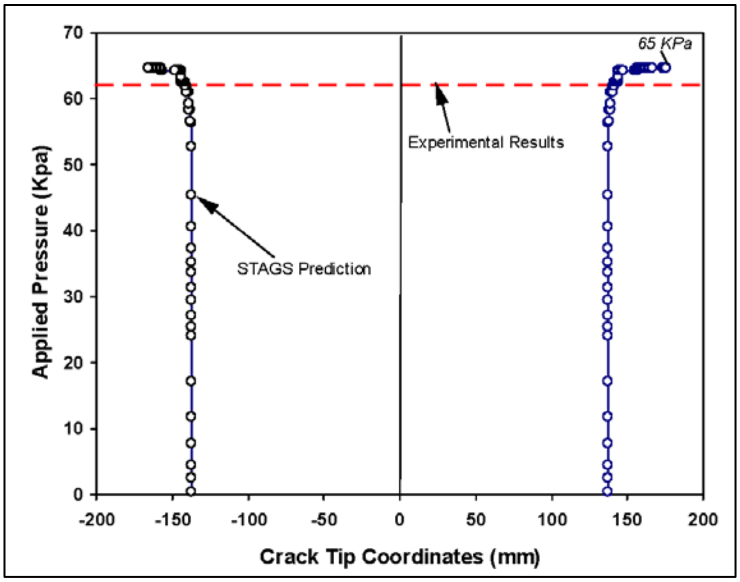


Figure 8.11-9: Comparison of Experimental and Predicted Failure Pressure for Damaged DC-9 Aft-Pressure Bulkhead with Large Lead Crack and MSD.

References

[1] Rankin, C. C., Brogan, F. A., Loden, W. A., and Cabiness, H. D.; "STAGS User Manual, Version 3.0", Lockheed Martin Missiles and Space Co., Inc., Advanced Technology Center, Report LMMS P032594, June 1998

[2] Seshadri, B. R.; Newman, J. C., Jr.; Dawicke, D. S. and Young, R. D.; "Fracture Analysis of the FAA/NASA Wide Stiffened Panels", The Second Joint NASA/FAA/DoD Conference on Aging Aircraft, C. E. Harris, ed., NASA CP-208982, 1999, pp. 513–524.

[3] Hsu, C.; James, L.; Yu, J.; Lee, X. and Tan, P.; "Residual Strength Analysis using CTOA Criteria for Fuselage Structures containing Multiple Site Damage", Engineering Fracture Mechanics, Vol. 70, No. 3-4, 2003, pp. 525–545.

[4] Swift, T. "Damage Tolerance Analysis of Redundant Structures", Fracture Mechanics Design Methodology, AGARD-LS-97, North Atlantic Treaty Organization, January, 1979.

8.12. Lessons Learned and Future Directions

Fatigue and fracture of metallic structures has been a major thrust of NASA Langley from the early years of flight. The fatigue crack growth analysis and residual strength analysis methodologies developed at NASA Langley Research Center have been recognized worldwide for their many contributions to the durability and damage tolerance design of air vehicle structures. These methodologies have been applied to test specimens ranging in complexity from small laboratory coupon specimens to full scale 2024-T3 stiffened fuselage panels. Fracture parameters used to predict the residual strength behavior of complex test specimens are typically obtained from small laboratory coupon specimens. Results have been determined for unstiffened and stiffened flat panels, small-scale unstiffened shells, and full-scale curved stiffened fuselage panels. This research was instrumental in NASA Langley being given a major national role in assessing multi-site damage tolerance of aging aircraft following the dramatic fuselage failure experienced on the Aloha Airlines 737. The excellent work done at Langley on the Aging Aircraft Program has been repeatedly recognized both within the government and in the airframe industry.

Langley's work in fatigue and fracture has been well documented in the literature from the early 1950s. Since the 1950s, events in the naval, nuclear, and aircraft industries have fostered the development of the field of fracture mechanics. The elegance and simplicity of the stress-intensity factor concept promoted by Langley rapidly developed into the durability and damage tolerance concepts currently used today to design fatigue- and fracture-critical components. The crack- closure concept put crack-propagation theories on a firm foundation and allowed the development of practical life-prediction methods for variable-amplitude and spectrum loading, such as experienced by modern-day commercial aircraft.

9. STRUCTURAL CONCEPTS AND MECHANICS

9.1. Structural Panel and Shell Testing: Historical Perspective and Major Accomplishments

Langley Research Center has been and continues to be recognized as a Center of Excellence in structures largely due to the excellent technical capabilities of the research staff. Although a large number of highly productive structures researchers have worked at Langley since the early days of NACA through the current time of NASA, perhaps the two most notable are Dr. Manuel Stein and Dr. James H. Starnes, Jr.

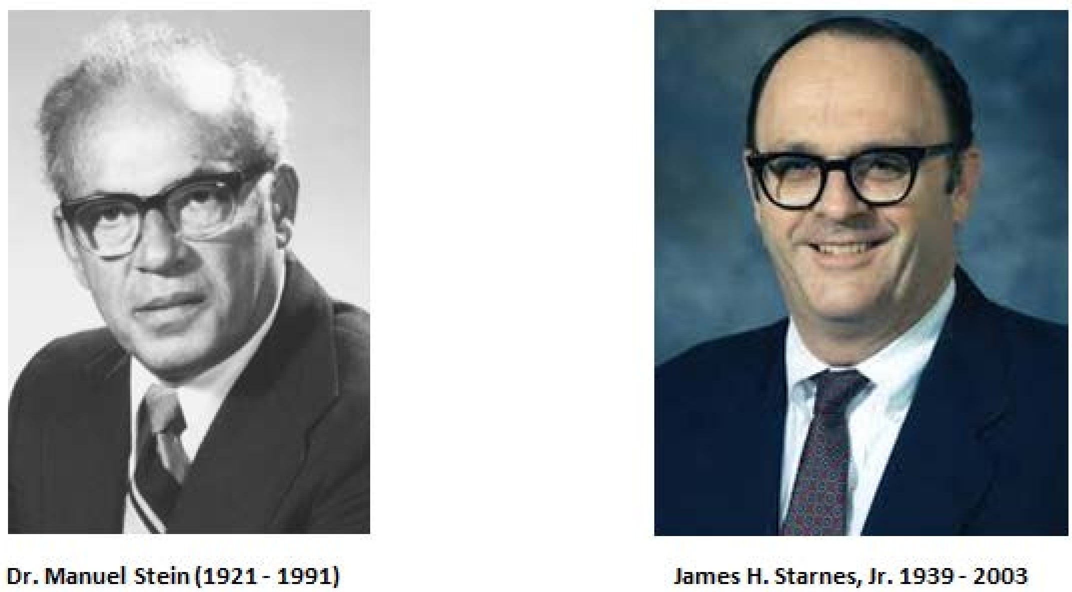


Figure 9.1-1: Structural Mechanics Pioneers at NASA Langley Research Center.

9.1.1. Tribute to Dr. Manuel Stein

Manuel Stein went to work for the National Advisory Committee for Aeronautics (NACA) in 1944 and left the National Aeronautics and Space Administration (NASA) in 1988. His research contributions spanned five decades of extremely defining times for the aerospace industry.

Problems arising from the analysis and design of efficient thin plate and shell aerospace structures have stimulated research over the past half century. The primary structural technology drivers during Dr. Stein's career included 1940s aluminum aircraft, 1950s jet aircraft, 1960s launch vehicles and advanced spacecraft, 1970s reusable launch vehicles and commercial aircraft, and 1980s composite aircraft. Dr. Stein's research was driven by these areas, and he made lasting contributions to each.

Dr. Stein's research can be characterized by a judicious mixture of physical insight into the problem, understanding of the basic mechanisms, mathematical modeling of the observed phenomena, and extraordinary analytical and numerical solution methodologies of the resulting mathematical models.

The breadth and depth of Dr. Stein's contributions led to his recognition as an international authority on buckling of plate and shell structures, and to his being awarded the NASA medal for exceptional scientific achievement.

Although Dr. Stein made numerous outstanding technical advancements throughout his career, perhaps his most lasting legacy is the unselfish sharing of his immense technical knowledge and insight with numerous researchers at and associated with the NASA Langley Research Center in Virginia. Dr. Stein's contribution to the aerospace community is poorly measured by publication numbers, but must instead be evaluated by technical quality and significance and by the several generations of structural mechanists that he mentored, consulted with, or otherwise positively influenced.

(From the 1997 tribute by Martin M. Mikulas, Michael Card, Jim Peterson, and James Starnes)

9.1.2. Tribute to Dr. James H. Starnes, Jr.

James H. Starnes, Jr. died on October 27, 2003 at the age of 64. Starnes served in the U.S. Navy and went on to work at Langley Research Center for more than 33 years. He was serving as chief engineer for the Structures and Materials Competency at the time of his death.

Starnes was internationally recognized as an expert in the fields of aerospace structures and composite structures technology. He directly contributed to the development of the International Space Station and the investigations of the shuttle *Challenger* and *Columbia* accidents. He was a technical advisor and program reviewer for other government agencies and represented NASA on the NATO Research and Technology Organization's Advanced Vehicle Technology Panel. He was leading NASA's efforts to support the National Transportation Safety Board's investigation of American Airlines' Flight 587 crash.

Starnes was the author of more than 250 journal articles and books, and he was a mentor to numerous graduate students and junior engineers. He was awarded NASA's Exceptional Engineering Achievement Medal in 1995 for development of reliable composite structures design technology for commercial transport aircraft.

Starnes received bachelor's and master's degrees in engineering mechanics from the Georgia Institute of Technology and a doctorate in aeronautics from the California Institute of Technology. He was a Fellow of the American Institute for Aeronautics and Astronautics (AIAA), the American Society for Composites, and the American Society of Mechanical Engineers. He was also a member of the Georgia Tech Academy of Distinguished Engineering Alumni.

"Dr. Starnes is greatly remembered at NASA Langley for his dedication to the NASA agency, exemplary service, positive attitude, and his friendly interactions with his colleagues," said Damodar Ambur, head of Langley's Mechanics and Durability Branch. "He was particularly recognized by his employees as an exceptional supervisor, mentor and technical leader. He routinely demonstrated great technical breadth and depth, enthusiasm and a willingness to listen to other views. In addition, Dr. Starnes was masterful at motivating his employees to make contributions that far exceeded their own expectations. He gained the respect of everyone whose life he touched and profoundly influenced the careers and lives of many."

9.1.3. Early Structures Research at Langley

A brief sampling of some of the structures testing going on at Langley in the early 1930s is included to put into perspective the fact that structures and materials research has been and continues to be a major research activity at Langley for more than 80 years.

In the early years, Langley was very active in testing cylinders in compression.[1] In a stressed-skin or monocoque structure, the strength and stability of the curved skin are closely related to the strength and stability of the walls of a thin-walled cylinder, not only for compression, but for other types of loading as well. The National Advisory Committee for Aeronautics, in cooperation with the Army Air Corps, the Bureau of Aeronautics, Navy Department; the Bureau of Standards; and the Aeronautics Branch of the Department of Commerce made an extensive series of tests on thin-walled cylinders and on truncated cones of circular and elliptic section at Langley Field, Virginia. In these tests, the absolute and relative dimensions of the specimens were varied in order to study the types of failure and to establish useful quantitative data in the following loading conditions: torsion, compression, bending, and combined loading. The first report of this series[2] presented the results obtained in the torsion (pure shear) tests on cylinders of circular section. The second report presented the results obtained in the compression tests on cylinders of circular section.

In addition to the results of the NACA compression tests on duralumin cylinders, there are presented, through the courtesy of Dr. L. H. Donnell of the California Institute of Technology, the unpublished results of 40 compression tests on steel and brass cylinders. There are also included the results of numerous compression tests on rubber and celluloid cylinders.

In the compression tests made by Donnell, brass and steel shim stock were used. The sheet that formed the walls of the cylinder was first cut to size and then wrapped about a mandrel and soldered at the seam. In order to stiffen the end for bearing against the heads of the loading machine, a light metal ring was soldered in place at each end of the cylinder. All the cylinders were tested in a special machine constructed at the California Institute of Technology. For more complete information, the reader is referred to the paper by Donnell[3] on the strength of cylinders in torsion. The compression cylinders were constructed in the same manner as the torsion cylinders and were tested in the same machine as the median length torsion specimens.

A sampling of some of the structures research going on at Langley during the late 1950s and early 1960s can be found in a paper by Richard R. Heldenfels and Eldon E. Mathauser.[4] In this paper, Heldenfels summarizes some NACA research on the strength and creep of aircraft structural elements and components at elevated temperatures. Experimental data for aluminum-alloy columns, plates, stiffened panels, and multi-web box beams was presented for temperatures up to 600°F and compared with results predicted from materials data. Methods are described for predicting maximum strength from material stress-strain curves and creep lifetime from isochronous stress-strain curves. Some observations on the probable effect of creep on the design of aircraft structures are also included to illustrate the influence of design criteria on the weight of aircraft structures at elevated temperatures.

Another key reference[5] outlining the type of structures and materials research being done during the early 1950s can be found in a compilation of papers presented at a NACA Conference on Aircraft Structures held at Langley Aeronautical laboratory, March 7, 1951.

Panel testing has been a focus of the structures R&D program at Langley for many years, and some of the early work is documented.[6,7,8,9,10,11] Houbolt was a very productive engineer during the 1940s and published several papers on structural topics related to sheer and bending stresses in wing structures of aircraft. Roger Anderson also worked with Houbolt on such topics as "effects of shear lag on bending vibration of box beams," "determination of coupled and uncoupled modes and frequencies of natural vibration of swept and unswept wings from uniform cantilever modes," and "calculation of uncoupled modes and frequencies in bending or torsion of non-uniform beams." The pioneering work done by the structures group at Langley Research Center in the post-World War II era made many significant contributions to the design and development of safer and more capable aircraft.

In the 1960s, much of the structures work at Langley was focused on compression testing of cylinders with different stiffener configurations. Key researchers during this period were Michael F. Card,[12,13] James P. Peterson,[14] Marvin B. Dow, John M. Hedgepeth,[15] Manuel Stein, and others. The work by Card and coworkers explored the effects of stiffener eccentricity on the buckling strength of stiffened cylinders. Buckling experiments were conducted on 12 axially compressed, longitudinally stiffened cylinders in order to study the relative effect of locating stiffeners on the internal or external surface of the cylinder. Externally stiffened cylinders were found to carry axial loads up to twice those sustained by their internally stiffened counterparts, a fact that had previously been predicted on theoretical grounds.

One of the analyses pioneers in structures at Langley was Dr. Manuel Stein (1944–1988). Solving problems arising from the analysis and design of efficient thin plate and shell aerospace structures was his passion. During the early part of Dr. Stein's career he focused on mathematical analyses and experimental investigation of the structural behavior of stiffened and unstiffened plates and shells. One of his many contributions was in the development of a nondimensional parameter for characterizing buckling of curved plates and cylindrical shells. Another significant contribution during this period was the formulation of a theory for stress analyses and buckling of sandwich plates and shells. This theory became the basis for most of the analytical work performed in plates and shells for the next thirty years. Dr. Stein is perhaps best known for his development of a refined analysis for predicting buckling of pressurized, unstiffened, circular cylindrical shells loaded in compression. His work in this area supported the development of spacecraft launch vehicles. His many contributions are discussed in detail in an AIAA paper by Martin M. Mikulas, Michael Card, Jim Peterson, and Jim Starnes.[16] This paper contains references to 70 of the papers published by Manuel Stein and coworkers.

Another noteworthy paper in the collection of papers on stability analyses of plates and shells (a collection of papers in honor of Dr. Manuel Stein) compiled by Norman F. Knight, Jr. and Michael P. Nemeth,[17] and is a paper by Norman Knight, Jr. and James H. Starnes, Jr. entitled "Developments in Cylindrical Shell Stability and Analyses" which reviewed much of the historical developments of shell buckling analyses and design. This paper cites 167 papers related to this topic and is an excellent source of information on past work on this important topic.

It should also be noted that structural dynamics has been for many years and continues to be a major focus at Langley. A historical perspective of some of this work can be found in a summary paper by Lucas Horta and Raymond G. Kvaternik.[18] Beginning in the early 1960s, Langley investigated several scale model and full-scale spacecraft including the NIMBUS and various concepts for Apollo and Viking landers. Langley engineers pioneered the use of scaled models to study the dynamics of launch vehicles including Saturn I, Saturn V, and Titan III. In the 1970s, work emphasized the space shuttle and advanced test and data analysis methods. In the 1980s, the possibility of delivering large structures to orbit by the space shuttle shifted focus towards understanding the interaction of flexible space structures with attitude control systems. Although Langley has maintained a tradition of laboratory-based research, some flight experiments were supported. This review emphasizes work that, in some way, advanced the state of knowledge of structural dynamics.

Another paper[19] outlining some of the excellent work done at Langley in structural dynamics was published by Irving Abel in 1997. This paper reviews much of the work performed during the early 1990s and earlier related to flutter clearance studies in the wind-tunnel on a high performance fighter, advances in the use of smart structures and controls to solve aeroelastic problems, including flutter and gust response, aeroelastic models program designed to support an advanced high-speed civil transport, an extension to transonic small disturbance theory that better predicts flows involving separation and reattachment and several other technologies worked by the structural dynamics division at Langley.

References

[1] Lundquiet, Eugene E.; “Strength Testing of Thin-Walled Duralumin Cylinders in Compression”, NACA REPORT No. 473, 1934. http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19930091547_1993091547.pdf.

[2] Lundquiet, Eugene E.; “Strength Tests on Thin-Walled Duralumin Cylinders in Torsion”, T.N. No. 427, N. A. C.A., 1932.

[3] Donnell, L. H.; “Stability of Thin-Walled Tubes under Torsion.”, T.R. No. 479, N.A.C. A., 1933.

[4] Heldenfels, Richard R. and Mathauser, Eldon E.; “A Summary of NACA Research on the Strength and Creep of Aircraft Structures at Elevated Temperatures”, NACA-Rm-L56D06, May 1956. http://naca.central.cranfield.ac.uk/reports/1956/naca-rm-L56D06.pdf

[5] NACA Conference on Aircraft Structures, A compilation of Papers Presented, at Langley Aeronautical Laboratory, Langley field, Va., March 7, 1951. http://www.dtic.mil/dtic/tr/fulltext/u2/b184875.pdf

[6] E.Z. Stowell, E.B. Schwartz, J.C. Houbolt: “Bending and shear stresses developed by the instantaneous arrest of the root of a moving cantilever beam”, NASA Report 828, 1945.

[7] S.B. Batfdorf and J.C. Houbolt: “Critical combinations of shear and transverse direct stress for an infinitely long plate with edges elastically restrained against rotation.”, NACA Report 847, 1946,

[8] J.C. Houbolt, and R.A. Anderson: “Calculation of uncoupled modes and frequencies in bending or torsion of non-uniform beams”, NACA-Langley Tech. Note 1522, 1948 Tables 1-8 for NACA Technical Report 1522

[9] R.A. Anderson and J.C. Houbolt;“Effect of shear lag on bending vibration of box beams”, NACA-Langley Tech. Note 1583, 1948.

[10] R.A. Anderson and J.C. Houbolt; “Determination of coupled and uncoupled modes and frequencies of natural vibration of swept and unswept wings from uniform cantilever modes”,NACA-Langley Tech. Note 1747, 1948.

[11] E.Z. Stowell, J.C. Houbolt, and S.B. Batdorf; “An evaluation of some approximate methods of computing landing stresses in aircraft”, NACA-Langley. Tech. Note 1584, 1948 Box 19: E.T.

[12] Card, Michael F.; “Preliminary Results of Compression Tests on Cylinders With Eccentric Longitudinal Stiffeners”, NASA TM X- 1004, 1964.

[13] Card, M. F.; and Jones, R. M;“Experimental and theoretical results for buckling of eccentrically stiffened cylinders”, NASA-TN-D-3639, 1966.

[14] Peterson, James P.; and Dow, Marvin B.;“Compression Tests on Circular Cylinders Stiffened Longitudinally by Closely Spaced Z-Section Stringers”, NASA MEMO 2-12-59L, 1959.

[15] Hedgepeth, John M.; and Hall, David B.; “Stability of Stiffened Cylinders”, AIAA J., i vol. 3, no. 12, Dec. 1965, pp. 2275–2286.

[16] Mikulas, Martin M.; Card, Michael F.; Peterson, Jim P.; and Starnes, James H., Jr.;“Manuel Stein's Five Decades of Structural Mechanics Contributions (1944-1988)”, AIAA Paper 97-1073, 1998.

[17] Knight, Jr., Norman F. and Nemeth, Michael P.;“Stability Analyses of Plates and Shells, A Collection of Papers in Honor of Dr. Manuel Stein”, NASA Cp-1998-206280, http://www.cs.odu.edu/~mln/ltrs-pdfs/NASA-98-cp206280.pdf.

[18] Horta, Lucas G. and Kvaternik, Raymond G.;“A Historical Perspective on Dynamics Testing at the Langley Research Center”, NASA/TM-2000-210295, 2000.

[19] Abel, Irving;“Research and Applications in Aeroelasticity and Structural Dynamics at the NASA Langley Research Center”, NASA Technical Memorandum 112852, 1997.

9.2. Structural Concepts

Much of the pioneering development of metallic thermal protection system (TPS) was led by NASA Langley. One of the most innovative engineers to work at NASA Langley in structures was L. Robert Jackson. He was very active in developing new structural concepts for aircraft and for space launch vehicles. Some of his best work was focused on concepts for hot structures. Many of the metallic heat shield concepts examined during the shuttle technology development period, the late 1960s and early 1970s were conceived by Robert Jackson. He is also credited for conceiving many of the hot structures concepts examined by different members of the Langley research staff. An example of some of his work can be found in a paper by Jackson, Davis, and Wichorek[1] entitled “Structural Concepts for Hydrogen-Fueled Hypersonic Airplanes.” Other references to selections of work led by Jackson, et al. can be found in research papers[2,3,4,5,6] related to hot structures. During the mid-to-late 1970s, Langley played a key role in structures and materials for hypersonic vehicles. Proceedings of a symposium[7] held at Langley Research Center in Hampton, Virginia in 1978 showcased work being done at Langley in hot structures.

Jackson [8] also played key role in conceiving new structural concepts for future space transportation system orbiters.

A number of other Langley researchers advanced some of Bob's concepts in an effort to develop lightweight metallic protection systems for reusable launch systems. Concepts progressed from early stand-off shields (Bohon[9]) to multiwall concepts (Jackson,[10] Shideler,[11] and Blair[12]) to prepackaged superalloy honeycomb sandwich panels (Blair,[13] Anderson,[14] and Gorton[15]). For many of the TPS studies Rohr Industries did the detailed design and fabrication of the multiwall and prepackaged superalloy honeycomb TPS concepts. One of the latest key research investigations directed at evaluating and improving the prepackaged superalloy honeycomb panel concepts was done by Max Blosser[16] for the Reusable Launch Vehicle (RLV) Program in 1996.

It should also be noted that in the 1980s, there was a very productive interaction between the materials researchers and the structural analysis. Tom Bales[17] led a manufacturing team that investigated new and innovative approaches to producing structural panels using superplastic forming and weld brazing. An example of one of the superplastically formed panels is shown in **Figure 9.2-1**. Half-hat beaded-web elements were successfully superplastically formed from titanium Ti-6AI-4V sheet and subsequently weld-brazed with other panel components to produce full-size panels with a unique corrugated design. Both single-corrugation and multiple-corrugation panels were fabricated. The use of low-cost, ceramic die tooling was demonstrated in the superplastic forming process for titanium with a minimum of surface interaction. The panels were tested in end compression to failure. They failed at compressive loads approaching the yield strength of the titanium material. At maximum load, the caps wrinkled with accompanying localized separation of the weld-braze joint in the wrinkle. None of the panels tested exhibited catastrophic failure of the weld-braze joint. Experimental test results were in good agreement with structural analysis of the panels. In a separate study, Bales and coworkers were able to demonstrate that beaded hat-stiffened panels had higher critical buckling strain than conventional hat-stiffened panels.

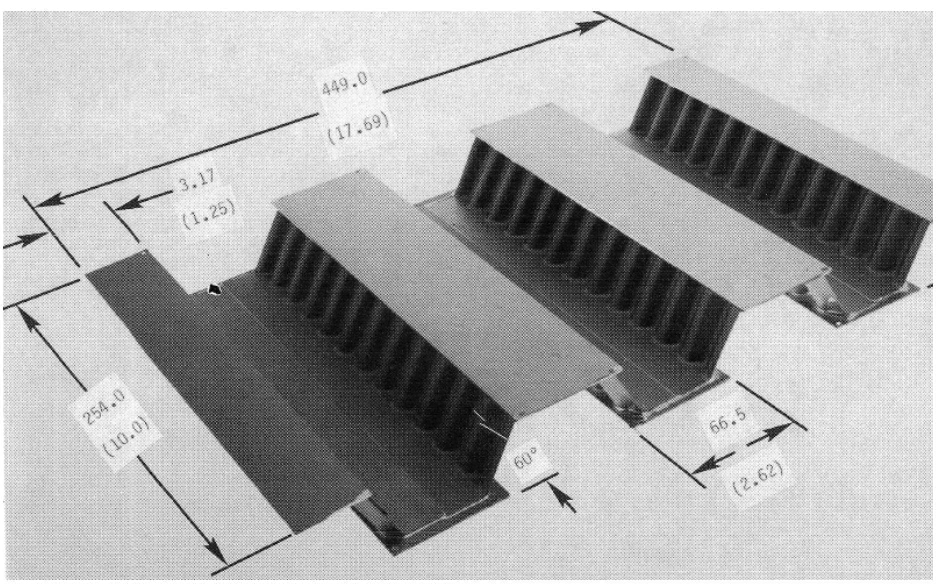


Figure 9.2-1: Multiple-Corrugation Compression Panel. Dimensions are in millimeters (inches).

Key structures researchers working compression panel behavior at this time included Bob Jackson, Randall Davis,[18] Gary Giles,[19] Charles Miller, and R. Prabhakaran. Other key references to the fabrication and testing of structural panels produced by Bales,[20] Royster,[21] and coworkers[22] can be found in the literature. The paper by Davis and coworkers is particularly noteworthy because of the pioneering work they did in the development of new structural concepts for minimum-mass compression structures. **Figure 9.2-2** shows the main concepts investigated in this study. These types of structural concept studies were very valuable for guiding manufacturing technology studies by the materials team.

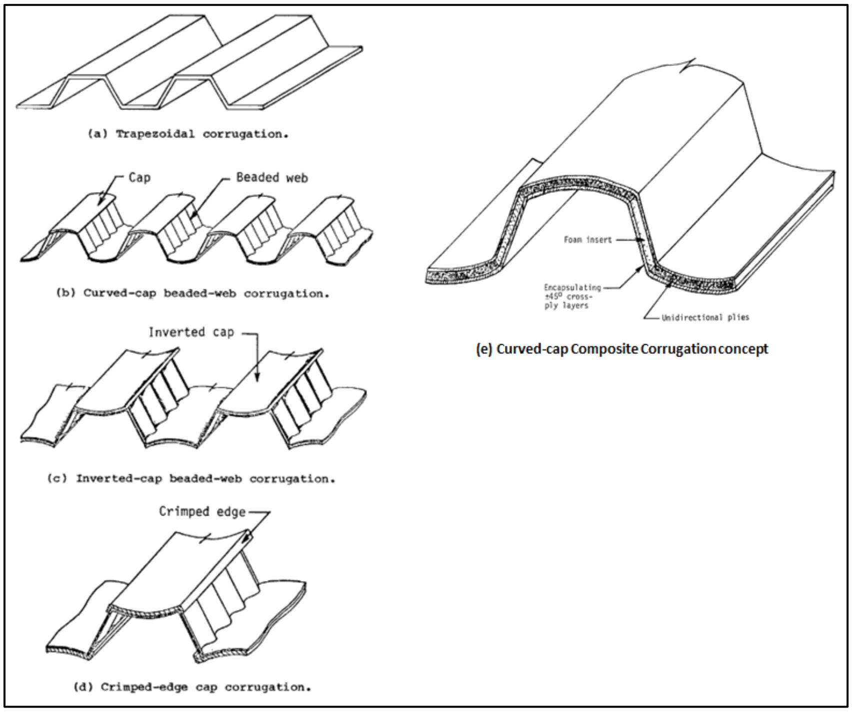


Figure 9.2-2: Geometrical Configurations for Corrugated Panels.

Another exceptional contributor to structures at Langley was James P. Peterson. During the 1950s and 1960s Peterson[23,24,25,26] and colleagues (including John M. Hedgepeth, Melvin S. Anderson, Michael F. Card, Martin M. Mikulas, Jr., and others) published extensively on results of compression testing of cylinders and panels with different stiffener design, spacing, and dimensions. A sampling of this body of work can be found in many NASA publications[27,28,29] from that era.

Another example of the type of structural concepts work done at Langley can be found in a paper by Vivel Mukhopadhyay[30] entitled "Structural Concepts Study for Non-Circular Fuselage Configurations." A structural concepts study of non-circular pressurized fuselage configurations was presented for flying wing applications. For an unconventional flying-wing type aircraft, in which the fuselage is inside the wing, multiple fuselage bays with non-circular sections need to be considered. A deep honeycomb sandwich-shell and a ribbed double-wall shell construction were considered. Combinations of these structural concepts were analyzed using both analytical– and simple finite-element models of isolated sections for a comparative conceptual study.

References

[1] Jackson, L. Robert, Davis, John G. and Wichorek, Gregory R.; "Structural Concepts for Hydrogen-Fueled Hypersonic Airplanes", NASA TN D-3162, 1966.

[2] Jackson, L. R.; and Anderson, M. S.; "A Carbon Dioxide Purge and Thermal Protection System for Liquid Hydrogen Tanks of Hypersonic Airplanes", Advances in Cryogenic Engineering. Volume 12, Plenum Press, Inc., 1967, pp. 146–156.

[3] Sharpe, L. Ellsworth and Jackson, L. Robert; "Performance of a Hypersonic Hot Fuselage Structure with a Carbon Dioxide Frost Protected, Non-integral Cryogenic Tank", NASA TN D-7799, 1975.

[4] Taylor, Allan H., Jackson, L. Robert and Weinstein, Irving; "Evaluation of Three Thermal Protection Systems in a Hypersonic High-Heating-Rate Environment Induced by an Elevon Deflected 30º", NASA Technical Memorandum 74077, 1977.

[5] Taylor, Allen H., Jackson, L. Robert, Cerro, Jeffery A. and Scotti, Stephen J.; "Analytical Comparison of two Wing Structures for Mach 5 Cruise Airplanes", J. of Aircraft, Vol. 21, no. 4, April 1984, pp. 272-–277.

[6] Jackson, L. Robert, Kirkham, F. S. and Weidner, J. P.;"Structural Concepts and Experimental Considerations for a Versatile High-Speed Research Aircraft", NASA TM 78743, 1978.

[7] NASA Conference Publication 2065 Part II, "Recent Advances in Structures for Hypersonic Flight", 1978. http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19790013264.pdf

[8] Taylor, Allan H., Jackson, L. Robert, Davis, Randall C. and Scotti, Stephen J.; "Structural Concepts for Future Space Transportation System Orbiters", Journal of Spacecraft and Rockets 22(3), June 1985.

[9] Bohon, H. L., Shideler, J. L., and Rummler, D. R.; "Radiative Metallic Thermal Protection Systems: A Status Report", Journal of Spacecraft and Rockets, Vol. 12, No. 10. pp. 626–631, October 1977.

[10] Jackson, L. R. and Dixon, S. C.; "A Design Assessment of Multiwall Metallic Stand-off and RSI Reusable Thermal Protection Systems Including Space Shuttle Application", NASA TM 81780, 96 pages, April 1980.

[11] Shideler, J. L., Kelly, H. N., Avery, D. E., Blosser, M. L., and Adelman, H. M. (1982) "Multiwall TPS—An Emerging Concept", Journal of Spacecraft and Rockets, Vol. 19, No. 4, July-August 1982, pp. 358–365.

[12] Blair, W., Meaney, J. E., and Rosenthal, H. A.; "Re-Design and Fabrication of Titanium Multi-Wall Thermal Protection System (TPS) Test Panels", NASA CR 172247, January 1984.

[13] Blair, W., Meaney, J. E., and Rosenthal, H. A.; "Fabrication of Prepackaged Superalloy Honeycomb Thermal Protection System (TPS) Panels", NASA CR 3755, October 1985.

[14] Anderson, J., LeHolm, R. B., Meaney, J.E. and Rosenthal, H.A.; "Development of Reusable Metallic Thermal Protection System Panels for Entry Vehicles", NASA CR181783, August 1989.

[15] Gorton, M. P., Shideler, J. L. ,and Web, G. L.; "Static and Aerothermal Tests of a Superalloy Honeycomb Prepackaged Thermal Protection System", NASA TP 3257, March 1993.

[16] Blosser, Max L.; "Development of Metallic Thermal Protection Systems for the Reusable Launch Vehicle", NASA TM 110296.

[17] Royster, Dick M., Davis, Randall C., Shinn, Jr., Joseph M., Bales, Thomas T. and Wiant, H. Ross; "Fabrication and Evaluation of Superplastically Formed/Weld-Brazed Corrugated Compression Panels With Beaded Webs", NASA Technical Paper 2512, 1985.
[18] Davis, Randall C.; Mills, Charles T.; Prabhakaran, R.; and Jackson, L. Robert; "Structural Efficiency Studies of Corrugated Compression Panels With Curved Caps and Beaded Webs", NASA TP-2272, 1984.
[19] Giles, Gary L.; "Structural Efficiencies of Five Compression Panels With Curved Elements", NASA TN D-6479, 1971.
[20] Royster, Dick M.; and Bales, Thomas T.; "Elevated Temperature Behavior of Superplastically Formed/Weld-Brazed Titanium Compression Panels Having Advanced Shaped Stiffeners", NASA TP-2123, 1983.
[21] Royster, Dick M.; Bales, Thomas T.; Davis, Randall C.; and Wiant, H. Ross; "Fabrication and Evaluation of Cold-Formed/Weld-Brazed Beta-Titanium Skin-Stiffened Compression Panels", NASA TP-2201, 1983.
[22] Royster, Dick M.; Bales, Thomas T.; and Wiant, H. Ross; "Superplastic Forming/Weld-Brazing of Titanium Skin-Stiffened Compression Panels, Materials Overview for 1982", Volume 27 of National SAMPE Symposium and Exhibition, Soc. Advance. Mater. & Process Eng., 1982, pp. 569–582.
[23] Kuhn, P. and Peterson, J.P.; "Strength analysis of stiffened beam webs", NACA TM 1364, 1947.
[24] Peterson, J.P. and Dow, M.B.; "Compression Tests on Circular Cylinders Stiffened Longitudinally by Closely Spaced Z-Section Stringers", NASA MEMO 2-12-59L, 1959.
[25] Peterson, J.P. and Whitley, R.O.; "Local buckling of longitudinally stiffened curved plates", NASA TN D-750, 1961.
[26] J. Peterson and M.F. Card; "Investigation of the buckling strength of corrugated webs in shear", NASA TN D-424, 1966.
[27] Peterson, James P.; "Weight-Strength Studies of Structures Representative of Fuselage Construction", NACA TN 4114, 1957.
[28] Peterson, James P.; and Anderson, James Kent; "Structural Behavior and Buckling Strength of Honeycomb Sandwich Cylinders Subjected to Bending", NASA TN D-2926, 1965.
[29] Peterson, James P.; "Structural Efficiency of Ring-Stiffened Corrugated Cylinders in Axial Compression", NASA Technical Note, NASA TN D-4073.
[30] Mukhopadhyay, Vivel; "Structural Concepts Study of Non-Circular Fuselage Configurations", AIAA Paper 96-WAC-67, 1996.

9.3. Structural Analyses Code Development (NASTRAN, Stags, Etc.)

The development of NASTRAN is one of the really big success stories of NASA and was highlighted in sections 2.6.2 and 8.9. MSC_NASTRAN, ANSYS, and ABAQUS are among the most widely used commercial structural computer programs by NASA and industry. The reader is referred to the earlier section for NASA's role in developing this structural analyses code.

Another computer code widely used by NASA and the aerospace industry for analyzing aerospace structures is a general-purpose, nonlinear static and dynamic finite-element code called the Structural Analysis of General Shells (STAGS). STAGS has static and transient analysis capabilities that can be used to predict local instabilities and modal interactions that occur due to destabilizing mechanical loads such as an applied compression or shear load. This code was developed and championed by Dr. Charles C. Rankin and is generally considered to be one of the true pioneers in the field of solid and structural mechanics. Research and development of STAGS by Rankin, Brogan, Almroth, Stanley, Cabiness, Stehlin, and others, formerly of the Computational Mechanics Department of the Lockheed Martin Advanced Technology Center, has been under continuous sponsorship from U.S. government agencies for the past 40 years. During this time, particular emphasis was placed on improvement of the capability to solve difficult nonlinear problems such as the prediction of the behavior of axially compressed stiffened panels loaded far into their locally post-buckled states. STAGS has been extensively used worldwide for the evaluation of stiffened panels and shells loaded well into their locally post-buckled states.[1]

Research on shell buckling at NASA Langley has been a key thrust of the structural mechanics branch at NASA Langley for many years. Dr. Norm Knight,[2,3] Dr. James Starnes,[4,5,6] Dr. Rick Young[7], Dr. James C. Newman, Dr. Dave Dawicke, Dr. Damodar Ambur, and other NASA researchers have championed the development of STAGS and have used its capabilities to solve many problems associated with the nonlinear behavior of structures under compression loading or other loading cases where nonlinear behavior is observed. Many advancements to STAGS were made in the 1990s under the NASA Airframe Structural Integrity Program (NASIP). Studies were conducted using the STAGS code to develop improved understanding of the nonlinear response of cracked fuselage structures subjected to combined loads. An integrated residual strength analysis methodology for metallic structure that models crack growth to predict the effect of cracks on structural integrity was demonstrated by Young and Rose[7] using the STAGS code.

Hypersizer is a one-of-a-kind Langley Research Center computer code for designing exotic hypersonic aircraft that was transferred to a private company for more pedestrian use in ground transportation, building construction, and marine industries. The Collier Research and Development (R&D) Corporation of Hampton, Virginia received the first ever Langley software copyright license agreement. The agreement was signed in May 1996.

Collier R&D transformed the NASA computer code into a commercial software package called HyperSizer™. The commercial software package integrates with other popular finite-element modeling codes. The NASA software, called ST-SIZE, was chiefly conceived as a means to improve and speed up the structural design of a future aerospace plane for Langley's Hypersonic Vehicles Office. Different classes of materials under consideration for use on a hypersonic plane could be computer modeled, then shown how they would react under extreme temperature changes, speeds, pressures, and other operating conditions. The software tool gave structural engineers the confidence to select the proper lightweight materials for use in high-speed aircraft.

Including the NASA computer code into the HyperSizer software package has equipped Collier R&D to look beyond aerospace to other high-tech applications. These include improved design and construction for offices, marine structures, cargo containers, commercial and military aircraft, rail cars and a host of everyday consumer products. HyperSizer can evaluate and optimize

- any cross sectional shapes, sizes, thicknesses, materials selections, and material layups;
- many composite material types such as polymer, ceramic, metal matrix, as well as concrete, wood, steel, and aluminum alloys;

- thermal stress problems caused by thermal gradients from aerodynamic heating and/or cryogenic fuels;
- weight estimations and structural integrity.

Failure mode checks performed with HyperSizer can recognize potential structural deficiencies of any component early in the project's design phase.

References

[1] Rankin, C. C.; "The use of shell elements for the analysis of large strain response", AIAA Paper 2007-2384, 48th AIAA Structures, Structural Dynamics, and Materials Conference, Hawaii, April 2007.

[2] Knight, Norman F. and Rankin, Charles C.; "STAGS Example Problems Manual", NASA/CR-2006-214281, 2006.

[3] Knight, N. F., Jr. and Starnes, J. H., Jr.; "Postbuckling Behavior of Axially Compressed Graphite-Epoxy panels with Circular Holes", ASME Journal of Pressure Vessel Technology, Vol 107, No. 4, November 1985, pp. 394–402.

[4] Starnes, J. H., Jr., Britt, Vicki O., and Rankin, C. C.; "Nonlinear Response of Damaged Stiffened Shells Subjected to Combined Internal Pressure and Mechanical Loads," AIAA Paper 95-1462, April 1995.

[5] Starnes, J. H., Jr., Britt, V. O., Rose, C. A., and Rankin, C. C.; "Nonlinear Response and Residual Strength of Damaged Stiffened Panels Subjected to Combined Loads," AIAA Paper No. 96-1555, April 1996.

[6] Starnes, J. H., Jr., Newman, J. C., Jr., Harris, C. E., Young, R. D., Rose, C. A., and James, M. A.; "Advances in Residual Strength Analyses from Laboratory Coupons to Structural Components," Proceedings of the ICAF 2001 International Committee on Aeronautical Fatigue 21st Symposium, Toulouse, France, June 2001.

[7] Young, Richard D. and Rose, Cheryl A.; "STAGS Developments for Residual Strength Analysis Methods for Metallic Fuselage Structures", AIAA Paper 2014-0848, NF1676L-16748, 2014.

9.4. Damage Tolerance and Residual Strength Analysis Methods

Dr. Jim Starnes was a leader in the structural mechanics research at Langley. He was the head of the Structural Mechanics Branch, which he led for 18 years. During his 33 years of NASA civil service, he received 32 NASA Achievement Awards including the NASA Exceptional Engineering Achievement Medal in 1995 for developing reliable composite structures design technology for commercial transport aircraft. He was a Fellow of AIAA, a Fellow of ASME, a Fellow of ASC, and Member of the Georgia Institute of Technology Academy of Distinguished Engineering Alumni. At the time of his death, Dr. Starnes was the Senior Engineer of structures and materials at the NASA Langley Research Center.

NASA publication NASA/TM-2006-214276 entitled "Collected Papers in Structural Mechanics Honoring Dr. James H. Starnes, Jr." contains 38 papers that relate to the work that Dr. Starnes was involved with during his NASA career. A discussion of even a small portion of the R&D

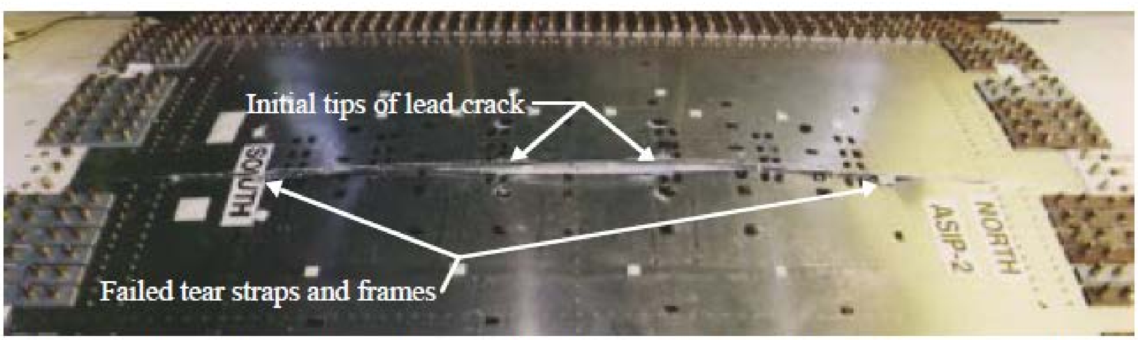
performed at Langley in structural mechanics is beyond the scope of this monograph. The authors have chosen to extract a portion of one of the 38 articles written to honor Dr. Starnes to illustrate the nature of the work performed in later years on metallic structures. The article authored by Richard D. Young, Cheryl A. Rose, and Charles E. Harris[1] entitled "Jim Starnes' Contributions to Residual Strength Analysis Methods for Metallic Structures" presents a summary of advances in residual strength analyses methods for metallic structures that were realized under the leadership of Dr. James H. Starnes, Jr.

The majority of research led by Jim Starnes in the area of damage tolerance and residual strength analysis of metallic structures was conducted in the 1990s under NASIP. This program, headed by Dr. Charles E. Harris, covered a wide range of topics including fatigue and fracture of materials, nondestructive inspection methods, and residual strength analysis methods for built-up structures with damage. Dr. Starnes led the structures element of the program, and, within this activity, Dr. Starnes supervised, mentored, and collaborated with junior researchers Ms. Vicki O. Britt, and Drs. Richard D. Young and Cheryl A. Rose. Dr. Starnes also worked closely with Dr. James C. Newman, "champion" of the critical crack-tip-opening angle (CTOA) fracture criterion for elasto-plastic fracture, to incorporate the elasto-plastic criterion in residual strength analysis methods, and to help define laboratory scale experiments and critical loading scenarios for validation of the criterion. In addition, Dr. Starnes supported and collaborated with Dr. Charles Rankin at Lockheed, Palo Alto, to incorporate crack modeling and residual strength analysis methodologies into the STAGS general-purpose finite-element code.

Dr. Starnes's approach to research in damage tolerance and residual strength analysis methods for metallic structures was typical of his approach to solving complex problems. The first step in the approach was defining the overall research problem. Several components contributed to the problem definition. First, there was a motivational component, or a driving force for solving the problem. Typically, the driving force was a problem experienced by the aeronautics industry. Dr. Starnes's connection with industry was invaluable; he had the respect and confidence of manufacturers and operators, and they often conveyed to him issues or failures that were occurring that they did not understand. He then relied upon his intuition and extensive expertise in structural mechanics to define preliminary studies to characterize the problem. The preliminary studies were typically tests or simplified analyses of complex built-up configurations, conducted to obtain qualitative information on relevant structural parameters, fundamental structural response characteristics and failure scenarios, and to identify critical loading conditions. Dr. Starnes would consider results from these studies and factor in industry input to formulate the overall problem definition, and then form a vision toward a solution. This vision often consisted of multiple research elements, and the integration of the individual elements. Each research element addressed a critical component of the larger problem, and was defined by breaking the complex response of built-up structure down into contributing factors to be studied separately. Research of each element consisted of detailed numerical and experimental studies of a simplified structural configuration conducted to develop a quantitative understanding of critical response mechanisms identified in the preliminary studies. Each research element provided a stand-alone technical result for a simple application and provided insight into understanding the response characteristics of a more complex configuration. In addition, the individual research elements often resulted in the development of new analysis capabilities that were eventually integrated to develop high-fidelity analysis capabilities for quantitative characterization of the real-world built-up structure.

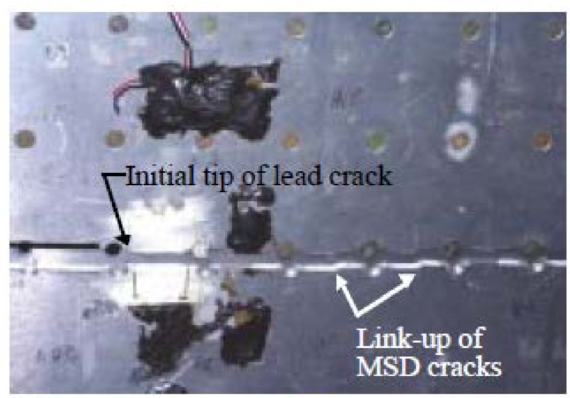
In their paper, Young, Rose, and Harris give the motivation for the research and the overall problem definition. Then, results of selected research activities that were defined based upon fuselage structure response characteristics observed in the preliminary studies conducted to define the problem are presented. The research activities described are presented in order of increasing complexity. First, results of a numerical study of nonlinear bulging factors in unstiffened aluminum shells are presented. This study examined the effect of geometric nonlinearity and combined loading conditions on the crack-tip stress intensity factor in an unstiffened shell. The second study extended the previous study's efforts in unstiffened shells to stiffened structure, including detailed modeling of stringer and fastener parameters. The final section presents a summary of research activities that were specifically focused on the development and validation of a high-fidelity residual strength analysis methodology for aircraft aluminum fuselage structures with cracks and subjected to combined internal pressure and mechanical loads. The method accounts for all of the complexities present in a fuselage shell structural response that must be represented to accurately predict fuselage structure residual strength. The methodology is based upon the critical CTOA elastic-plastic fracture criterion to represent stable crack growth and fracture in ductile materials, and a geometric and material nonlinear shell analysis code to perform the structural analysis.

Multiple panels were fabricated and tested to failure to validate analyses codes (Figure 9.4-1**)**. **Figure 9.4-2** shows a typical analysis results for panel ASIP2 showing crack growth in the lead crack and MSD cracks.



(a) Self-similar crack growth over the entire length of panel, failing adjacent tear straps and frames

(b) Failed tear strap and frame



(c) Crack trajectory with link-up of MSD cracks

Figure 9.4-1: Panel ASIP2 After Testing To Failure.

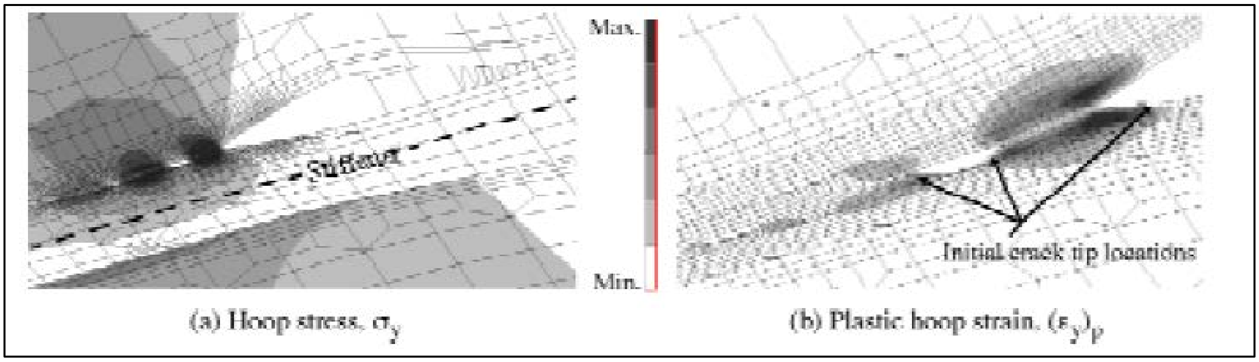


Figure 9.4-2: Typical Analysis Results for Panel ASIP2 Showing Crack Growth in the Lead Crack and MSD Cracks.

The research efforts in residual strength analysis of metallic fuselage contributed to advances in residual strength analysis methods for metallic structures. Perhaps the major contribution was in identifying the effect of combined internal pressure and mechanical loads and geometric nonlinearity on the response of built-up structure with damage. Through Dr. Starnes's leadership, research was conducted that demonstrated that the linear pressure-only case often used by industry may be unconservative in some cases and over-conservative in other cases. In addition, a residual strength analysis methodology for fuselage structure with cracks has been developed and verified by experiments. Fifteen years ago, the aircraft industry would not consider using nonlinear analysis for structures with cracks. Today, personal communications indicate that the verified analysis methodology and analysis code described in this paper have been used by the aircraft industry to realize improved analyses and design capability. A few examples include Boeing's use of nonlinear parametric analyses to update their damage tolerance design guide for stiffened panels, and using nonlinear residual strength analyses to predict the strength of a DC-9 aft bulkhead and KC-135 fuselage panels. In addition, Lockheed Marietta has used this analysis methodology to improve life predictions and refine inspection schedules for Strategic Airlift Aircraft (C-5). The residual strength analysis methodology is currently being incorporated into the ABAQUS–commercial finite-element code. The CTOA fracture criterion has already been implemented in the ABAQUS code and efforts are underway to adopt residual strength solution algorithms from STAGS for use in ABAQUS.

In 1999, NASA recognized this research with a "Turning Goals into Reality" Award for valuable contributions to the NASA Airframe Structural Integrity Team and exceptional progress toward aviation safety. The success of this research can be largely attributed to the technical guidance and vision that Jim Starnes provided for the research team. The research effort spanned several years, involved many complex phenomena, and required contributions from several disciplines and many researchers. Through Dr. Starnes's vision, the team was able to address the complex research problem through a series of smaller problems, and then integrate the research findings into a general capability for solving real world fuselage problems.

One of the major accomplishments coming out of NASA's Airframe Structural Integrity Program, was the development of a structural integrity analysis methodology[2] for predicting the onset of widespread fatigue damage. The ability to analytically predict the onset of widespread fatigue damage in fuselage structures requires methodologies that predict fatigue crack initiation, crack growth, and residual strength. Mechanics-based analysis methodologies are highly desirable because differences in aircraft service histories can be addressed explicitly and rigorously by analyzing different types of aircraft and specific aircraft within a given type. Each aircraft manufacturer has developed mature in-house durability and damage-tolerance design and analysis methodologies that are based on their product development history. To enhance these existing successful methodologies, NASA has adopted the concept of developing an analytical “tool box” that includes a number of advanced structural analysis computer codes which, taken together, represent the comprehensive fracture mechanics capability required to predict the onset of widespread fatigue damage. The structural analysis tools have complementary and specialized capabilities ranging from a nonlinear finite-element-based stress-analysis code for two- and three-dimensional built-up structures with cracks to a fatigue and fracture analysis code that uses stress-intensity factors and material-property data found in “look-up” tables or from equations. The development of these advanced structural analysis methodologies has been guided by the physical evidence of the fatigue process assembled from detailed tear-down examinations of actual aircraft structure. In addition, NASA is conducting critical experiments necessary to verify the predictive capability of these codes and to provide the basis for any further methodology refinements that may be required. The NASA experiments are essential for analytical methods development and verification, but represent only a first step in the technology validation and industry-acceptance processes. Each industry user of this advanced methodology must conduct an assessment of the technology, conduct an independent verification, and determine the appropriate integration of the new structural analysis methodologies into their existing in-house practices. NASA has established cooperative programs with United States aircraft manufacturers to facilitate this comprehensive transfer of this technology by making these advanced methodologies available to industry.

References

[1] Young, Richard D.; Rose, Cheryl A.; Harris, Charles E.; “Jim Starnes’ Contributions to Residual Strength Analysis Methods for Metallic Structures”, AIAA Paper 2005-1876, 2005.

[2] C. E. Harris, J. H. Starnes, Jr. and J. C. Newman, Jr.; “Development of Advanced Structural Analysis Methodologies for Predicting Widespread Fatigue Damage in Aircraft Structures”, NASA Technical Memorandum 110187. August 1995.

9.5. Testing of Large Structural Elements

Langley has many test capabilities to evaluate mechanical properties of built up structure. Notable among the many test frames are the million-pound test frame, the biaxial test frame, and the Combined Loads Test System (COLTS).[1] These capabilities are invaluable to test built-up structure for the purpose of first understanding failure mechanisms and to validate failure prediction analyses codes. A brief overview of the capabilities of the COLTS facility (**Figure 9.5-1**) is given because of its unique capabilities.

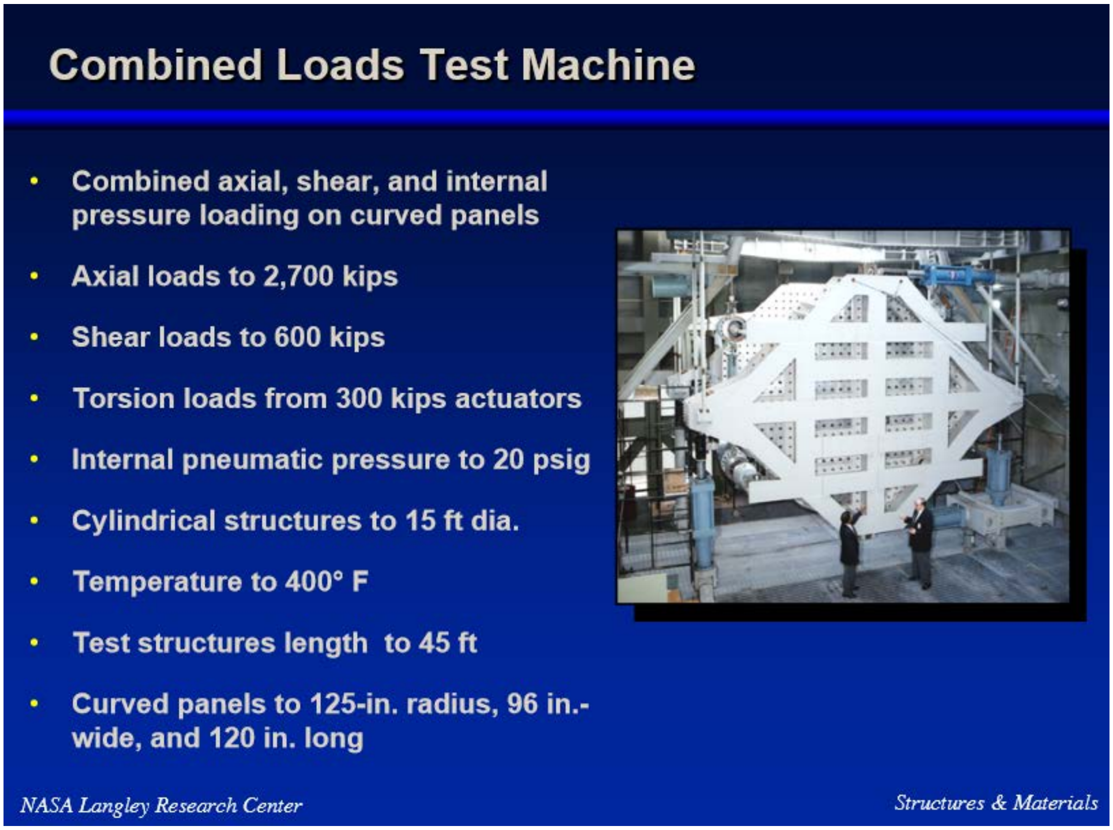


Figure 9.5-1: COLTS Facility.

9.5.1. Combined Loads Test System (COLTS)

The Combined Loads Test System facility at NASA Langley Research Center is designed to validate new or unique structures technologies. This facility consists of a multi-actuator test machine capable of applying combined loads and internal pressure loading to validate structures technology. COLTS can easily produce quasi-static and cyclic-loading conditions on large curved panels and cylindrical shell structures. Realistic flight loads on aircraft and space structures can be simulated using a combination of mechanical, internal-pressure, and thermal loads. The COLTS test chamber may also be configured for non-aerospace applications by adjusting its mechanical, pressure, and thermal-loading capabilities. COLTS users are also able to select from a comprehensive set of capabilities for data acquisition. In order to accommodate the complex nature of mechanical and thermal loading on a particular study article, the data-acquisition system has been designed to provide comprehensive real-time and post-processing of test data.

One of the recent applications of the COLTS facility is a planned test[2] of a multi-bay test article to be subjected to mechanical loads and internal pressure loads up to design ultimate load. Mechanical and pressure loads will be applied independently in some tests and simultaneously in others. A sequence of combined mechanical and pressure loadings will be applied to a large-scale multi-bay pressure box to experimentally verify the structural performance of a composite structure which is 9.1 m long. This test article is representative of a section of a hybrid wing body center fuselage section and supports NASA's Environmentally Responsible Aviation Project (**Figure 9.5-2**).

Figure 9.5-2: Multi-Bay Box Located Between Platens.

It should also be noted that large structural tests of metal structures have also been performed in the COLTS facility.

In 1999, Starnes and coworkers[3] tested an aluminum panel that was approximately 10 ft long and 10 ft wide. Its 0.084 in thick skin is made from 7475-T61 aluminum alloy. The panel had a frame spacing of 20 inches and a stringer spacing of 8.5 inches. Dr. Jim Starnes was instrumental in advancing our understanding of the effects of combined loads and geometric nonlinearity on the response of complex built-up fuselage structure. A sampling of some of his work is contained in key papers[4,5,6] published during the 1990s.

References

[1] Ambur, D. R., Rouse, M., Starnes, J. H., and Shuart, M. J.; "Facilities for Combined Loads Testing of Aircraft Structures to Satisfy Structural Technology Development Requirements", presented at the 5th Annual Advanced Composites Technology Conference, Seattle, WA, August 22-36, 1994.

[2] Rouse, Marshall; Jegley, Dawn; "Preparation for Testing a Multi-Bay Box Subjected to Combined Loads", Conference Paper NF1676L-20919, 2015.

[3] Starnes, James H., Jr.; Ambur, Damodar R.; Young, Richard D.; Harris, Charles E.; "Experiment Verification of the Analytical Methodology to Predict the Residual Strength of Metallic Shell Structure",

[4] Starnes, J. H., Jr., Britt, Vicki O., and Rankin, C. C.; "Nonlinear Response of Damaged Stiffened Shells Subjected to Combined Internal Pressure and Mechanical Loads", AIAA Paper 95-1462, April 1995.

[5] Starnes, J. H., Jr., Britt, V. O., Rose, C. A., and Rankin, C. C.; "Nonlinear Response and Residual strength of Damaged Stiffened Panels Subjected to Combined Loads", AIAA Paper No. 96-1555, April 1996.

[6] Starnes, J. H., Jr., Rose, C. A., Young, R. D., and Rankin, C. C.; "Effects of Combined Loads on the Nonlinear Response of Stiffened Shells with Long Cracks", Presented at the 19th International Committee on Aeronautical Fatigue Symposium, Edinburgh, Scotland, UK, June 18-20, 1997.

9.6. Shell Buckling Knockdown Factor (Mark Hilburger)

High-performance aerospace shell structures are inherently thin-walled because of weight and performance considerations and are often subjected to destabilizing loads. Thus, buckling is an important and often critical consideration in the design of these structures and reliable, validated design criteria for thin-walled shells are needed, especially for shells made of advanced composite materials. Shell-buckling design criteria have a history steeped in empiricism. From approximately 1930 to 1967, many shell-buckling experiments were conducted on metallic shells. Typically, the experiments yielded buckling loads that were substantially lower than the corresponding analytical predictions, which were based on simplified linear bifurcation analyses of geometrically perfect shells with nominal dimensions and idealized support conditions. The primary source of discrepancy between corresponding analytical predictions and experimental results is attributed to small deviations from the idealized geometry of a shell, known as initial geometric imperfections. Empirical design factors, known as "knockdown" factors, were determined from these test data and were to be used in conjunction with linear bifurcation analyses for simply supported shells to adjust or "knockdown" the unconservative analytical prediction. This approach to shell design remains prominent in industry practice, as evidenced by the extensive use of the NASA space vehicle design recommendations. Recent advancements in digital computers, high-fidelity structural analysis tools, and testing technologies are enabling the development of a new shell buckling design philosophy, namely, analysis-based knockdown factors. Key enabling technology developments and their implementation in ongoing NASA Shell Buckling Knockdown Factor development activities are being worked by Principle Investigator Dr. Mark Hilburger and coworkers at NASA Langley and MSFC. This work is being performed under the Shell-Buckling Knockdown Factor (SBKF) Project supported by the NASA Engineering Safety Center (NESC) located at NASA Langley Research Center.

The NESC Shell-Buckling Knockdown Factor Project was established in March 2007 to develop and validate new analysis-based shell buckling design factors (i.e., knockdown factors) for Ares I and V metallic and composite launch vehicle structures. Refined knockdown factors will enable significant weight savings in future launch vehicles and will help mitigate launch vehicle development and performance risks. The project is an innovative and long overdue research effort that examines the safety margins needed to design future launch vehicle structures. Test results will be used to–develop new shell-buckling knockdown factors—a complex set of engineering design standards essential to heavy launch vehicle design.

The current aerospace–industry's shell-buckling knockdown factors date back to the Apollo era, when high-tech materials, manufacturing processes, and advanced computer modeling were things of the future. The new analyses will update design considerations for large structures like the main fuel tank of a future heavy-lift launch vehicle.

In a throwback to the beginning of the U.S. space program, the full-scale test happened at Marshall's Structural and Dynamics Engineering Test Laboratory. Originally built to test Saturn rocket stages, building 4619 was key in the development of the lightweight space shuttle external tank and tested International Space Station modules.

The NESC has supported a significant portion of the SBKF Project, including funding for the design and fabrication of a large-scale test facility, the first series of large-scale buckling test articles, programmatic and technical support, peer reviews, and advocacy.

In FY09 and FY10, the SBKF Project made significant progress in several key work areas including sub-component and component testing and analysis, Ares V structures trade studies and associated mass savings estimates, and testing of an alternate aluminum-lithium alloy for Ares V core stage. Some of the highlights included successful testing of four 8-foot-diameter Al-Li orthogrid barrel test articles one of which was representative of a 45 percent-scale Ares I upper stage liquid hydrogen tank barrel section. The high-fidelity analysis predictions of these large-scale tests continue to correlate well with the test result and, once fully validated, will become the basis of new analysis-based design factors. The calculations correlated with the test data to within 5% as compared with a 30%–50% discrepancy, historically. That improvement in correlation will enable a reduction in conservatism and can translate into weight savings in structural design, which can be significant in large pieces like the core stage of a heavy-lift launch vehicle.

The subcomponent analysis and test activity within the SBKF Project performed path-finding, stiffened–panel, crippling tests at LaRC. These tests were used to integrate a typical local stiffener failure mode that is not well understood and is not accounted for explicitly in current Agency design practice. Analysis tools and nonlinear orthotropic material models have been developed to aid in the design of these important detail features. The Advanced Aluminum Alloy Development activity and the Structures Trade Study activity worked together to identify the benefits of other Al-Li alloy materials on the design of several Ares V vehicle concepts. The results of the study indicated thicker Al-Li material would enable more structurally efficient orthogrid barrel components by increasing the height of the machined stiffeners. To this end, Al-Li 2050 was identified as a candidate replacement material for Al-Li 2195 in the Ares V core stage because it is available in thick plate gages, has similar material properties to 2195, and is currently being used in commercial aircraft. The NESC supported the purchase of a large plate of 4-inch-thick 2050 material for preliminary material property and subcomponent screening tests to assess the performance of the material in typical launch-vehicle specific environments. The SBKF Project was peer reviewed in March 2009, and has published 13 technical reports summarizing trade studies, testing, analysis, and design activities and results.

Figure 9.6-1 shows a test cylinder in the test fixture at MSFC. The massive test structure is 27.5 feet in diameter, 20 feet tall, reaching up three stories when mounted on its base. There were almost 70,000 white dots on the test tank, photogrammetry polka dots that turn a snow leopard pattern into meaningful engineering data showing stress and strain. High-speed cameras are used to monitor angles of buckles, ripples, and tears to record critical data. More than 800 electronic sensors on the test article sent data to the Stress Analysis Station on the ground floor room and up to Hilburger, who directed the application and withdrawal of hundreds of thousands of pounds of external pressure at a time. There was pressure inside the test article at 1 pound per square inch, too. It does not sound like much, but considering the massive size of the cylinder, it adds up to 32,000 cubic feet of air pressure that stabilizes the shell and simulates the conditions inside a pressurized fuel tank.

“What a great test,” said Hilburger. “I was holding my breath the whole time waiting for the next thing to happen. We certainly have a lot of data to review, and we’re reviewing for computer models. But just when you think you had it all figured out, there was something new that we had to go uncover. And that’s good for us because it keeps us testers in business.”

Before the full-scale test, the shell buckling team tested four 8-foot diameter aluminum-lithium cylinders. Current research suggests applying the new design factors and incorporating new technology could reduce the weight of large heavy-lift launch vehicles by as much as 20 percent. Up next, the shell buckling team will test carbon-fiber composite structures that are 20-30% lighter than aluminum and widely used in the automotive and aerospace industries. Marc Schultz is an aerospace engineer at NASA Langley and is leading the composite material testing segment of the SBKF project.

The NESC team already has held two workshops for NASA engineers, and they have published their findings in NASA technical memorandums.[1] The “biggest challenge,” Hilburger says, is persuading engineers to accept the new figures his team is developing. “The second-biggest challenge is to develop a technology-infusion strategy and a set of guidelines that will last another 20 or 30 years, and in a way that they’re applicable to who knows what vehicles get built later on,” he says.

In addition to greater accuracy in designing structures, the new knockdown factors will give engineers a better understanding of how new manufacturing techniques and build tolerances can affect the buckling of the structure. NASA spent millions on friction-stir welding tooling for the Ares vehicles, and learned how the heating associated with the process alters the geometry of the metal being welded. That knowledge has allowed much greater accuracy in predicting shell buckling, in part because the welds are so uniform compared with traditional welds and result in very repeatable quality and geometry.

“That’s why you have to start including not only your designers, but the folks who are building these parts, and get an understanding of how we can tweak these tolerances, so you start building on your knowledge and help guide the manufacturing to make better structures.”

NASA Administrator Charlie Bolden said this type of research is critical to NASA’s developing a new heavy-lift vehicle. “The Authorization Act of 2010 gave us direction to take the nation beyond low-Earth orbit, but it is the work of our dedicated team of engineers and researchers that will make future NASA exploration missions a reality,” Bolden added.

Figure 9.6-1:A Large Diameter Cylinder under Test at MSFC.

References

[1] Thornburgh, R. P.; and Hilburger, M. W.; "Design of Orthogrid Cylinder Test Articles for the Shell Buckling Knockdown Factor Assessment", NASA/TM-2010-216866, November 2010.

10. HOT STRUCTURES

Thermal protection systems (TPS) and hot structures are required for a range of hypersonic vehicles ranging from ballistic reentry to hypersonic cruise vehicles, both within Earth's atmosphere and non-Earth atmospheres. Air-breathing hypersonic vehicles in the Earth's atmosphere includes single-stage-to-orbit (SSTO), two-stage to orbit (TSTO) accelerators, access to space vehicles, and hypersonic cruise vehicles. Many believe that in the future there will be a move from rocket-based vehicles to air-breathing vehicles. To make these vehicles viable there will likely be a move away from the insulated airplane approach used on the space shuttle orbiter to a wide range of TPS and hot structure approaches. NASA Langley has a rich history of developing advanced air-breathing vehicle concepts and analyzing new hot structure concepts including TPS.

10.1. Advances in Hot Structures

An excellent review of Langley's work in high-temperature materials and structure was published by E. A. Thornton[1] in a book entitled "Thermal Structures for Aerospace Structures," AIAA Education Series, 1996. In addition, key summary papers[2,3] have been published on structures and materials technology for reusable launch vehicles. Dr. Thornton[4] also published an excellent summary paper on hot structures which covers much of the work performed at NASA Langley Research Center.

References

[1] Thornton, Earl A.; Book entitled "Thermal Structures for Aerospace Applications," AIAA Education Series, J..S. Przemieniecki, Series Editor-in-Chief, 1996, AIAA, ISBN 1-56347-190-6.

[2] Dixon, Sid C., Tenney, Darrel R., Rummler, Donald R., Wieting, Allan R., and Bader, R.M.; "Structures and Materials Technology Issues for Reusable Launch Vehicles," NASA Technical Memorandum 87626 ,.Oct. 1985.

[3] Tenney, Darrel R., Lisagor, W. Barry, and Dixon, Sidney C.; "Materials and Structures for Hypersonic Vehicles," Journal of Aircraft, Vol. 26, No.11 (1989), pp. 953–970.

[4] Thornton, E. A.; "Thermal Structures: Four Decades of Progress," Proceedings of the 31st AIAA/ASME/ASCH/AHS Structures, Structural Dynamics and Materials Conference, Long Beach, CA, 1990, pp. 794–814.

10.2. Thermal Protection System (TPS) Concepts

Vehicles, such as the X-15 or the National Aero-Space Plane (NASP), shown in **Figure 10.2-1**, experience significant aerodynamic heating when traveling at hypersonic speeds through the Earth's atmosphere. The heating can be severe enough that a thermal protection system is required to limit the temperature of the vehicle structure. Because the heating varies over the surface of a vehicle, several different types of TPS may be used on the same vehicle. Some of the TPS concepts that have been considered are shown schematically in **Figure 10.2-2**.

Figure 10.2-1: National Aerospace Plane (NASP).

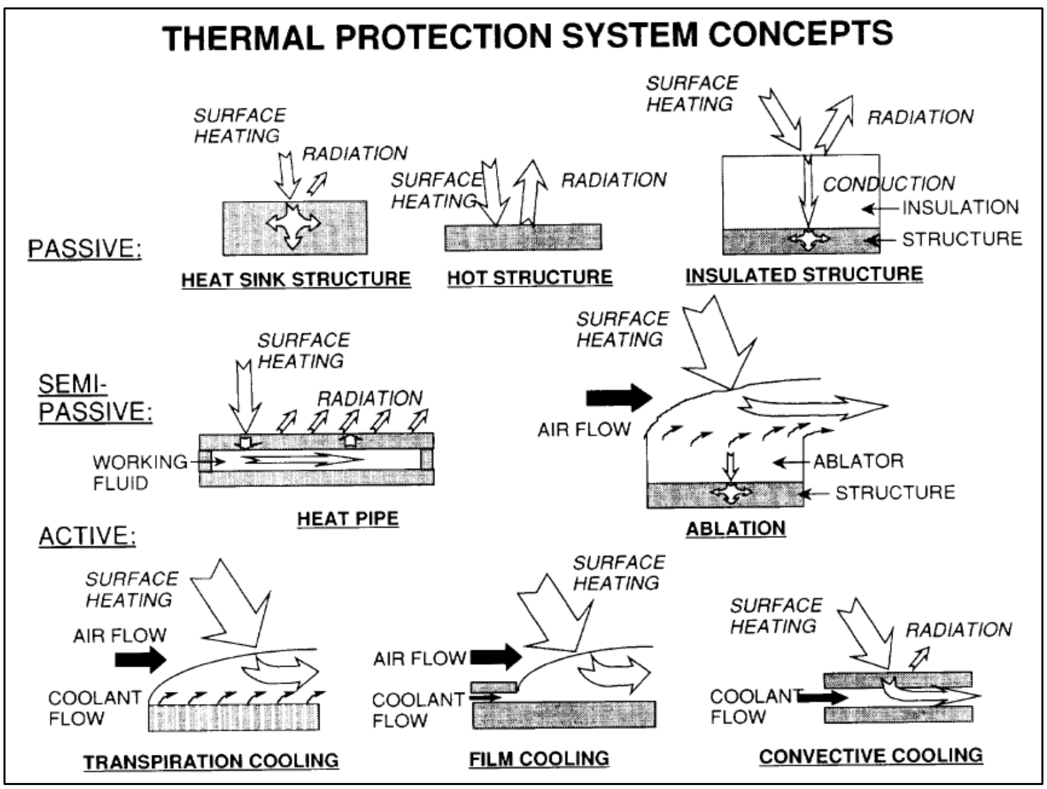


Figure 10.2-2: Thermal Protection System Concepts.

The concepts[1] are divided into three broad categories: passive, semi-passive, and active. As defined in **Figure 10.2-2**, passive concepts have no working fluid to remove heat; the heat is either radiated from the surface or absorbed in the structure. An example[2] of this is shown in **Figure 10.2-3.** The X-15 was a heat sink concept vehicle[2] (**Figure 10.2-4**).

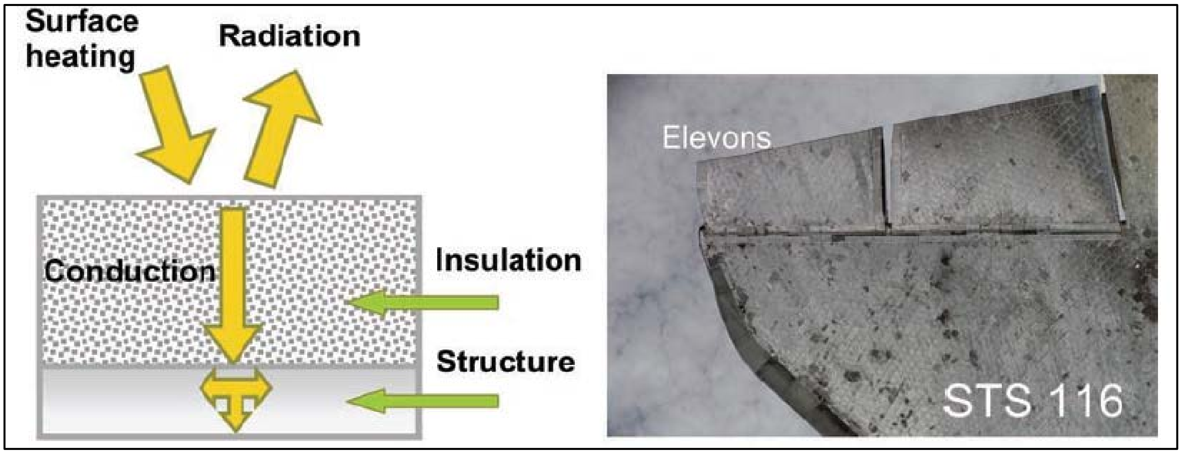


Figure 10.2-3: Schematic and Photograph (Space Shuttle Orbiter Elevons) of an Insulated Structure.

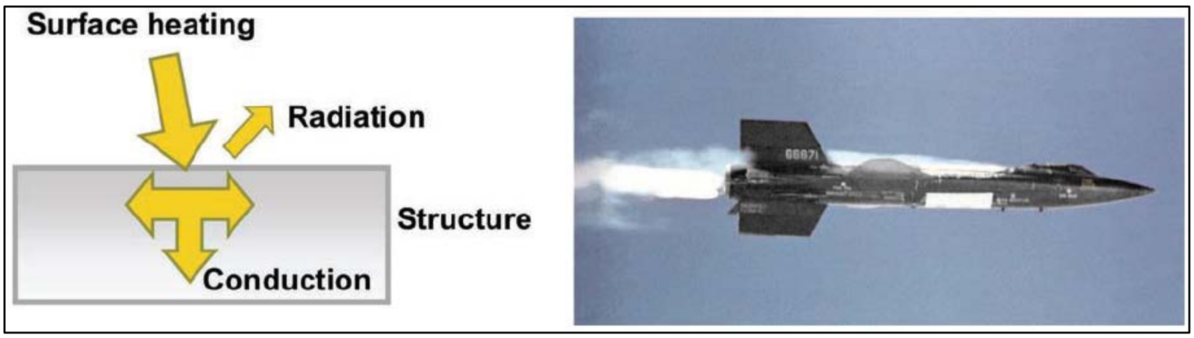


Figure 10.2-4: Schematic and Photograph (X-15) of a Heat Sink Structure.

Semi-passive concepts have a working fluid that removes heat from the point of application, but they require no external systems to provide or circulate the coolant during flight. An example[2] of a heat-pipe-cooled wing leading edge is shown in **Figure 10.2-5**.

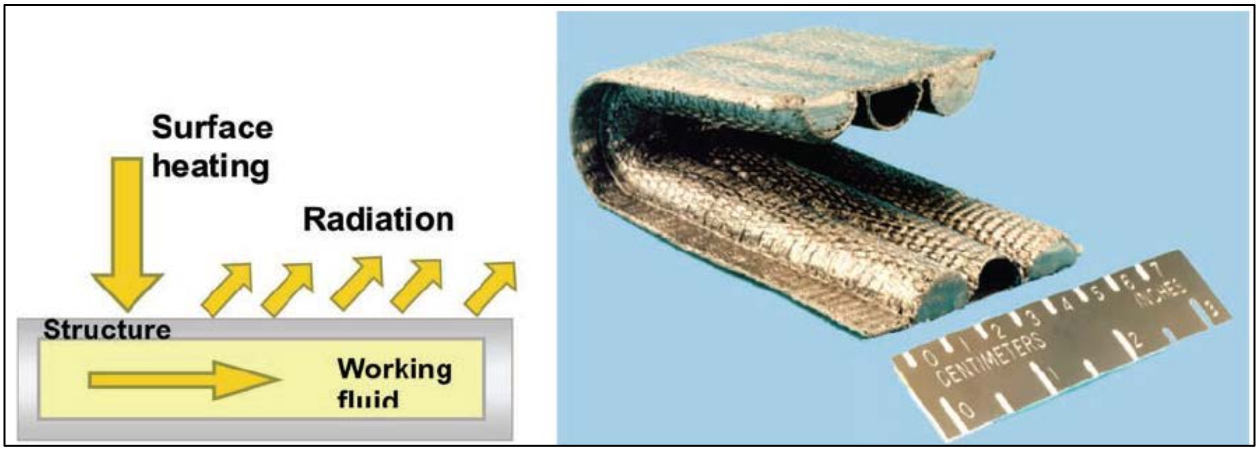


Figure 10.2-5: Schematic and Photograph Illustrating a Heat-Pipe-Cooled Leading Edge.

Active concepts have an external system that provides coolant during the flight to continually remove heat from the structure or prevent heat from reaching the structure. The simplest, lightest weight TPS concept that will accommodate the design surface heating is generally selected.

The X-33 was a sub-orbital experimental vehicle that NASA funded (but canceled prior to flight) that was intended to be the predecessor for an SSTO rocket vehicle. The TPS on the X-33 was similar to the space shuttle orbiter TPS, except that it had a metallic TPS on the windward surface. As shown in **Figure 10.2-6**, blankets were used on the leeward surface and metallic TPS was used on the windward surface of the X-33. Both vehicles utilized carbon/carbon leading edges, nose cap, chin, and skirt. The X-33 metallic TPS is shown in **Figure 10.2-7**.

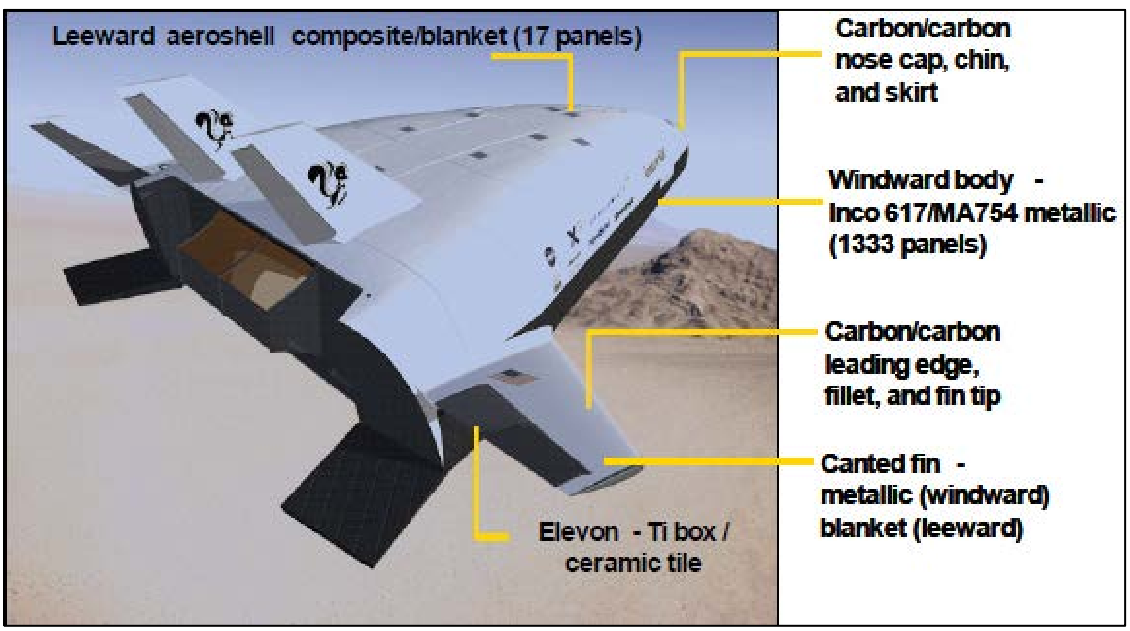


Figure 10.2-6: Thermal protection system utilized on the X-33[2]

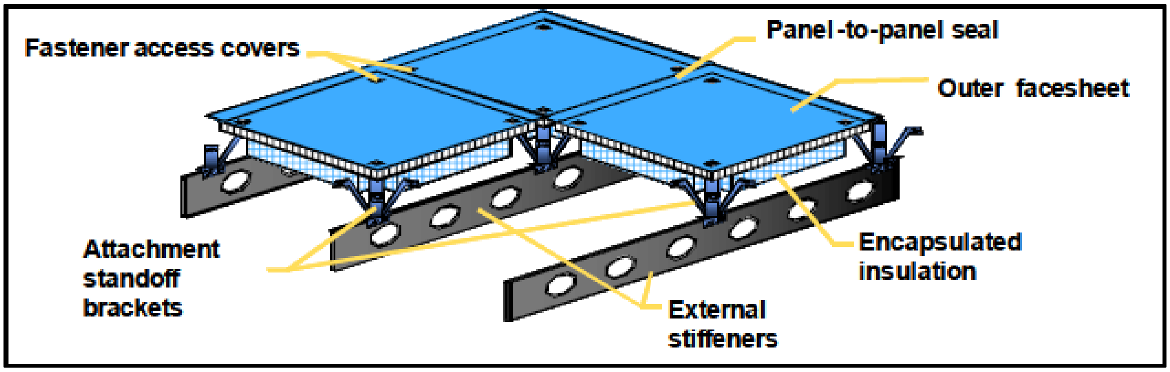


Figure 10.2-7: Schematic Drawing of X-33 Metallic TPS Illustrating Stand-Off TPS Attachment to Sub-Structure.

Max Blosser[3] was one of the pioneers at Langley that worked TPS concepts. One of the concepts that received a lot of attention was multiwall panels. Multiwall sandwich is a unique structural sandwich concept that was originally designed as a vacuum-sealed insulation for cryogenic tankage[4] (**Figure 10.2-8**). Jackson and coauthors investigated this multiwall sandwich concept that combines the evacuated thermal protection, tankage, and load-carrying functions into a single component. They also studied another variation of this concept based on the use of an unsealed structure that does not require vacuum sealing, but rather uses carbon dioxide gas to purge the insulation space between the structure and tanks. Results of their work can be found in reference 4.

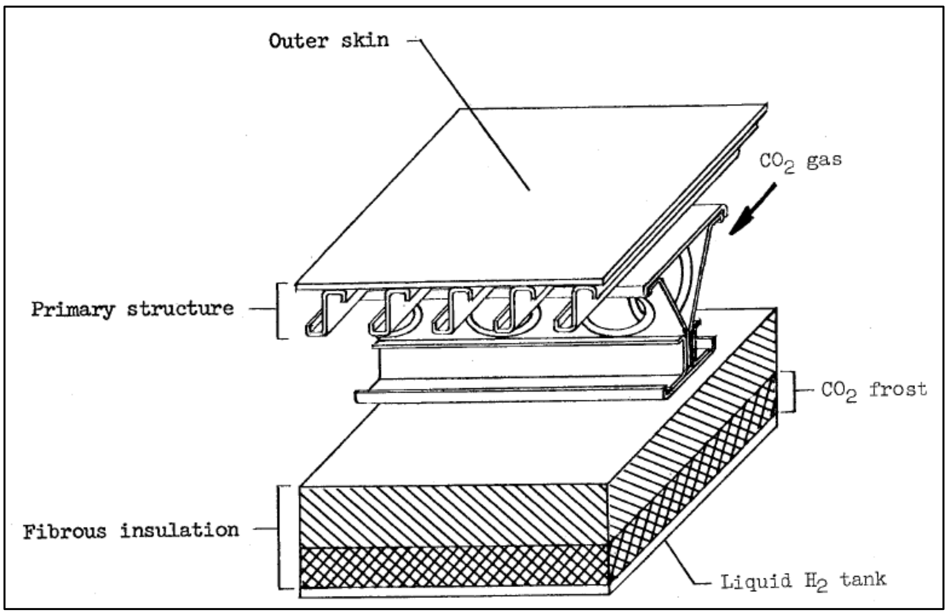


Figure 10.2-8:Structural Concept for Hydrogen Fueled Hypersonic Airplane (Carbon Dioxide Concept). NASA TN D-3162 http://dodreports.com/pdf/ada307306.pdf.

As an outgrowth from this concept, several studies have considered an unsealed version of the multiwall sandwich for use as a thermal protection system.[5,6,7] An exploded view and cross section of a typical TPS tile made of multiwall sandwich are shown in **Figure 10.2-9**. The sandwich consists of alternate layers of flat and dimpled, foil-gauge metal sheets bonded together at the crests of the dimples. As shown in the cross-sectional view, bonding of the flat and dimpled sheets forms a complex, three-dimensional structure.

The inherent ductility and design flexibility of metal TPS offer the potential for a more robust system with lower maintenance costs than competing systems. The foil-gage construction of current metallic TPS concepts makes it simple to improve durability by increasing the thickness of the outer face sheet to meet robustness requirements. Metallic TPS can be designed to prevent water from reaching the internal insulation, thereby eliminating the need for time-consuming re-waterproofing procedures required for current ceramic TPS. The relatively large, mechanically attached metallic TPS panels can be designed to be readily removed for inspection or repair.

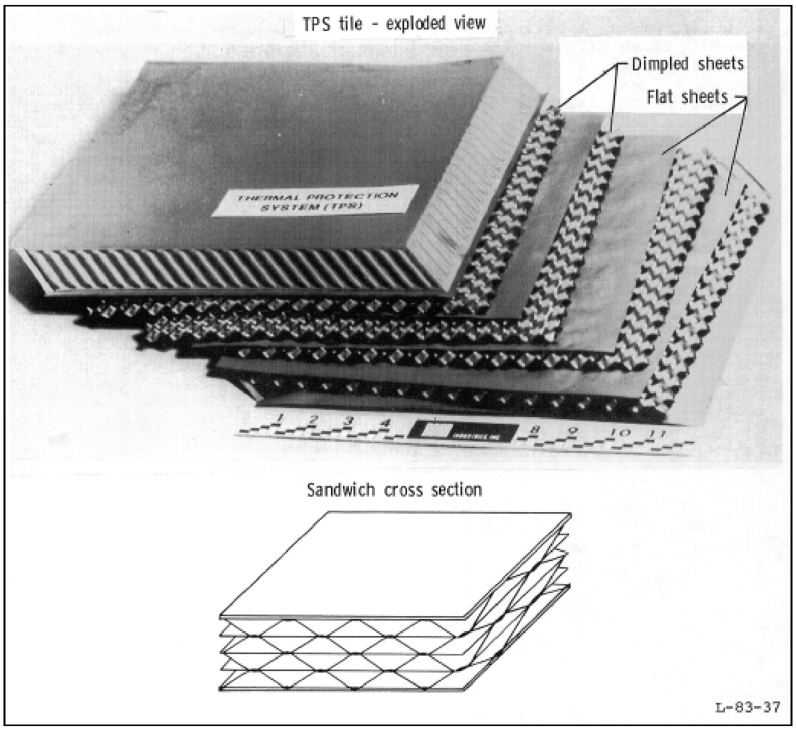


Figure 10.2-9: Titanium Multiwall Sandwich

In a paper by Blosser and coauthors[8], a new adaptable, robust, metallic, operable, reusable (ARMOR) thermal protection system concept was proposed. Blosser and coworkers claim to have used lessons learned from previous metallic TPS development efforts in the design, analyses and fabrication of the ARMOR TPS (**Figure 10.2-10**) with improved features that enhanced the robustness of this metallic TPS concept. The TPS panels consisted of an Inconel 617 honeycomb core sandwich panel on the top side (hot side), titanium alloy base (cool side), Inconel 625 standoffs and bolt access tubes, Saffil insulation, and a hybrid of Inconel 600 and commercially pure titanium (CP Ti) foil edge closeouts.

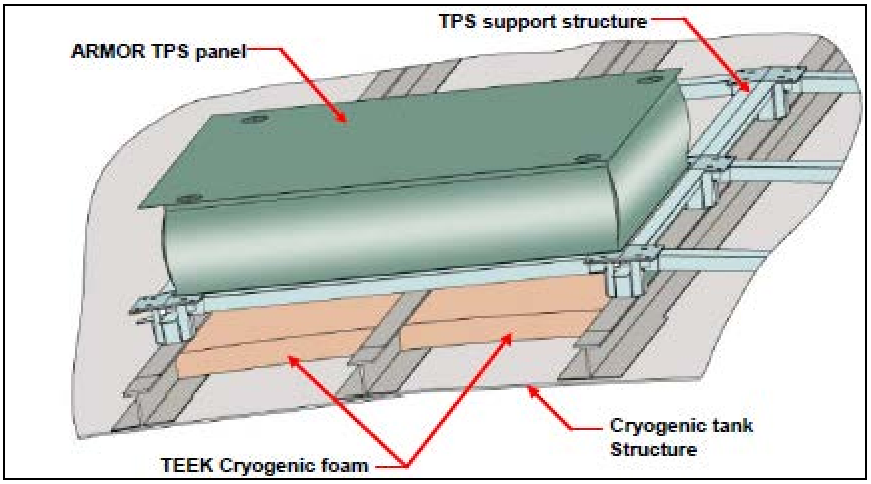


Figure 10.2-10: ARMOR TPS with Standoff Support Structure[8]

Inconel 617, with a maximum estimated reuse temperature between 1800°F and 1900°F. Although these peak temperatures are well below those of some competing ceramic TPS systems, they may be adequate for the majority of surfaces on orbiters of proposed fully reusable systems. Large, low density orbiters with internal fuel tanks can be flown in entry trajectories that have lower peak heating than the space shuttle orbiter. In addition, other metal alloys may offer advantages over the Inconel. Low-density titanium aluminide alloys may offer significant weight savings for peak temperatures below 1500°F. Iron and nickel aluminides may offer the potential to extend maximum use temperature for metallic TPS to above 2000°F.

In their summary comment, the authors conclude that the ARMOR TPS provides an attractive solution for the next generation of reusable launch vehicles that are striving for economic viability. The robust ARMOR TPS panels offer the potential to greatly reduce maintenance costs and increase the range of weather conditions acceptable for flight compared to competing TPS alternatives.

References

[1] Kelly, H. Neale and Blosser, Max L.; “Active Cooling from the Sixties to NASP”, Conference Paper, Current Technology for Thermal Protection Systems”, NASA CP 3157, 1992, pp. 189–249.

[2] Glass, David E.; “Ceramic Matrix Composite (CMC) Thermal Protection Systems (TPS) and Hot Structures”, AIAA Paper 2008-2682, 15th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, 28 Apr.1 May 2008, Dayton, OH.

[3] Max L. Blosser; “Bending Stiffness of Multiwall Sandwich”, NASA TM 84613, 1983. http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19830014352_1983014352.pdf

[4] Jackson, L. Robert; Davis, John G., Jr.; and Wichorek, Gregory R.; “Structural Concepts for Hydrogen-Fueled Hypersonic Airplanes”, NASA TN D-3162, 1966.

[5] Jackson, L. Robert; “Multiwall TPS”, Recent Advances in Structures for Hypersonic Flight, NASA CP-2065, Part II, 1978, pp. 671–706.

[6] Jackson, L. Robert; and Dixon, Sidney C.; “A Design Assessment of Multiwall, Metallic Stand-Off, and RSI Reusable Thermal Protection Systems Including Space Shuttle Application”, NASA TM-81780, 1980.

[7] Shideler, John L.; Kelly, H. Neale; Avery, Don E.; Blosser, Max L.; and Adelman, Howard M.; “Multiwall TPS - An Emerging Concept”, NASA TM-83133, 1981.

[8] Blosser, M. L.,Chen, R. R., Schmidt, I. H., Dorsey, J. T., Poteet, C. C., Bird, R. K.; “Advanced Metallic Thermal Protection System Development”, AIAA 2002-0504, 40th Aerospace Sciences Meeting & Exhibit, 14–17 January 2002, Reno, Nevada

10.3. TPS Materials

TPS materials research at Langley included work on superalloys, coated refractory metals, carbon-carbon, reusable surface insulation (RSI), and phenolic ablators. A search of the literature for research on metallic thermal protection systems at Langley Research Center on the NASA Technical Report Server (NTRS) show that over 700 publications were authored by NASA researchers. Some of the more prominent authors included Bland A. Stein, W. Barry Lisagor, Darrel R. Tenney, Donald R. Rummler, Ronald K. Clark, Dick M. Royster, William D. Brewer, Howard G. Maahs, Charles J. Camarda, C. M. Pittman, John L. Shidler, H. Neale Kelly, Allen R. Wieting, Max L. Blosser, Sid C. Dixon, L. R. Jackson, John T. Dorsey, R. Keith Bird, Carl C. Poteet, T. A Wallace, S.N. Sankaran, Ion O. Macconochie, H. L. Bohon, A. H. Taylor, Wayne Sawyer, and others.

10.3.1. Superalloys

Several different superalloys have been studied for TPS applications. Notable among these are commercially available nickel-based alloys Rene 41, Hastelloy X, Inconel 625, and Inconel 718; and cobalt-based alloys Haynes No. 25 and Haynes No.188. Additional alloys studied also include Inconel 617, dispersion–strengthened iron-based superalloy MA-956, and TD-NiCr (Thoria dispersion strengthened NiCr alloy). Much of the pioneering development of metallic TPS was led by NASA LaRC. Concepts progressed from early stand-off heat shields (Bohon 1977) to multiwall concepts (Jackson 1980, Shidler 1982, and Blair 1984) to prepackaged superalloy honeycomb sandwich panels (Blair 1985, Anderson 1989, and Gorton 1993). The detailed design and fabrication of the multiwall and prepackaged superalloy honeycomb TPS concepts were performed by Rohr Industries.

A typical example of one of the metallic thermal protection systems concepts studied at Langley[1] as part of the X-33 R&D Program is shown in **Figure 10.3-1**. The superalloy honeycomb TPS is designed to be mechanically attached to the vehicle structure. The outer surface of the metallic box is comprised of a honeycomb sandwich with 0.005-inch-thick face sheets and a 0.0015-inch-thick, 3/16 inch cell honeycomb core. The 0.003-inch-thick side walls are beaded to help alleviate thermal stresses and to resist buckling when carrying compressive loads. Both the outer honeycomb sandwich and the sides are made from Inconel 617, a nickel-based superalloy that enables the TPS to operate at a maximum temperature between 1800°F and 1900°F with limited temperature excursions up to 2000°F. The inner surface of the metallic box is made of a titanium alloy, Ti-6Al-4V. In the previous design, the lower surface consisted of titanium honeycomb sandwich, with 0.006-inch-thick face sheets and a 0.0015-inch-thick, 3/16 inch cell honeycomb core. A paper by Max Blosser[2] gives an excellent review of the different tests used to evaluate the metallic TPS concept.

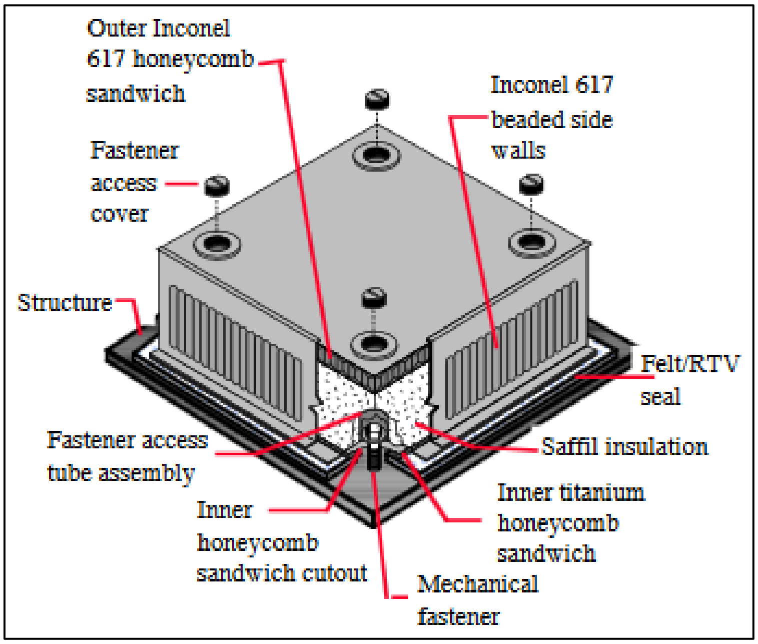


Figure 10.3-1: Prepackaged Superalloy Honeycomb TPS Panel.

A number of excellent papers on different metallic TPS concepts studied over the years at Langley for different vehicle concepts can be found in the literature. However, a review of these concepts is beyond the scope of this monograph.

10.3.2. Refractory Metals

Research conducted at Langley Research Center on refractory metals for potential heat shield applications has been documented in key technical papers by Tenney,[3] Lisagor,[4,5] Stien,[6] Royster,[7] and others. Lisagor and coworkers conducted studies on the properties of Cb-1OTi-5Zr columbium alloy sheet with 12 oxidation-resistant coatings. Oxidation tests were performed in dry air at 2000°F, 2400°F, and 2700°F (1365 K, 1590 K, and 1755 K) at atmospheric pressure and also at pressures of 0.5 and 0.05 torr (67 and 6.7 N/m2). Tensile tests were conducted at room-temperature and elevated-temperature on both uncoated and coated material before and after exposure and room-temperature bend tests were conducted on oxidation coupons before and after exposure. Test results indicated that an upper limit for protection of this alloy from oxidation is approximately 2400°F (1590 K) using modified silicide coatings containing titanium and chromium and that the usefulness of thin-gage coated columbium alloy sheet may be determined by substrate embrittlement rather than by oxidation. Because of oxidation and embrittlement issues with Cb alloys, work on refractory alloys for heat shields was abandoned in favor of ceramic thermal protection materials like silica RSI and carbon-carbon.

References

[1] Blosser, Max L.; "Development of Metallic Thermal Protection Systems for the Reusable Launch Vehicle", NASA Technical Memorandum 110296. October 1996.
[2] Blosser, M.L, C.J. Martin, D. Kamran, C.C. Poteet; "Reusable Metallic Thermal Protection Systems Development", Third European workshop on thermal Protection Systems, ESTEC, Noordwijk, The Netherlands, March 1998.
[3] Tenney, Darrel R.; Lisagor, W. Barry; Dixon, Sidney C.; "Materials and Structures for Hypersonic Vehicles", NASA-TM-101501, NAS 1.15:101501, 1988.
[4] Lisagor, W. B.; Stein, B. A.; "A study of several oxidation-resistant coatings on Cb-10Ti-5Zr alloy sheet at 2000 deg F, 2400 deg F, and 2700 deg F /1365 deg K, 1590 deg K, and 1755 deg K/", NASA-TN-D-3275, 1966.
[5] Lisagor, W. B.; Stein, B. A.; "Preliminary Results of a Study of 12 Oxidation-resistant Coatings for Cb-10Ti-5zr Columbium-alloy Sheet", NASA-TM-X-51973, 1964.
[6] Lisagor, W. B.; Stein, B. A.; "Oxidation and Embrittlement in Silicide-coated Columbium-alloy and Aluminide-coated Tantalum- Alloy Sheet", NASA-TM-X-56813, 1965.
[7] Royster, D. M.; Lisagor, W. B.; "Effect of high temperature creep and oxidation on residual room temperature properties for several thin sheet superalloys", NASA-TN-D-6893, L-8180, 1972.

10.4. Arc Jet Testing of Metallic Materials and Structural Concepts

10.4.1. Hypersonic Materials Environmental Test System (HYMETS)

NASA Langley Research Center's Hypersonic Materials Environmental Test System (HYMETS) facility, shown in **Figure 10.4-1**[1], was installed in 1968 as a 100 kW segmented-constrictor-direct-current-electric-arc-heated plasma wind tunnel. A HYMETS facility schematic and test setup are shown in **Figure 10.4-2** .Throughout the 1970s, 80s, 90s, and early 2000s, it was used primarily for emissivity, catalysity, and dynamic oxidation testing of metals and coatings for hypersonic vehicles.[2,3,4] The range of test conditions for the HYMETS facility during that time is presented in **Table 10.4-1**. The facility was upgraded to 400 kW in 2005 expanding its range of test conditions to those presented in second part of **Table 10.4-1.** Since then, HYMETS has been used primarily for characterization of ceramic matrix composite (CMC) materials, rigid and flexible ablators, high-temperature coatings, and for performing research and development on plasma flow diagnostics.

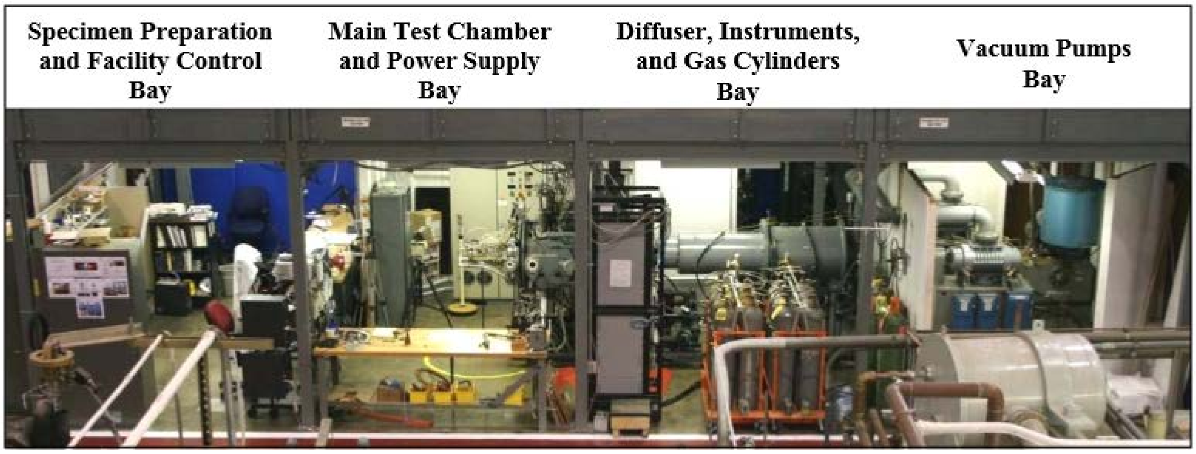


Figure 10.4-1: HYMETS Facility.

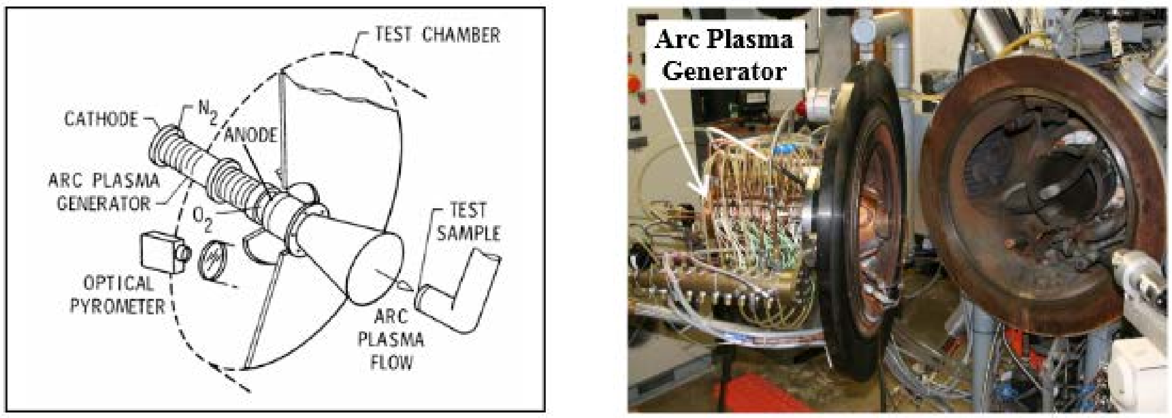


Figure 10.4-2: HYMETS Facility Schematic and Test Setup.

Table 10.4-1: HYMETS Test Conditions

Table 1. HYMETS Historic Test Conditions

Specimen Surface Temperature (°F)	1472 – 2732
Specimen Stagnation Pressure (atm)	0.004 – 0.008
Free Stream Mach Number	3.5
Free Stream Enthalpy (Btu/lb_m)	1719 – 4730
Cold Wall Heating Rate (Btu/ft^2.s)	70 – 400

Table 2. HYMETS Current Test Conditions

Specimen Surface Temperature (°F)	2300 – 4500
Specimen Stagnation Pressure (atm)	0.013 – 0.079
Free Stream Mach Number	5.0
Free Stream Enthalpy (Btu/lb_m)	2300 – 11500
Cold Wall Heating Rate (Btu/ft^2.s)	100 – 600

This facility has been used extensively at NASA to study the performance of superalloys and coated refractory metals for thermal protection systems for space vehicles. Other important facilities used for these studies included the 8-Foot High-Temperature Tunnel at Langley; ARC Jet facilities at Langley, Ames, and Johnson Space Flight Centers; specialized environmental loading facilities such as the Multiparameter Test Facility developed at Langley principally by Donald Rummler; and other loading test stands used to evaluate mechanical performance under simulated space reentry conditions.

Research on metallic TPS systems was and is driven by the desire to build efficient and reusable launch vehicles (RLV). The goal for the reusable launch vehicle is to reduce the cost of delivering payloads to low-Earth orbit by an order of magnitude. To help achieve this goal, the thermal protection system for the RLV must be durable and operable, as well as low weight. Metallic TPS have several attractive features that offer the potential to help reach the RLV goals. The inherent ductility of metallic materials offers the potential of a more robust TPS outer surface. The geometric parameters in the metallic TPS offer the opportunity to modify the design to accommodate different conditions. Because prepackaged metallic TPS panels are inherently waterproof, they can be designed to support all weather operation by making the outer surface thick enough to resist required levels of rain erosion. Mechanical attachments can allow TPS panels to be quickly and easily removed for refurbishment, replacement, or inspection of the underlying vehicle structure. Metallic TPS had been a key area of NASA R&D for application to the RLV.

Many excellent papers were published on metallic thermal protection systems by NASA Researchers including Bland Stein, Don Rummler, W. Barry Lisagor, Darrel R. Tenney, Ronald K. Clark, S. Sankaran, Max L. Blosser, John Dorsey, Robert L. Jackson, Sidney C. Dixon, Allen H. Taylor, John L. Shideler, James Wayne Sawyer, Don Avery, H. Kevin Rivers, David E. Glass, and many others. A web search of reusable metallic TPS will turn up numerous publications by these and other authors, all of which made valuable contributions to the development and understanding of TPS for reusable launch vehicles.

It should also be noted that another excellent body of work was performed by Dr. Ron Clark[5,6,7] and coworkers[8,9,10,11,12] related to the oxidation and emittance properties–of candidate high-temperature alloys after exposure to simulated reentry flow conditions and conditions expected for hypersonic flight vehicles.

References

[1] Splinter, Scott C.; Bey, Kim S.; Gragg, Jeffrey G. and Brewer, Amy,;"Comparative Measurements of Earth and Martian Entry Environments in the NASA Langley HYMETS Facility", American Institute of Aeronautics and Astronautics, 49th AIAA Aerospace Sciences Meeting, Jan. 4-7, 2011, Orlando, Florida. AIAA Paper 2011-1014, NF1676L-11103.

[2] Wiedemann, K.; Clark, R.; and Sankaran, S.; "Emittance, Catalysis, and Dynamic Oxidation of Ti-14AL-21Nb," NASA TP-2955, November 1989.

[3] Glass, D.; "Oxidation and Emittance Studies of Coated Mo-Re," NASA CR-201753, October 1997.

[4] Bird, R., Wallace, T., and Sankaran, S.; "Development of Protective Coatings for High-Temperature Metallic Materials," Journal of Spacecraft and Rockets, Vol. 41, No. 2, pp. 213 –220, March-April 2004.
[5] Clark, R. K.; Dicus, D. L.; Lisagor, W. B.; "Emittance of TD-NiCr after simulated reentry", NASA-TM-78784, 1978.
[6] Tenney, D.R.; Young, C.T.; and Herring, H.W.; "Oxidation Behavior of TD-NiCr in a Dynamic High Temperature Environment", Metallurgical Transactions, Vol. 5, May 1974, pp. 1001–1012.
[7] Young, C.T.; Tenney, D.R.; and Herring, H.W.; "Dynamic Oxidation Behavior of TD-NiCr Alloy with Different Surface Pretreatments", Metallurgical Transactions A, Vol.6A, Dec. 1975, pp. 2253–2265.
[8] Wiedemann, K. E.; Clark, R. K.; Unnam, J.; "Oxidation and emittance of superalloys in heat shield applications", NASA-TP-2578, L-16104, NAS 1.60:2578, 1986.
[9] Clark, R. K.; Unnam, J.; Wiedemann, K. E.; "Effect of oxygen barrier coatings on oxidation and embrittlement of Ti-6Al-2Sn-4Zr-2Mo foil in heat shield applications", AIAA PAPER 86-0889, 1986.
[10] Cunnington, George R.; Clark, Ronald K.; Robinson, John C.; "Thermal coatings for titanium-aluminum alloys", NASA-TM-107760, NAS 1.15:107760, 1993.
[11] Clark, R. K.; Unnam, J.; "Response of Inconel 617 superalloy to combined ground-based and STS reentry exposure", AIAA PAPER 84-1768, 1984.
[12] Clark, R. K.; Wallace, T. A.; Mullaly, J. R.; and Wiedemann, K.E.; " Oxidation/Thermal Control Coatings for Titanium-Aluminide Intermetallic Alloys", NASA TM-4152, 1990.

10.5. Thermal Structural Testing

Extensive aerothermal testing of metallic thermal protection systems was performed at NASA Langley Research Center in the 8-Foot High-Temperature Tunnel. Perhaps the best example of that testing was testing by Sawyer[1] and coworkers[2] of metallic TPS concepts for the windward surface of the X-33 vehicle. An artist view of the Venture Star (X-33) is shown in **Figure 10.5-1**.

Figure 10.5-1: Venture Star Single Stage-To-Orbit Launch Vehicle

The TPS on the windward surface of the X-33 consisted of Inconel 617 or PM-1000 (the PM-1000 material was used in the slightly higher heating areas near the nose cap) superalloy honeycomb sandwich surface panels and fibrous insulation enclosed in attached foil bags– The 8-Foot High-Temperature Tunnel provided a combination of aerodynamic heating and pressure loading on the TPS array that was representative of critical flight conditions on the X-33. These tests were the first aerothermal tests of a metallic X-33 TPS array and were used to validate the TPS for the X-33 flight program.

The metallic TPS panel concept is shown above in **Figure 10.3-1**. A schematic of the metallic TPS panel array tested in the 8-foot tunnel is shown in **Figure 10.5-2**.

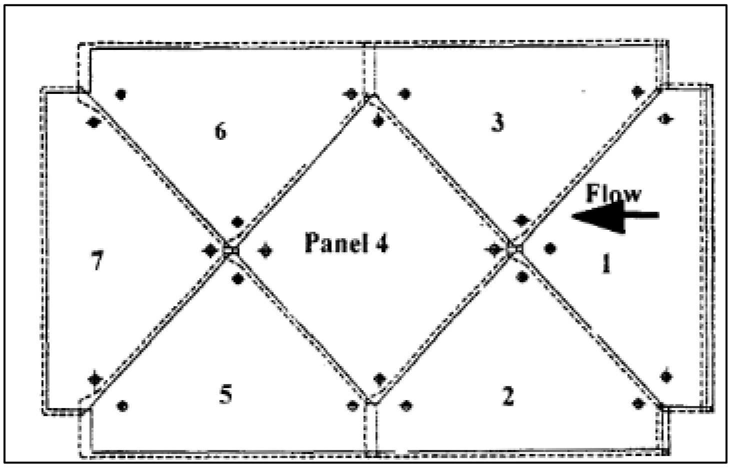


Figure 10.5-2: Metallic TPS Panel ARRAY Tested in the 8-Foot High-Temperature Tunnel Tests (Top View).

A total of 16 aerothermal tests and 7 radiant heater tests up to temperatures of 1273 K or greater were conducted on the windward surface TPS. The test conditions for the TPS panel array were representative of the aerothermal conditions expected during the X-33 flights.

Another specialized test facility located at the Langley Research Center specifically designed to study thermal/mechanical/pressure cyclical loading of curved cryogenic tank panel concepts is the Cryogenic Pressure Box (CPB) Test Facility.[3] A schematic cross-section of this facility is shown in **Figure 10.5-3**. Specimens can be loaded in biaxial tension by internal pressure and mechanical actuators. In addition, both cryogenic and elevated internal temperatures and an elevated external temperature can be applied. Circumferential, or hoop, loads due to pressurization are induced by the reaction force from the load frame, through load introduction plates, into the test specimen. Curved tank panel concepts can be tested in this facility at a relatively low cost compared to a full-scale or scaled tank test at cryogenic temperatures.

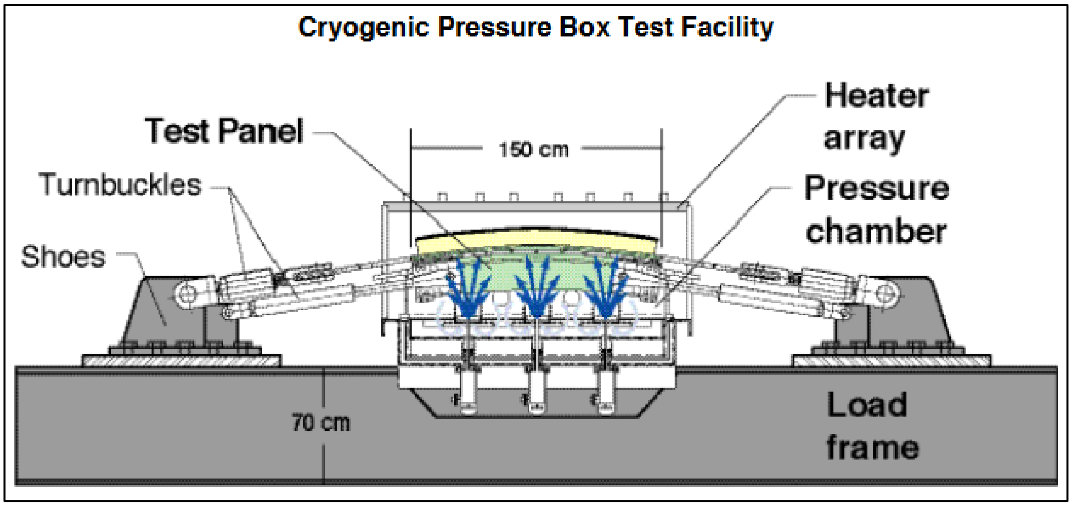


Figure 10.5-3: Schematic of the CPB Test Facility for Subcomponent Tests.

This facility has been used to investigate new concepts for integrated cryogenic propellant tank systems. One such study was conducted by Theodore F. Johnson[4] and coworkers. An example of an all metal tank concept they studied is shown in **Figure 10.5-4**. The Ti sandwich wall acts as the pressure vessel, cryogenic insulation, primary structure, and TPS support. The results of the analytical studies identified honeycomb sandwich tank with mechanically attached metallic TPS as a preferred approach for a reusable liquid hydrogen (LH2) tank system for a RLV. Over the years many such studies have been conducted at Langley.

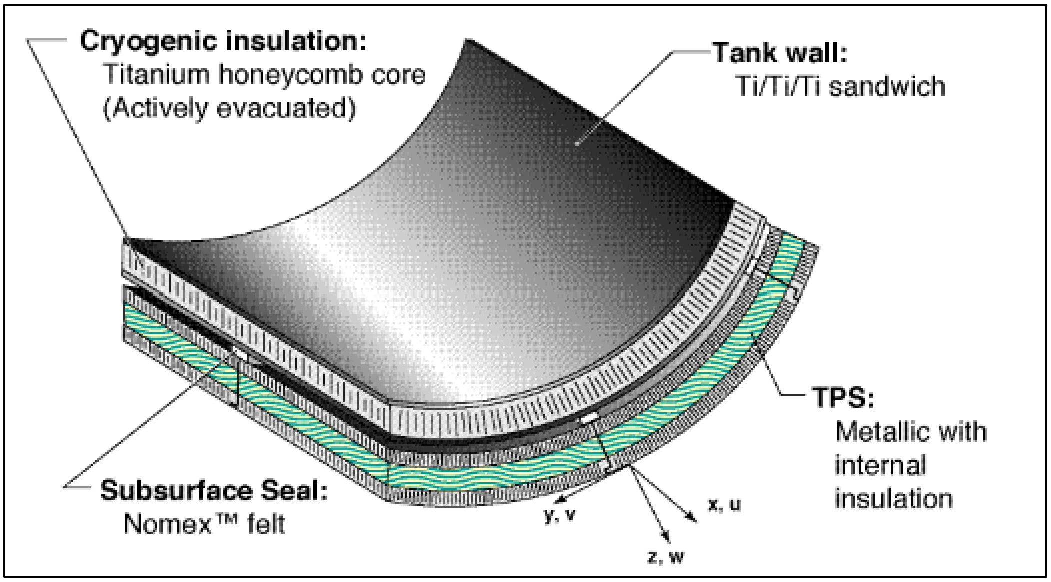


Figure 10.5-4: Example of an all-Metallic Ti/Ti/Ti Sandwich Cryogenic Tank with Metallic TPS in an Integrated Tank System Concept for a RLV.

Metallic TPS tests[5] were conducted in the NASA-LaRC Mach 7 High-Temperature Tunnel at NASA Langley. The available data are being analyzed and being used to correlate analytical models to be used for X-33 flight design analysis.

References

[1] Sawyer, James Wayne, Hodge, Jefferson and Moore, Brad; "Aerothermal Test of Metallic TPS for X-33 Reusable Launch Vehicle", Aerospace Sciences; 37th, 11–14 Jan. 1999, Reno, NV.

[2] Bouslog, Stanley A., Moore, Brad, Scanlon, Ron J. and Sawyer, James Wayne; "X-33 Metallic TPS Tests in NASA-LaRC High Temperature Tunnel", Aerospace Sciences; 37th; 11–14 Jan. 1999, Reno, NV.

[3] Ambur, D. R., Sikora, J., Maguire, J. F. and Winn, P. M.; "Development of Pressure Box to Evaluate Reusable Launch Vehicle Cryogenic Tank Panels", Presented at the American Institute of Aeronautics and Astronautics (AIAA) 37th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Salt Lake City, Utah, April 1996, AIAA-96-1640.

[4] Johnson, Theodore F., Natividad, Roderick, Rivers, H. Kevin and Smith, Russell; "Thermal Structures Technology Development for Reusable Launch Vehicle Cryogenic Propellant Tanks", NASA TM-2005-213913.

[5] Bouslog, Stanley A., Moore, Brad, Scanlon, Ron J., Sawyer, James Wayne; "X-33 Metallic TPS Tests in NASA-LaRC High Temperature Tunnel", Aerospace Sciences; Reno, NV; 11–14 Jan. 1999; 37th.

11. Corrosion

11.1. Scope of Corrosion and Oxidation Research Performed at Langley Research Center

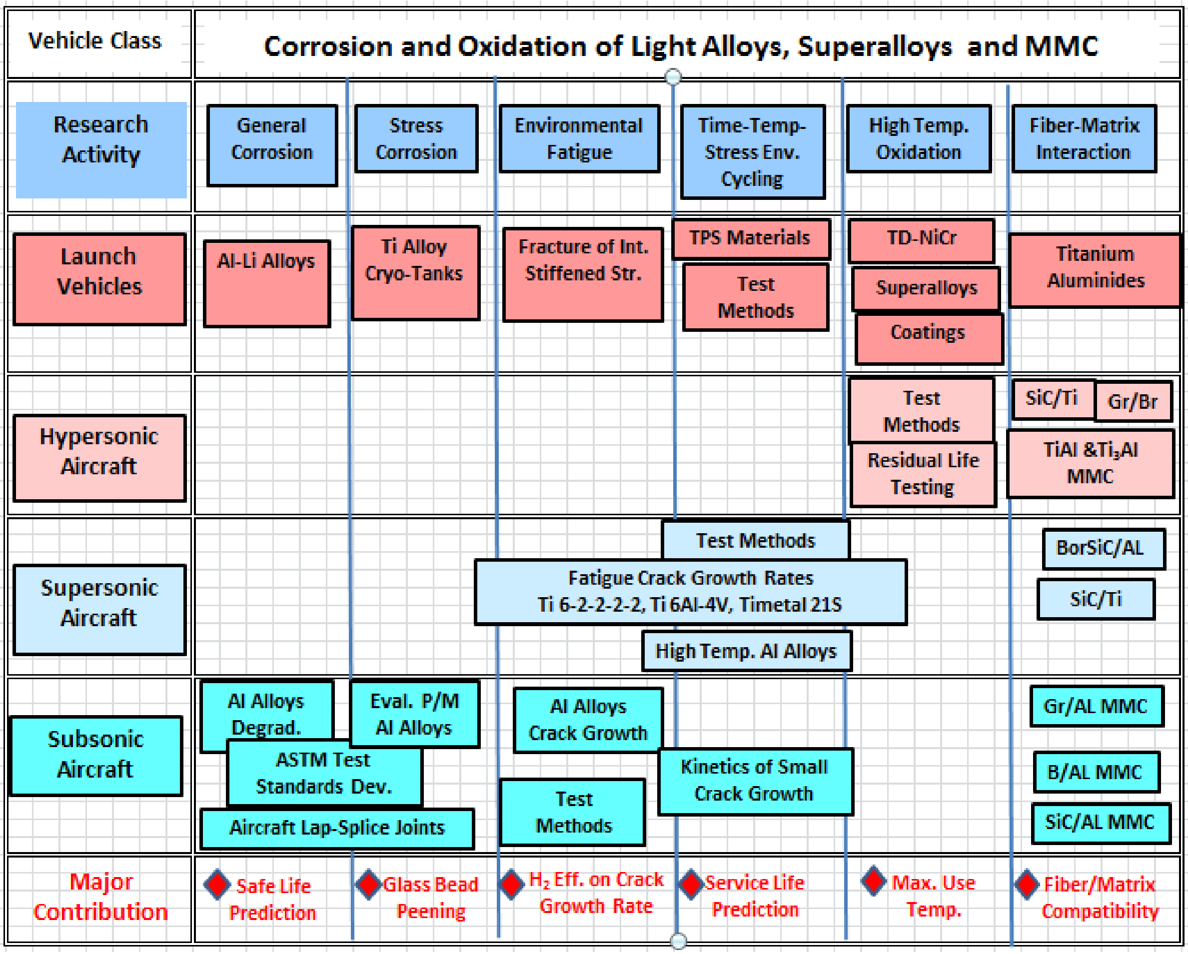


Figure 11.1-1: Corrosion and Oxidation of Aerospace Alloys Studied at Langley

Determining the performance of aerospace materials and structures under simulated service life conditions has been a key research thrust at Langley since NACA was formed. In the early years, these studies were primarily focused on atmospheric corrosion of aluminum alloys. Researchers performing fatigue studies soon recognized that corrosion had a significant–effect on fatigue-crack growth rates and therefore fatigue life. The issue of corrosion fatigue interaction was a major focus during the NASA-FAA Aging Aircraft Program and highlights of the work performed by Bob Piascik at Langley and Dr. Richard P. Gangloff at UVA under the NASA_UVA Light Alloy Grant has been included. A very significant amount of work was performed on Al alloys under the NASA-UVa Light Alloy Grant managed by Dennis Dicus. Corrosion related studies were performed by graduate students advised and directed by Dr. Richard P. Gangloff, Dr. Glenn E. Stoner, and Dr. John R. Scully. Much of this work was on Al-

Li-Cu alloy systems and other high-temperature alloys of interest for the High-Speed Supersonic Transport Aircraft Program being researched during the 1990s. Stress corrosion was also a significant research thrust of Barry Lisagor's as well as development of ASTM corrosion test standards. Barry Lisagor was awarded the prestigious Francis L. LaQue Memorial Award in 2002, the ASTM Award of Merit and the title of Fellow.

The corrosion activities worked at Langley are shown in **Figure 11.1-1**. The research activities studied are shown in the top row of the figure. The next three rows show the focus of the research activities for different flight regimes. Al alloys and high-strength steels were studied primarily for subsonic aircraft applications, titanium alloys for supersonic applications, and Ti aluminides and superalloys for hypersonic applications. Test method development was a key research focus and cuts across all vehicle classes and flight regimes. In all these studies, the focus was on determining the effect of corrosion on the mechanical properties of the metal and studying the effect of fatigue crack growth rate and damage tolerance.

Supersonic flight introduced another environmental factor, hot structure. The elevated temperatures experienced during supersonic flight brought about research on elevated temperature Al alloys and titanium alloys. Extensive work was performed on the elevated creep behavior of candidate Al alloys of interest for the supersonic transport (SST) in the late 1960s and early 1970s. For the proposed high-speed research aircraft studied during the 1990s, there was a major effort placed on testing materials under simulated service life conditions that gave rise to the Time-Temp.-Stress Testing Program conducted at Langley and under contract with the major airframe companies. Selected highlights of the results of that program are presented in section **12.2.3**.

When NASA was formed and space launch vehicle development became a major national priority research on materials turned to high-temperature materials that could withstand the rigors of hypersonic flight in the atmosphere during both launch and Earth reentry. Hot structures research included work on structural concepts, materials selection and fabrication technology, and studies of the performance of heat shield structural panels to reentry conditions. Langley did an extensive amount of work on metallic thermal protection systems for the space shuttle. Arc-Jet testing of metallic TPS concepts was performed at Langley and at Ames Research Center. The primary materials of interest for these studies were superalloys and coated refractory alloys. Oxidation protection was a major issue for both systems, and several different alloy variants were examined to find superalloys that could survive the harsh environment encountered during reentry. The major focus of the coated refractory alloy testing was the durability of the coating. Even a small pin hole in the protective coatings was found to result in unacceptable oxidation and spallation of the coatings. Although metallic heat shields were not selected for the shuttle TPS, significant advancements in high-temperature materials and hot structures came out of the Langley research. The major research thrust for the different vehicle systems worked over several decades is shown in the figure above.

11.1.1. Research Staff

W. Barry Lisagor
1962 - 1998

Thomas T. Bales
1962 - 1998

Dr. Robert S. Piascik
1990 - Present

Although many different researchers (Royster, D. M., Bales, T. T.; Lisagor, W. B.; Manning, C. R., Jr.; Gardner, J. E.; Royster, D. M., Phillips, E. P, Pride, R. A.; Woodward, J. M., Heimerl, George J.; Hardrath, Herbert F, Johnson, W. Steven; Weeks, Carrell E., Wallace, T. A.; Bird, R. K.; Sankaran, S. N., Smith, Stephen W.; Piascik, Robert S., Wiedemann, Karl E.; Bird, R. Keith;.Clark, Ronald K., Figge, I. E.; Hudson, C. M., Braski, D. N.; Dexter, H. B., and others) made contribution to NASA metallic materials environmental degradation program, three researchers standout as being particularly noteworthy. The first was W. Barry Lisagor recognized earlier for his overall contributions to the metallic materials program and for his recognition by ASTM cited above. The second researcher was Tom Bales recognized for his overall contributions to fabrication and processing of metallic materials and for their assessment in aircraft and space launch vehicle environments. The third researcher, who was recently named a NASA Technical Fellow, is Dr. Robert S. Piascik. Dr. Piascik joined NASA Langley Research Center (LaRC) in 1990 as a senior materials scientist in the Mechanics of Materials Branch and the Metals and Thermal Structures Branch. In November 2003, he joined the newly formed NASA Engineering and Safety Center. At LaRC, he has conducted basic and applied materials research and led NASA, industry, universities, and government agency research teams. Dr. Piascik's research has focused on damage science with particular emphasis on advancing the durability and damage tolerance engineering practice and the development of advanced metallic structural materials for aerospace vehicles. His research has made significant contributions to a variety of NASA programs, including the Vehicle Systems Program, the Aging Aircraft Program, the High-Speed Research Program, and more recently to the NASA Engineering Safety Center (NESC). Dr. Piascik is also a NASA Technical Fellow for Materials.

11.2. Corrosion of Aluminum Alloys

A comprehensive review of the corrosion work performed at Langley over the past several decades (1920–2014) is beyond the scope of this monograph. A search of the NASA Technical

Report Server will show that the topics studied include atmospheric corrosion of Al alloys, stress corrosion cracking of Al alloys, effect of corrosion on fatigue-crack-growth rates, growth of small cracks in 2024, environment fatigue of Al-Li alloys, nondestructive evaluation (NDE) methods to detect corrosion damage, and many other topics. Therefore, the approach taken in the review will be to select a few examples of the type of work performed to illustrate the significance of the contributions made by NASA Langley researchers to the fundamental understanding of the performance of metallic materials in aircraft and launch vehicles under service life environmental conditions.

In the mid-1970s, a systematic investigation was conducted by Lisagor and Bhandarkar[1] to examine the fracture behavior of the structural aluminum alloys 2024, 6061, 7075, and 7178 (in selected heat treatments) tested under several controlled conditions. The investigation included both time independent (tensile, shear, and precracked notch-bend) fractures and time dependent (fatigue and stress corrosion) fractures. Specimens were obtained from both sheet and plate material and tested in longitudinal and transverse orientations. Strain rate effects on fracture morphology were examined in tension and shear tests. Fatigue fracture studies included an examination of the influence of minimum-to-maximum-load ratio on fracture morphology. Second-phase particles observed on fracture surfaces and metallographically prepared sections and corrosion products associated with stress corrosion fractures were analyzed chemically using scanning electron microscopy and energy-dispersive X-ray analysis. Fracture morphology was related to the microstructural features, the testing conditions, and the form of commercial product.

Langley sponsored research on corrosion of Al alloys under the NASA-UVA Light Aerospace Alloy and Structures Technology Program. Several students worked on projects related to corrosion of light alloys under the direction of professors Dr. J. R. Scully, Dr. Richard P. Gangloff, Dr. Glen E. Stoner, Dr. Edgar A. Starke, Jr., and Dr. John Wert.

Work performed by Glenn E. Stoner and his student Rudolph G. Buchheit, Jr. on aqueous corrosion of Al-Li alloys is representative of the types of research sponsored by NASA under the NASA-UVA Grant. The following is an abstract of that work taken from one of the grant progress reports.

Like most heat treatable aluminum alloys, localized corrosion and stress corrosion of Al-Li-Cu alloys is strongly dependent on the nature and distribution of second phase particles. To develop a mechanistic understanding of the role of localized corrosion in the stress corrosion process, bulk samples of T_1 (Al_2CuLi) and a range of Al-Cu-Fe impurity phases were prepared for electrochemical experiments. Potentiodynamic polarization and galvanic couple experiments were performed in standard 0.6 M NaCl and in simulated crevice solutions to assess corrosion behavior of these particles with respect to the alpha-Al matrix. A comparison of time to failure versus applied potential using a constant load, smooth bar stress-corrosion cracking (SCC) test technique in Cl(–), Cl(–)/CrO_4(2–), and Cl(–)/CO_3(2–) environments shows that rapid failures are to be expected when applied potentials are more positive than the breakaway potential (E_{br}) of T_1 (crack tip) but less than E_{br} of alpha-Al (crack walls). It is shown that this criterion is not satisfied in aerated Cl(–) solutions. Accordingly, SCC resistance is good. This criterion is satisfied, however, in an alkaline isolated fissure exposed to a CO_2-containing atmosphere. Rapid failure induced by these fissures was recently termed preexposure embrittlement. Anodic polarization shows that the corrosion behavior of T_1 is relatively unaffected in alkaline CO_3(2–) environments, but the alpha-Al phase is rapidly passivated. X-ray diffraction of crevice walls from artificial crevices suggests that passivation of alpha-Al occurs as hydrotalcite-type compound $(LiAl_2(OH)_6)2(+) – CO_3(2–) – nH_2O$.

11.2.1. Breaking Load Test

Typically, the well-documented forms of corrosion for aluminum alloys are localized and exfoliation (intergranular) corrosion; often these two forms lead to severe damage, such as stress corrosion cracking and corrosion fatigue. Under high-strength conditions, most aluminum alloys are generally highly susceptible to exfoliation (intergranular) corrosion and stress corrosion cracking in saltwater environments. Since most aluminum alloys used as structural materials require high strength, their susceptibility to stress corrosion cracking is of great concern. The breaking load test technique provided a new and more quantitative approach to evaluating and rating the stress corrosion cracking performances of aluminum alloys. It has been claimed that the test is more discriminating than any other accelerated laboratory practice known for distinguishing the stress corrosion cracking resistance of materials with relatively close resistance levels.

Langley sponsored work at Alcoa to develop the Breaking Load Test.[2] A key reference on this work is found in ASTM STP 1134 V.S. Agarwala and G. M. Ugiansky, Eds.[3,4] This method, named the “breaking load” test, is based on the apparent decrease of the ultimate tensile strength, or the breaking strength, of the material after exposure to an aggressive environment. It measures corrosion damage by comparing the post-exposure fracture stress (residual strength) of stressed specimens with the tensile strength of unstressed and unexposed specimens. Since post-exposure fracture stress reflects the extent of corrosion damage, residual strength data can be directly related to the so-called “effective flaw” size, which represents the maximum depth of corrosion attack in the specimen at the time of test. Thus, the method enables evaluation of materials in terms of their ability to initiate and propagate stress corrosion cracks, and eliminates problems associated with the effect of specimen size and geometry on experimental results. In contrast to traditional pass/fail testing, the breaking load method does not require the specimens to fail in the solution, and thus shortens markedly the duration of the test. Extensive experimental work carried out by Alcoa indicated that the quantitative nature of the breaking load method opens new possibilities for investigation of stress corrosion cracking phenomena and other forms of environmental degradation, such as corrosion fatigue.

In 1987, Marcia Domack published an article [5] on stress corrosion evaluation of powder metallurgy aluminum alloy 7091 with the breaking load test method. An excerpt from that publication states:

> *The stress corrosion behavior of powder metallurgy (PM) aluminum alloy 7091 has been evaluated using a new technique called the breaking load test method,[6] which was developed by Alcoa Laboratories under NASA contract NAS1-16424. Direct tension specimens machined from extruded material in the T7E69 and T7E70 conditions were tested in both the longitudinal and transverse orientations. Specimens were exposed to a 3.5% NaCl solution in alternate immersion for up to 9 days at stress levels as high as 90% of themateria1 yield strength. Optical and scanning electron microscopy was used to evaluate specimen fracture surfaces to determine the extent of stress corrosion and to identify attack by other mechanisms. Breaking stress data were analyzed with extreme value statistics to determine threshold stress levels for stress corrosion cracking, probability of*

survival at specific stress levels, and 99% survival stresses. The results of this study are in agreement with data reported in the literature, and indicate that PM 7091 aluminum is highly resistant to stress corrosion cracking for the orientations tested. Preliminary data analysis indicates that the effects of test variables such as heat treatment, specimen orientation, and exposure conditions can be better discriminated by the breaking load test method than by conventional pass-fail data analysis.

Martcia Domack also published corrosion articles on stress corrosion testing of 7075-T6 aluminum alloy plate,[7] and evaluation of KIscc and da/dt measurements for aluminum alloys.[8]

Lisagor was active with ASTM organizing and running conferences on topics related to stress corrosion cracking and hydrogen embrittlement. A key reference that illustrates his activities is W.B. Lisagor, T.W. Crooker, and B.N. Leis, Eds., “Environmentally Assisted Cracking: Science and Engineering, ASTM STP 1049,” ASTM International, West Conshohocken, PA, 1990. It should also be noted that NASA supported Richard P. Gangloff through the NASA-UVA Light Alloy grant and part of the work was focused on environmental degradation of aerospace alloys. An excellent review[9] of the effects of hydrogen on cracking of high strength alloys by Gangloff can be found on the web.

11.2.2. ASTM Corrosion Test Standards

Development of ASTM test standards is the collective result of many researchers and organizations cooperating on common test procedures and sharing results. Many ASTM test standards took years of collective work to develop and validate in different laboratory and field tests. Lisagor made very significant contributions to many different test standards and was highly respected for his many contributions and tireless efforts to share his testing expertise with others.

References

[1] Bhandarkar, M. D.; Lisagor, W. B.; “Metallurgical characterization of the fracture of aluminum alloys”, Conference Proceedings, Fractography in failure analysis; Symposium; Toronto; Canada, May 1–6, 1977.

[2] Sprowls, D. O., Bucci, R. J., Ponchel, B. M.,Brazill, R.L.,Bretz, P.E.; “A Study of Environmental Characterization of Conventional and Advanced Aluminum Alloys for Selection and Design. Phase II – The Breaking Load Test Method”, NASA CR 172387, August 1984.

[3] D. A. Lukasak, R. J. Bucci, E. L. Colvin, and B. W. Lifka; “Damage-Based Assessment of Stress Corrosion Performance Among Aluminum Alloys”, ASTM STP 1134, 1991, p.101.

[4] E. L. Colvin and M. R. Emptage; “The Breaking Load Method; Results and Statistical Modification From the ASTM Inter-Laboratory Test Program”, New Methods for Corrosion Testing of Aluminum Alloys, ASTM STP 1134, V. S. Agarwala and G. M. Ugiansky, Eds., American Society for Testing and Materials, Philadelphia, 1992, p. 82.

[5] Domack, Marcia S.; “Stress Corrosion Evaluation of Powder Metallurgy Aluminum Alloy 7091 with the Breaking Load Test Method”, AFWAL, Proceedings of the 1987 Tri-Service

Conference on Corrosion, Volume 1, pp. 257-276 (1987). https://namis.alionscience.com/conf/tscc/search/pdf/B132981.pdf.

[6] Sprowls, D. 0.; Bucci, R. J.; Ponchel, R. M.; Brazill, R. L.; Bretz, P. E.; “A Study of Environmental Characterization of Conventional and Advanced Aluminum Alloys f o r Selection and Design. Phase II- The Breaking Load Test Method”, NASA CR 172387, August 1984.

[7] Domack, M. S.; “Critical Assessment of Precracked Specimen Configuration and Experimental Test Variables for Stress Corrosion Testing of 7075-T6 Aluminum Alloy Plate, Corrosion Cracking”, V. S. Goel, ed., Proceedings of the Corrosion Cracking program, International Conference and Exposition on Fatigue, Corrosion Cracking, Fracture Mechanics, and Failure Analysis, p. 191 (1985).

[8] Domack, Marcia S.; “Evaluation of KIscc and da/dt Measurements for Aluminum Alloys Using Precracked Specimens. ASTM STP 1049 Environmentally Assisted Cracking: Science and Engineering”, 1990, ed. by Lisagor, Crooker and Leis

[9] Gangloff, Richard P.; “Hydrogen assisted Cracking of High Strength Alloys”, http://www.virginia.edu/ms/faculty/gangloffCSIChapterFinalProofed.pdf.

11.3. Corrosion of Titanium Alloys

Titanium alloys are used extensively in aerospace applications because they have very high tensile strength and toughness (even at extreme temperatures). They are light in weight, have extraordinary corrosion resistance, and have the ability to withstand extreme temperatures. They are used in military applications, aircraft, spacecraft medical devices, connecting rods on expensive sports cars and some premium sports equipment, and consumer electronics. The excellent resistance of titanium to many highly corrosive environments, particularly oxidizing and chloride-containing process streams, has led to widespread non-aerospace (industrial) applications.

The excellent corrosion resistance of titanium alloys results from the formation of very stable, continuous, highly adherent, and protective oxide films on metal surfaces. Because titanium metal is highly reactive and has an extremely high affinity for oxygen, these beneficial surface oxide films form spontaneously and instantly when fresh metal surfaces are exposed to air and/or moisture. A damaged oxide film can generally re-heal itself instantaneously if at least traces of oxygen or water are present in the environment. However, anhydrous conditions in the absence of a source of oxygen may result in titanium corrosion, because the protective film may not be regenerated if damaged.

The nature, composition, and thickness of the protective surface oxides that form on titanium alloys depend on environmental conditions.[1] In most aqueous environments, the oxide is typically TiO^2, but may consist of mixtures of other titanium oxides including TiO^2, Ti^2O^3, and TiO. High-temperature oxidation tends to promote the formation of the chemically resistant, highly crystalline form of TiO, known as rutile, whereas lower temperatures often generate the more amorphous form of TiO, anatase, or a mixture of rutile and anatase.

Titanium alloys are widely used in hydrogen-containing environments and under conditions in which galvanic couples or cathodic charging causes hydrogen to be evolved on metal surfaces.

Although excellent performance is revealed for these alloys in most cases, hydrogen embrittlement has been observed.

Stress-corrosion cracking is a fracture, or cracking, phenomenon caused by the combined action of tensile stress, a susceptible alloy, and a corrosive environment. The metal normally shows no evidence of general corrosion attack, although slight localized attack in the form of pitting may be visible. Usually, only specific combinations of metallurgical and environmental conditions cause SCC. This is important because it is often possible to eliminate or reduce SCC sensitivity by modifying either the metallurgical characteristics of the metal or the makeup of the environment.

Another important characteristic of SCC is the requirement that tensile stress is present. These stresses may be provided by cold work, residual stresses from fabrication, or externally applied loads.

The key to understanding SCC of titanium alloys is the observation that no apparent corrosion, either uniform or localized, usually precedes the cracking process. As a result, it can sometimes be difficult to initiate cracking in laboratory tests by using conventional test techniques.

It is also important to distinguish between the two classes of titanium alloys. The first class, which includes ASTM grades 1, 2, 7, 11, and 12, is immune to SCC except in a few specific environments. These specific environments include anhydrous methanol/halide solutions, nitrogen tetroxide (N_2O_4), and liquid or solid cadmium. The second class of titanium alloys, including the aerospace titanium alloys, has been found to be susceptible to several additional environments, most notably aqueous chloride solutions.

The coupling of titanium with dissimilar metals usually does not accelerate the corrosion of titanium. The exception is in strongly reducing environments in which titanium is severely corroding and not readily passivated. In this uncommon situation, accelerated corrosion may occur when titanium is coupled to more noble metals. In its normally passive condition, materials that exhibit more noble corrosion potentials beneficially influence titanium.

Stress corrosion cracking of titanium alloys has been a topic of considerable study by NASA Langley researchers.

11.3.1. Stress Corrosion Cracking (SCC) of Titanium Alloys

The phenomenon of hot-salt stress corrosion of titanium alloys was of interest in the early 1960s because of the desire to use Ti alloys for the fuselage of supersonic aircraft. Of the several titanium alloys available, Ti-8Al-lMo-lV appeared to be the most desirable for sheet application. However, many titanium alloys, including Ti-8Al-lMo-lV, that exhibit good structural properties show poor resistance to salt-stress corrosion at elevated temperatures. Braski[2] showed that severe salt-stress-corrosion cracking occurs at load-induced tensile stresses of 50 ksi (345 MN/m^2) when the material is exposed at a temperature of 550°F (5610 K) for times as short as 500 hours. Additional laboratory investigations [3,4,5] conducted at Langley and in other laboratories demonstrated that other titanium alloys were also susceptible to embrittlement at elevated temperatures while being stressed in the presence of moisture and halides. Ti-8Al-1Mo-1V which was the leading candidate material for the SST aircraft was dropped from the program because of the hot-salt stress-corrosion issues uncovered in the Langley tests.

References

[1] Corrosion of Titanium and Titanium Alloys, Total Materia, Sept. 2001. http://www.totalmateria.com/Article24.htm.
[2] Braski, David N.; and Heimerl, George J.; "The Relative Susceptibility of Four Commercial Titanium Alloys to Salt Stress Corrosion at 550° F", NASA TN D-2011, I963.
[3] Heimerl, G. J.; and Braski, D. N.; "A Stress Corrosion Test for Structural Sheet Materials", Mater. Res. Std., vol. 5, no. 1, Jan. 1965, pp. 18–22.
[4] Heimerl, G. J.; Braski, D. N.; Royster, D. M.; and Dexter, H. B.; "Salt Stress Corrosion of Ti-8Al-1Mo-IV Alloy Sheet at Elevated Temperatures". Stress-Corrosion Cracking of Titanium, Spec. Tech. Publ. No. 397, Am. SOC. Testing Mater., c.1966, pp. 194–214.
[5] Pride, R. A. and Woodard, J. M.; "Salt Stress-Corrosion Cracking of Residually Stressed Ti-8Al-lMo-lV Brake-Formed Sheet at 550°F (561 K)", NASA TM X-1082.

11.4. Ti SCC and the Apollo Tank Shot Peening Story

11.4.1. Apollo Tank Failures

On July 11, 1965, a reaction control system (RCS) oxidizer tank containing nitrogen tetroxide (N_20_4) failed during a test to demonstrate propellant compatibility with titanium tanks. This was the first of seven titanium Ti-6Al-4V alloy tanks to fail from a group of ten tanks put into test to investigate a failure that occurred during February 1965. These results caused an intensive investigation to be undertaken. As a result, the Langley Research Center was requested to participate in the investigation of the tank failures. A team of three researchers, who had recently completed graduate studies in metallurgical engineering, in the Structural Materials Branch of the Structures Division at Langley were assigned the task.

The team was aware that a colleague who was conducting salt-stress-corrosion studies in support of the National Supersonic Transport Program was having difficulty obtaining repeatable results with recent specimens. After investigating the procedures used to prepare his specimens, it was determined that the strips used for the recent test specimens had been deburred by vibratory peening using aluminum oxide triangles while the prior specimen strips had been deburred simply by filing the edges. This lead to the premise that either the surface finish or induced cold work was altering the test results. The specimen used was a self-stressed specimen made by spot welding the ends of two titanium strips together and then using a fixture to bow the strips to a curvature creating the desired outer stress and then spot welding the ends together. Based on the effect of the vibratory peening on the stress corrosion specimens and assuming that cold work could be beneficial in reducing the effect of the applied stress required for stress corrosion failure, glass bead peening that would increase the amount of cold work in the surface was chosen as a process to evaluate. The team assigned to investigate the tank failures quickly initiated a study to investigate the possibility of stress corrosion being the cause of the tank failures using the small self-stressed specimens.

Stress corrosion of Ti-6Al-4V alloy titanium alloy, in N_2O_4, was investigated[1] using small self-stressed specimens and tanks. Data was generated over a range of temperatures and exposure times to define the conditions where stress corrosion cracking would occur. Stress cracking of bare titanium self-stressed specimens, when exposed at a temperature of 165°F was severely damaged as specimen failure occurred in 4 hr. Specimens that had been glass-bead peened to induce a compressive stress into the surface experienced no failure after exposure for a week. As a result, studies were initiated to investigate the glass-bead peening of Apollo RCS tanks and to verify the effect on stress corrosion cracking.

A small 12.5-inch–diameter, 39-inch-long mild steel dummy tank[2] was fabricated containing titanium test strips that were heat treated to the same material condition as the Apollo tanks. Langley personnel, with assistance from the peening equipment manufacturer, were able to devise a procedure to glass-bead peen the inner surface of the dummy tank and the titanium strips. When examined by X-ray diffraction, the peened strips were shown to have a compressive stress of the desired magnitude (100 ksi) induced into the surface. The less than precise procedure developed for peening was then repeated to peen an Apollo test tank. The peened Apollo tank was returned to Langley and survived a 30 day test at service conditions without failure. As a result of the successful test, a project to design and build equipment to precision treat the Apollo tanks to avoid a possible slip in the schedule of a lunar landing was initiated. Equipment was successfully built in-house at Langley in 30 days and was proven to be capable of reliably glass-bead peening Apollo flight tanks ranging in size from 12.5 to 51 inches in diameter and from 20 inches to 14 feet in length. A total of 26 tanks were peened at Langley. At the request of Dr. Wernher von Braun, the Langley equipment was later transferred to the Douglas Aircraft Company in Santa Monica, California for peening the auxiliary propulsion tanks for the Saturn SIVB stage. A team from Langley was sent to Douglas to reassemble the equipment and to train Douglas personnel in its operation.

11.4.2. Investigation of Glass-Bead Peening Parameters

When the surface of a material is plastically deformed by glass-bead peening, a compressive stress is induced in the surface of the material. The magnitude and depth of the residual stress induced is dependent on the extent of the plastic deformation, the restraint imposed by the underlying material, and the shape of the part being peened as well as other factors that are related to the mechanical properties of the material. The objective in glass-bead peening the titanium alloy tanks was to induce a compressive stress of approximately 100 ksi into the surface of the tanks to overcome the operational tensile stresses of 90 ksi resulting from pressurization. Glass beads were chosen as the peening media rather than metal shot to avoid contamination of the peened surface and to minimize any detrimental effects on the mechanical properties of the titanium. The stress induced into the surface of the titanium strips by the glass-bead peening process was determined to be 100 ksi. The strips were held flat and glass-bead peened using an air pressure of 50 psi, glass beads having a diameter of 0.006–0.010 inches, and a peening time of approximately 10 seconds. The induced compressive stress in the vibratory peened specimens was 35 ksi as determined by X-ray diffraction.

Early test results on the small self-stressed specimens demonstrated that a bare Ti-6Al-4V sheet in the solution treated and aged condition exposed in N_2O_4 at 165°F failed by stress-corrosion cracking in approximately 4 hr. Failure of the vibratory peened specimens was erratic but generally failed in less than 8 hrs while those specimens that had been glass-bead peened survived the effects of exposure for a week at the same conditions with no damage. As a result, a study was immediately launched to investigate development of procedures to glass-bead peen Apollo propellant tanks.

11.4.2.1. Glass-Bead Peening of an Apollo Dummy Tank

A mild steel tank replicating the size of a small, Apollo RCS tank was fabricated and Ti-6Al-4V solution heat treated and aged strips, which replicated the heat treat condition of the Apollo tank material, were attached to the inner surface. The dummy tank was approximately 39 inches in length and 12.5 inches in diameter. Following discussions with the manufacturer of the glass-bead peening equipment, three representatives of Langley traveled to Palo Alto, California to examine the peening equipment that the manufacturer had that could possibly be used to glass-bead peen the inner surface of the tank.

On arrival, the only equipment that Vacu-Blast, the manufacturer of the equipment, had operational to peen the inner surface of a tank or a pressure vessel consisted of twin fixed nozzles on a lance which traveled the length of a rotating gas pressure vessel. Langley personnel wanted the capability of impacting the surface being peened at an angle close to 90 degrees in order to obtain the maximum benefit of introducing cold work into the surface. With the cooperation of Vacu-Blast personnel, an apparatus was developed to rotate the dummy tank while a lance containing a glass bead peening nozzle was driven by a small cart at a controlled speed the length of the tank. The nozzle angle for peening the cylindrical section was at 90 degrees. The nozzle could be repositioned manually to a given angle to peen a section of the dome and repositioned several times at different angles to attempt a near-normal impact of beads on the wall of the dome section of the tank.

Using this apparatus, the dummy tank containing the test strips, held in place using sheet holders, was glass-bead peened. Peening parameters were selected that had previously been shown to induce a residual compressive stress of 100 ksi into the peened surface of the titanium test strips. To achieve the desired appearance and coverage of the peened surface, several peening passes were made. Test strips were removed after each peening pass to visually inspect coverage of the surface.

Even though the procedures used for peening were far from being optimized the titanium test strips removed from the dummy tanks indicated that the residual compressive stresses induced into the titanium test strips from peening were of the desired magnitude of 100 ksi and the treatment was successful in demonstrating the ability to successfully glass bead peen the inner surface of the oxidizer tanks.

11.4.2.2. Peening of an Apollo Test Tank

An Apollo Reaction Control System tank of essentially the same size as the dummy tank was peened at Vacu-Blast, duplicating the peening procedures used for the dummy tank, and returned to Langley for test in the N_2O_4 test facility. The peened Apollo tank survived 30 days when subjected to the simulated flight service conditions of a temperature of 105°F and a pressure of 250 psi, resulting in a nominal hoop stress of 90 ksi on the cylindrical section.

11.4.2.3. Equipment and Procedures for Glass-Bead Peening Apollo Flight Tanks

Based on the successful test of the peened Apollo test tank, Langley initiated a crash program with approval of the Center Director requiring a large fraction of the manpower in the Fabrication Division and selected support groups working with the engineers in the Structures Research Division to design and build the equipment to reliably glass-bead peen titanium N_2O_4 tanks for spaceflight systems.

Extensive research was also conducted to develop a thorough understanding of each of the glass-bead peening parameters and their ability to achieve reliable quantifiable results required to glass-bead peen flight tanks.[5]

The peening equipment was built without any formal drawings and was made operational within 30 days to have the capability of reliably glass-bead peening titanium propellant flight tanks ranging in size from 20 inches to 14 feet in length and 12.5 to 51 inches in diameter.

A total of 26 tanks were peened: 13 of test and 13 for flight in the SIVB stage of Apollo.

11.4.2.4. Recognition for a Job Well Done

The value and the benefits of the research conducted at the Langley Research in 1965–67 is probably best stated in the following references:

- Dr. Wernher von Braun, Director of the Marshall Space Flight Center, was aware of the status of the stress corrosion problem, and Dr. von Braun sent a teletype to Dr. Floyd Thompson, Director of the Langley Research Center, congratulating him on the fine work Langley was doing on the titanium tank stress corrosion problem. Dr. Von Braun stated that the shot peening process developed by Langley would considerably improve the confidence in using the nitrogen tetroxide in the titanium tanks of the auxiliary propulsion system for the Saturn SIVB stage.
- In recognition of Langley's effort, a commendation memo from the Apollo Program Director was sent to the Director, Office of Advanced Research and Technology, NASA Hdqtrs. on March 7, 1966 which stated:

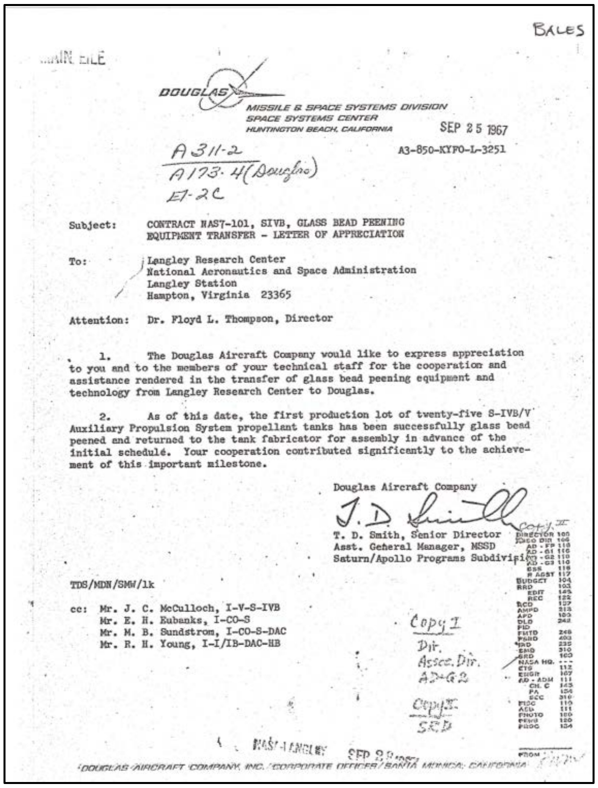
> In July 1965, the Apollo Program encountered stress corrosion of titanium tanks from nitrogen tetroxide propellant, and that through his auspices Langley Research Center initiated a crash effort that had been a key factor in solving the problem. Phillips said that Langley's effort had been vigorous, thorough, and of the highest professional caliber. An excellent team relationship had been maintained with MSC, MSFC, Kennedy Space Center, vehicle contractors, and tank subcontractors and LaRC personnel had given dedicated and outstanding support. He cited that
>
> 1. within nine days of go-ahead, a test facility was constructed, equipped, and in operation;
> 2. within one hour after the request from MSC, coupon tests were under way in support of the Gemini VII flight;
> 3. glass bead peening was demonstrated as a solution and many tanks were peened on a crash schedule for flight and test use;
> 4. coupon tests in direct support of AS-201 were instrumental in providing confidence for proceeding with that flight.

Memo, Phillips to Director, Research Div., NASA OART, "Compatibility of Titanium Propellant Tanks with Nitrogen Tetroxide," March 7, 1966."

Additional Recognition came from Douglas Aircraft.

As a result, Langley dismantled the peening equipment and had it shipped to the Douglas Aircraft Company located in Santa Monica, California. Langley personnel were then sent to California to reassemble the equipment and to train the personnel at Douglas in its use to glass-bead peen the tanks for the SIVB stage of Apollo.

On September 11, 1967, a letter was sent to Dr. Floyd L. Thompson, Director of the Langley Research Center, from T.D. Smith, Director Asst. General Manager MSSD Saturn/Apollo Programs Subdivision who said:



BALES

MAIN FILE

DOUGLAS
MISSILE & SPACE SYSTEMS DIVISION
SPACE SYSTEMS CENTER
HUNTINGTON BEACH, CALIFORNIA

SEP 25 1967

A3-850-KYFO-L-3251

A311-2
A173.4(Douglas)
E1-2C

Subject: CONTRACT NAS7-101, SIVB, GLASS BEAD PEENING EQUIPMENT TRANSFER - LETTER OF APPRECIATION

To: Langley Research Center
National Aeronautics and Space Administration
Langley Station
Hampton, Virginia 23365

Attention: Dr. Floyd L. Thompson, Director

1. The Douglas Aircraft Company would like to express appreciation to you and to the members of your technical staff for the cooperation and assistance rendered in the transfer of glass bead peening equipment and technology from Langley Research Center to Douglas.

2. As of this date, the first production lot of twenty-five S-IVB/V Auxiliary Propulsion System propellant tanks has been successfully glass bead peened and returned to the tank fabricator for assembly in advance of the initial schedulé. Your cooperation contributed significantly to the achievement of this important milestone.

Douglas Aircraft Company

T. D. Smith

T. D. Smith, Senior Director
Asst. General Manager, MSSD
Saturn/Apollo Programs Subdivision

TDS/MDN/SMW/lk

cc: Mr. J. C. McCulloch, I-V-S-IVB
Mr. E. H. Eubanks, I-CO-S
Mr. M. B. Sundstrom, I-CO-S-DAC
Mr. R. H. Young, I-I/IB-DAC-HB

Copy I
Dir.
Assoc. Dir.
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Copy II
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NASA-LANGLEY SEP 28 1967

DOUGLAS AIRCRAFT COMPANY, INC. / CORPORATE OFFICES / SANTA MONICA, CALIFORNIA

1. "The Douglas Aircraft Company would like to express appreciation to you and your technical staff for the cooperation and assistance rendered in the transfer of glass bead peening equipment and technology from Langley Research Center to Douglas."

2. "As of this date the first production lot of twenty-five S-IVB/V Auxiliary Propulsion System Propellant tanks has been successfully glass bead peened and returned to the tank fabricator for assembly in advance of the initial schedule. Your cooperation contributed significantly to the achievement of this important milestone."

Following the successful development of the glass-bead peening process for the prevention of stress corrosion by Langley, data was generated that demonstrated that the stress corrosion cracking of titanium in N_2O_4 could be eliminated by modifying the chemistry of the N_2O_4. An investigation, at Bell Aerosystems Company reported that the addition of nitric oxide or NO to the oxidizer eliminated the problem. This was later verified by Langley after stress corrosion testing using the modified N_2O_4.

References

[1] Lisagor,W. Barry, Manning, JR., Charles R. and Bales, Thomas T.; "Stress-Corossion Cracking of Ti-bAl-4V Titanium Alloy in Nitrogen Tetraoxide", NASA Technical Note D-4289, Jan. 1968.

[2] Bales, Thomas T.; Manning, Charles R., Jr.; and Lisagor, W. Barry (With appendix by Stephen K. Park); "Equipment and Procedures for Glass-Bead Peening Titanium Alloy Tanks", NASA TN D-4288, 1967.

12. DAMAGE PROCESSES

Aerospace materials and structural performance under simulated service life conditions has been a key research thrust at LaRC since NACA was formed. Understanding complex damage processes that drive important durability and damage-tolerant metallic materials behavior has been the focus of Mr. Barry Lisagor's and Dr. Robert Piascik's materials research and engineering from 1964–1995 and 1990–2015, respectively. To understand aerospace materials damage processes, the effects of an extremely wide range environment (aqueous, gaseous, temperature, and loading (cyclic and sustained)) must be studied. Unique laboratory capabilities were constructed at LaRC that replicated service environments so that first-of-a-kind research could address critical durability and damage tolerance issues for Apollo and space shuttle components and aging civilian and DoD aircraft. The following paragraphs summarize a portion of their contributions to the aerospace community and the future direction of damage science as it applies to mechanics-based predictive methodologies.

Dr. Robert Piascik, NASA Technical Fellow for Materials

12.1. Damage Processes: 1964–1995

Efforts at LaRC from 1964–1995 focused on the effects of extreme environments on lightweight and high-temperature structural materials for use in the Apollo and shuttle programs. Throughout this period, there were several investigations focused on stress corrosion cracking and environmentally assisted cracking of many alloys, including Al, Ti, and Ni-based alloys to develop understanding of damage processes for specific needs for the space program. Three of the more significant studies that represent the scope of the work during this period were– (1) development of oxidation-resistant coatings for high-temperature alloys, (2) stress corrosion cracking (SCC) of Ti-6Al-4V propellant tanks, and (3) evaluation of damage processes for Al-Li alloys for space shuttle external tanks. Brief summaries of each of these studies are provided below.

12.1.1. Oxidation Resistant Coatings for High-Temperature Alloys

When NASA was formed and space launch vehicle development became a major national priority, research on materials turned to high-temperature materials that could withstand the rigors of hypersonic flight in the atmosphere during both launch and Earth reentry. Oxidation effects on high-temperature alloys and the development of oxidation-resistant coatings for several molybdenum,[1] niobium,[2] cobalt and tantalum,[3] and superalloys[4] were investigated by Dick Royster, Barry Lisagor, and coworkers. These efforts focused on reducing the effects of oxidation temperatures in excess of 2000°F (1093°C). Oxidation protection was found to be a major issue for superalloys as well as coated refractory alloys. A major focus of the coated-refractory-alloy testing was the durability of the coating. Even a small pin hole in the protective coatings was found to result in unacceptable oxidation and spallation of the coatings. Several coatings, including silicide and aluminide coatings, were examined throughout the course of this work. Although metallic heat shields were not selected for use in the Apollo program or later in the Shuttle Program, significant advancements in high-temperature materials and hot structures were developed.

12.1.2. Stress Corrosion Cracking of Ti 6Al-4V in N_2O_4

In February 1965, the first of seven reaction control system (RCS) oxidizer tanks designed to contain nitrogen tetroxide (N_2O_4) failed during testing. Barry Lisagor, Tom Bales, and Charles Manning led the Langley effort to investigate the root cause and possible corrective actions. As part of this study, a test rig was developed to evaluate materials in pressurized N_2O_4, and this setup was used to reproduce the SCC processes for the Ti-6Al-4V material in the failed oxidizer tanks. Here, it was determined that the oxidizer tanks experienced an operational tensile stress of 90 ksi as a result of pressurization, and this resulted in failure from SCC in the presence of N_2O_4. To overcome the applied tensile stress on the surface of the tank exposed to the N_2O_4, a peening process was developed to impart a surface compressive stress. A series of experiments were run to evaluate the peening process, quantify the compressive residual stress, understand the effect of a compressive residual stress on the SCC process in N_2O_4 and develop a reliable and– reproducible process. A glass-bead media was used to avoid contamination that may result from metal shot; the glass beads used were 0.006–0.010 in in diameter, and a pressure of 50 psi was used. By peening the surface for 10 seconds, test specimens were able to survive exposure in N_2O_4 at 165°F for a week with no visible signs of damage, while an untreated specimen failed by SCC in approximately 4 hours.[5]

Upon the completion of a successful test study, the Langley researchers worked with personnel from Vacu-Blast Co., who manufactured the peening equipment used in the test study, to develop an apparatus to peen the inside of the oxidizer tanks while rotating and translating the tanks to insure a complete and consistent peeing process for flight tanks. The process developed through this collaboration was demonstrated on an Apollo flight article and the peened tank was shown to survive a 30 day simulated flight service exposure.[6] Upon completion of this successful test, new peening equipment was developed to reliably peen titanium flight tanks ranging in size from 20 inches to 14 feet in length and 12.5 to 51 inches in diameter. This equipment was used by the Apollo Program to not only treat the RCS oxidizer tanks, but was also to treat the auxiliary propulsion tanks for the Saturn SIVB stage. See section **11.4** for more details.

12.1.3. Aluminum-Lithium Alloy for Shuttle Lightweight External Tank (ET)

The super lightweight tank (SLWT) was first flown by the Shuttle Program in 1998. The SLWT utilized aluminum-lithium alloy 2195 for a large portion of the external tank structure. The SLWT is approximately 7000 lbs lighter than the previous external tank design. This reduction in weight is a primary design modification that made it possible to carry more payload with the orbiter vehicle to the higher orbit of the International Space Station (ISS), thereby making it feasible to construct and equip the ISS. Prior to the use of aluminum-lithium alloys in the SLWT, LaRC examined the behavior of these alloys for the Shuttle Program. Examining the damage processes that are expected under the loading conditions for the external tank was of primary interest with the highly anisotropic alloys, as well as evaluating the corrosion and environmentally assisted cracking processes for these alloys. The examination of corrosion and environmentally assisted cracking processes was conducted through collaboration between NASA and the University of Virginia (UVA). During this collaboration, Barry Lisagor, and Dennis Dicus were the NASA contract monitors and Rick Gangloff and Edgar Starke were the UVA PIs. The work at UVA examined the effects of corrosion in Al-Li alloys from the initiation of corrosion damage,[7] stress corrosion cracking process,[8] hydrogen embrittlement,[9] and the characterization of damage progression.[10] Collectively, this work assisted in establishing sufficient reliability in Al-Li alloys for use in the SLWT.

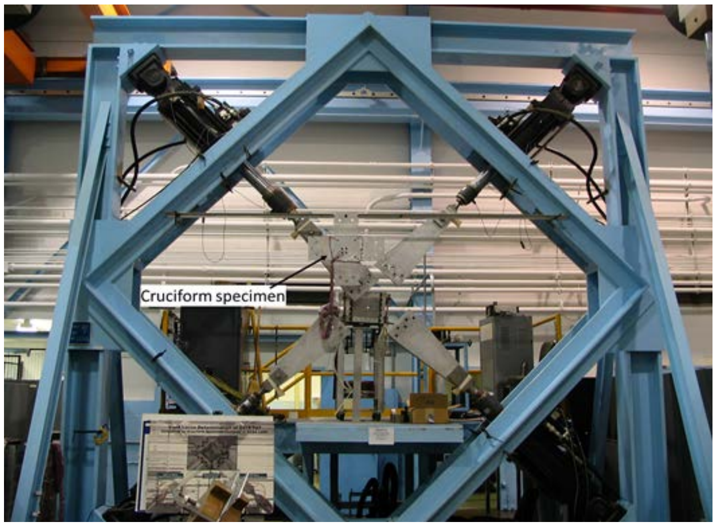


Figure 12.1-1: Large Biaxial Load Frame and Cruciform Specimen designed for testing new materials for external tank application.

To understand Al-Li material performance under the complex biaxial stress state generated under ET operation, LaRC conducted extensive studies to examine the effect of a biaxial loading on these highly anisotropic materials. Mr. Edward Phillips designed and constructed the unique biaxial load frame shown in **Figure 12.1-1**. Here, four independently controlled actuators were used to apply selected loads to simulate ET in-service hoop and longitudinal forces. First-of-a-kind testing was conducted to develop room temperature and cryogenic fracture data required for the design of the new lightweight shuttle external tank.

References

[1] W.B. Lisagor, and B.A. Stein; “Diffusion studies of several oxidation resistant coatings on Mo-0.5Ti Molybdenum alloy at 2,500 degrees F”, NASA-TN-D-2039, NASA Langley, Hampton, VA, August 1964.

[2] W.B. Lisagor, and B.A. Stein; “Oxidation and embrittlement in silicide-coated columbium-alloy and aluminide-coated tantalum-alloy sheet”, Symposium on Refractory Metals, October 3–5, 1965.

[3] W.B. Lisagor, and B.A. Stein; “A study of several oxidation-resistant coatings on Cb-10Ti-5Zr alloy sheet at 200oF, 2400oF, and 2700oF / 1365oK, 1590oK, and 1755oK”, NASA-TN-D-3275, NASA Langley, Hampton, VA, March 1966.
[4] D.M. Royster, W.B. Lisagor; “Effect of high temperature creep and oxidation on residual room temperature properties for several thin sheet superalloys”, NASA-TN-D-6893, NASA Langley, Hampton, VA, November, 1972.
[5] W.B. Lisgor, C.R. Manning, Jr., T.T. Bales; “Stress Corrosion Cracking of Ti-6Al-4V Titanium Alloy in Nitrogen Tetroxide”, NASA-TN-D-4289, NASA Langley, Hampton, VA, January 1968.
[6] T.T. Bales, W.B. Lisgor, C.R. Manning, Jr.; “Equipment and procedures for glass-bead peening titanium-alloy tanks”, NASA-TN-D-4288, NASA Langley, Hampton, VA, January 1968.
[7] 7. R.G. Buchheit; “Mechanisms of localized aqueous corrosion in aluminum-lithium-copper alloys”, Ph.D. Dissertation University of Virginia, 1991.
[8] J.P. Moran; “Mechanisms of localized corrosion and stress corrosion cracking of an Al-Li-Cu alloy 2090”, Ph.D. Dissertation University of Virginia, 1990.
[9] S.W. Smith; “Hydrogen interactions and their correlation to the hydrogen embrittlement susceptibility of Al-Li-Cu-Zr alloys”, Ph.D. Dissertation University of Virginia, 1995.
[10] D.C. Slavik; “Environmental fatigue crack growth and microscopic damage mechanisms in AA2090”, Ph.D. Dissertation University of Virginia, 1993.

12.2. Damage Process: 1990–2015

A primary effort led by Dr. Piascik and his team during the 1990s was to construct unique Agency laboratory capabilities that were directed towards damage processes research and specifically support the objectives of the Aging Aircraft and the High-Speed Civil Transport Programs. This world-class experimental fatigue and fracture research capability, Environmental Effects Laboratory, studied the microstructural-property-environmental relationships that govern the durability and damage tolerance mechanisms (aging processes) in aerospace materials. **Figure 12.2-1** shows the servo-hydraulic test machine mounted ultra-high vacuum test chamber with high-purity gases and elevated temperature (1200°F) capability; this test capability is used to understand damage related to mechanical driving force and the additive damaging effects of high-purity gaseous environments.

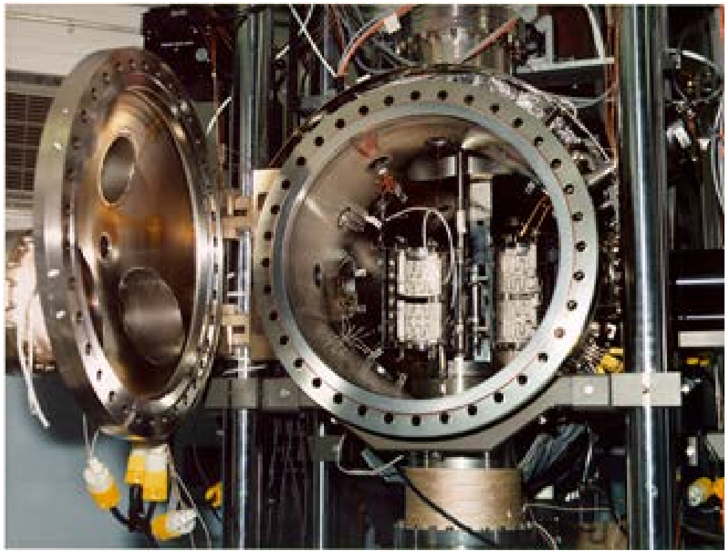


Figure 12.2-1: Ultra-High-Purity Gases Vacuum and Test Facility.

The laboratory also has the capability of conducting corrosion fatigue research by performing electrochemically controlled aqueous (corrosive) testing; especially designed chambers using either long focal length microscopy or electrical potential drop methods monitor real-time in situ fatigue crack growth and corrosion behavior is shown in **Figure 12.2-2**.

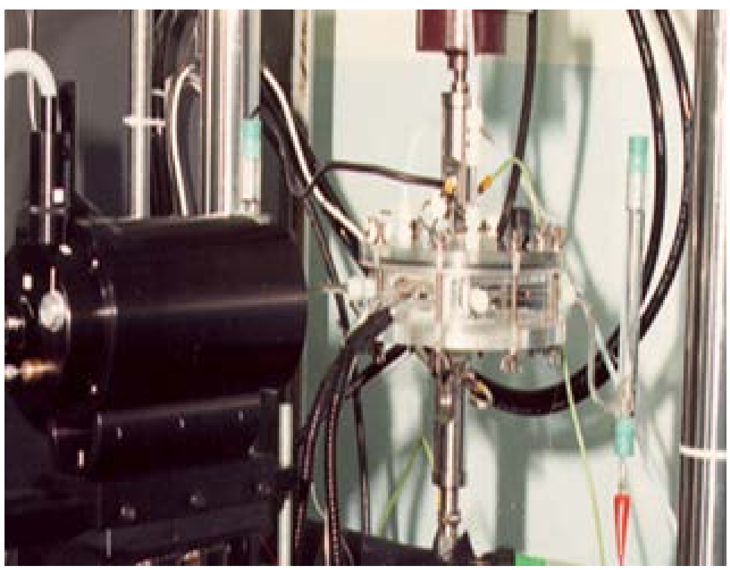


Figure 12.2-2: Corrosion-Fatigue Test Cell with Long-Focal Length Microscope.

The new laboratory capabilities also included an environmental scanning electron microscope (ESEM), shown in **Figure 12.2-3**, that contains a loading stage, water vapor, and elevated temperature environment used for near crack-tip-microstructures-environment interaction studies. Additional capabilities have been added more recently including a near crack-tip digital imaging system that allows for near-crack-tip microscopic strain measurements required for developing micromechanics crack growth understanding necessary for advanced physics based life prediction models.

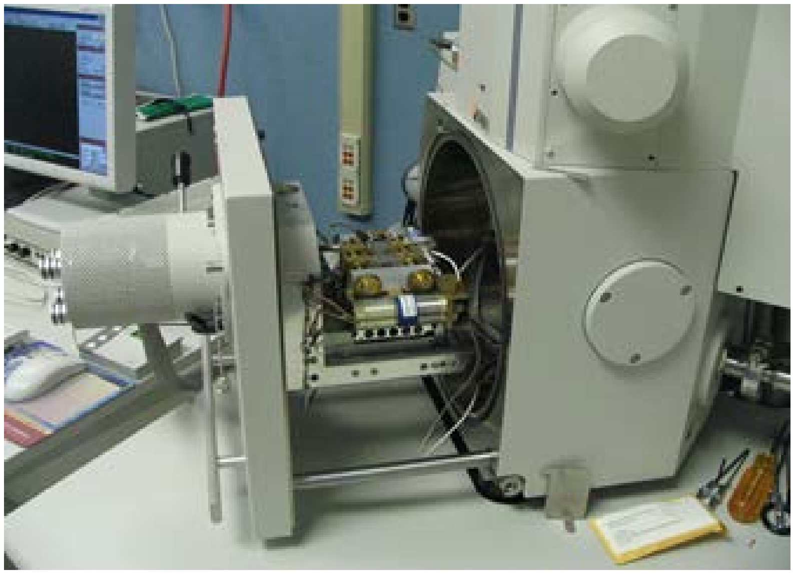


Figure 12.2-3: The ESEM with Mechanical Load Frame.

12.2.1. Fatigue Crack Damage Processes

12.2.1.1. Environmental Effects: Fatigue Crack Growth Threshold and Small Fatigue Cracks

As a direct result of Barry Lisagor's and Tom Bale's efforts to develop advanced aluminum-lithium aerospace alloys, Dr. Richard P. Gangloff of the University of Virginia and Dr. Robert Piascik conducted basic research (**Figure 12.2-4**) investigating fatigue crack growth microstructure environment interaction.[1,2,3]

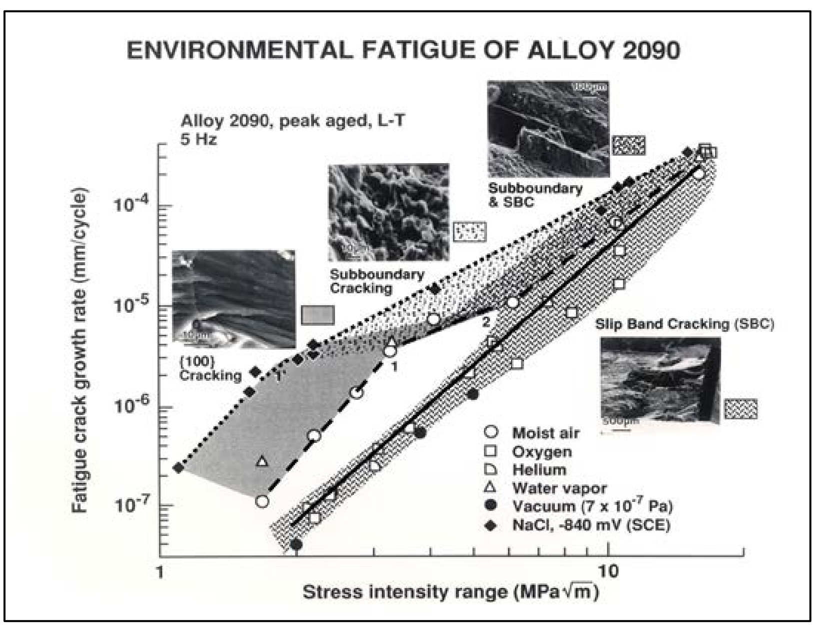


Figure 12.2-4: Correlation of Environmental Fatigue Crack Growth Rate and Microscopic Fracture Path.

Here, accelerated near-threshold fatigue crack growth rate (d_a/d_N) versus crack-tip stress intensity range (ΔK) was linked to damaging hydrogen-containing environment and brittle 100 cracking and sub-boundary cracking. This research became the foundation of a continuing LaRC research effort to understand crack-tip damage processes and the role of microstructure environment-plasticity interactions; this research continues today in new computational materials-based research described in the section 12.3, "Damage Science." Understanding these damage processes is critical to predicting aerospace component aging and useable life.

Because the growth of small fatigue cracks is critical to fatigue life prediction, and little was known about the effects of environment on small fatigue cracks in aluminum alloys, much of LaRC research concentrated on first-of-a-kind corrosion fatigue crack research. An extended compact tension specimen (ECT) [4] was designed so that the aqueous environment damage processes (corrosion pit nucleation and small fatigue crack growth) could be monitored in situ. The ECT specimen was later recognized as a unique design and incorporated into the ASTM fatigue crack growth specification E647. The test specimen was cyclically loaded while immersed in an electrochemically controlled corrosive environment, shown in **Figure 12.2-2**. The specimen notch region was monitored by a long focal length microscope so that corrosion-pit evolution and the growth of small fatigue cracks could be accurately measured. The growth rates of small cracks contained in aluminum alloy 7074 (open round symbols) are compared to the near threshold growth rate of long cracks in **Figure 12.2-5**.

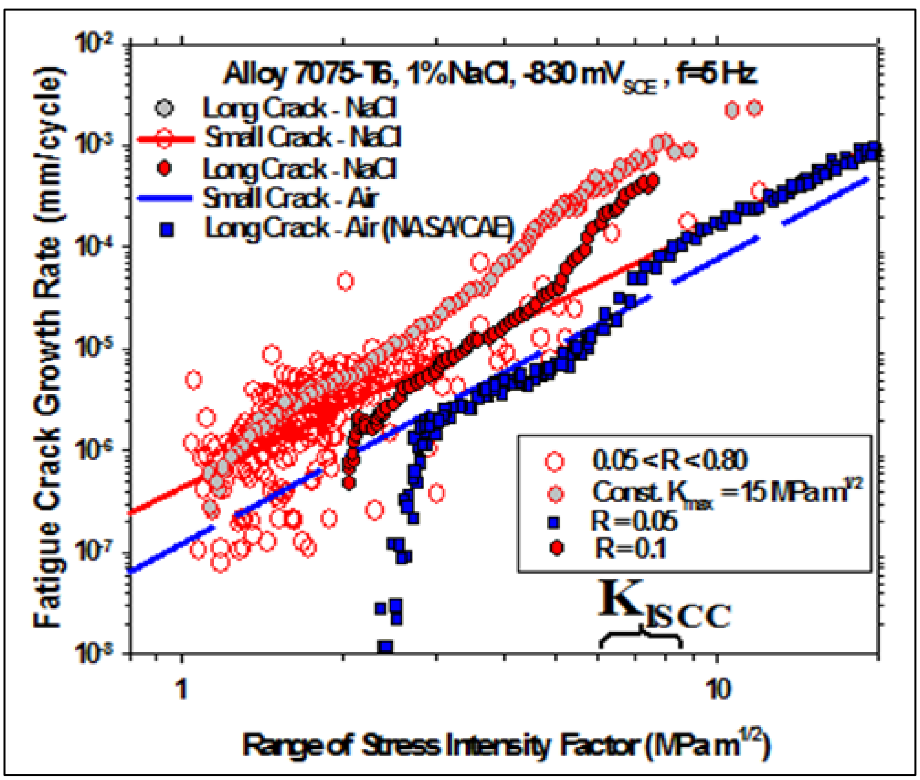


Figure 12.2-5: Accelerated Growth Rate of Small Corrosion Fatigue Cracks.

These first-of-a-kind studies were conducted for both aluminum alloys 7075 and 2024 and revealed that small corrosion fatigue cracks exhibit thresholds at extremely low crack-tip driving forces, <1 MPam$^{1/2}$.[5,6]

12.2.2. Aging Aircraft Program

Much of the damage-processes-related research conducted at LaRC was the result of a cooperative effort with the U.S. airframe manufacturers and the USAF. This applied research was conducted based on the knowledge gain as a result of basic understanding developed through fatigue crack growth threshold and small fatigue crack growth research.

The major objective of NASA's Aging Aircraft Program was to understand and predict the behavior of fatigue crack growth resulting in the phenomenon termed widespread fatigue damage (WFD) that resulted in multi-site damage that caused the Aloha aircraft accident. This effort, described in **Figure 12.2-6**, required a basic understanding of the growth kinetics of physically small fatigue cracks of length less than 0.1 mm (0.004 inch).

To achieve this objective, Dr. Piascik and colleagues conducted detailed studies of fatigue crack fracture surfaces extracted from aging aircraft fuselage lap joints. Precise measurements of key fatigue crack surface details enabled the accurate measurement of crack growth increments (Δa) for known fuselage pressure cycles (ΔN). These data resulted in the accurate characterization of the growth rate (d_a/d_N) of small fatigue crack cracks emanating from fuselage lap joint structure rivet holes. These first-of-a-kind data led to accurate fatigue life predictions of small fatigue crack prior to adjacent crack linkup which was critical to the basic understanding of WFD.[7,8,9,10]

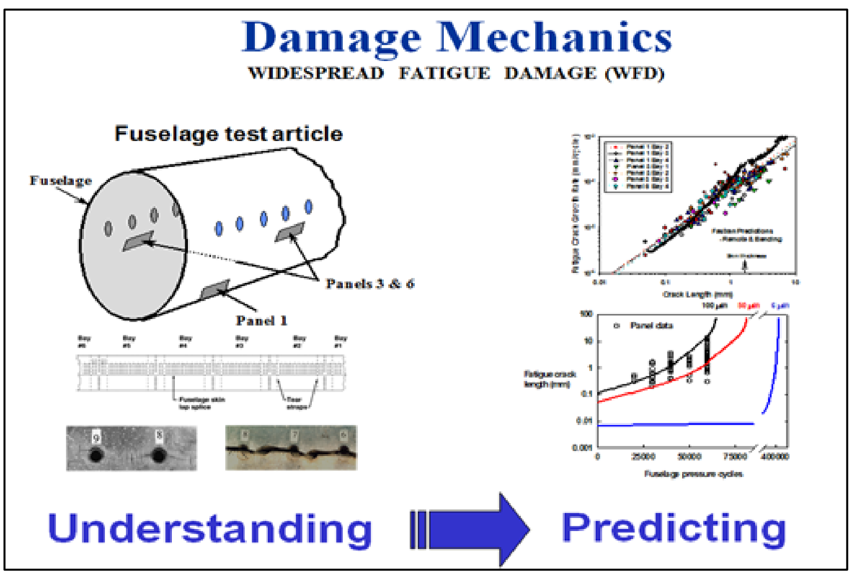


Figure 12.2-6: The Study of Small Fatigue Crack Growth in Fuselage Lap-Splice Joints.

Because aircraft-aging-damage processes are greatly influenced by environment, the purely mechanical fatigue effects typically replicated in laboratory tests must be altered to include the complex effects of environment. Much of the USAF heavy lift and refueling fleet was built during the 1960s and 1970s and was exhibiting signs of significant aging resulting from corrosion, which can have profound effects on aircraft component fatigue life. **Figure 12.2-7** illustrates the wide range of aging related to corrosion damage: (1) stress-assisted environmental cracking contained in a large aluminum 7075 alloy horizontal stabilizer, (2) upper-wing-skin galvanic corrosion, (3) voluminous lap joint corrosion causing rivet region budging (pillowing), and (4) interior airframe stringer corrosion.

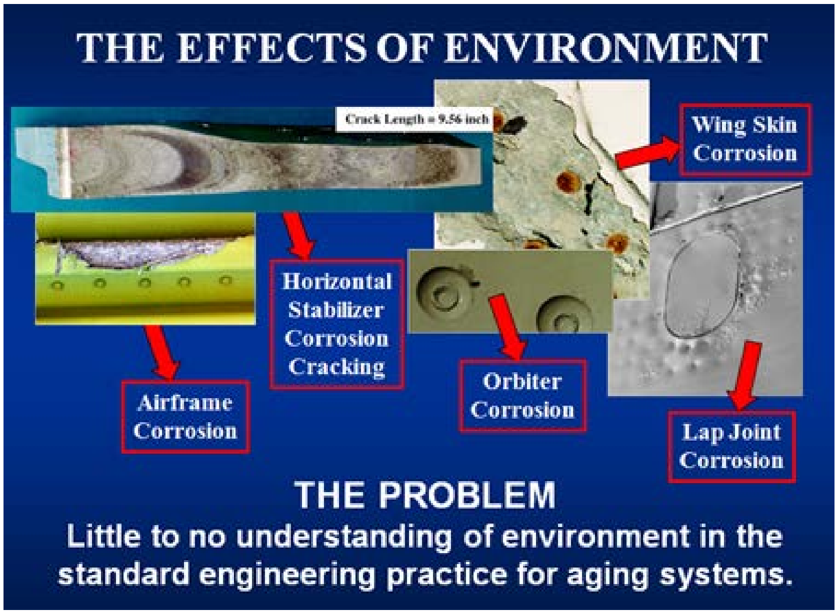


Figure 12.2-7: The study of environmental effects on airframe damage

The unique environmental fatigue capabilities at LaRC assisted the USAF relative to KC-135 and C5 fleet management. Detailed destructive examinations conducted on C5 horizontal stabilizer forging leading to the critical decision of forging a replacement are outlined in **Figure 12.2-8**.[11]

First-of-a-kind research (with Prof. Robert Kelly, UVA) resulted in understanding of the complex effect of occluded region (lap joint) corrosion chemistry and the damaging effect on the growth of small fatigue cracks. These data were used to understand the profound influence of environment on fatigue life, shown in Figure 12.2-8, (FASTRAN predicted fatigue life versus exposure to coastal salt water and air).[12] This research showed that great care was required to mitigate corrosion effects in order to extend operational life of the aging KC-135 fleet.

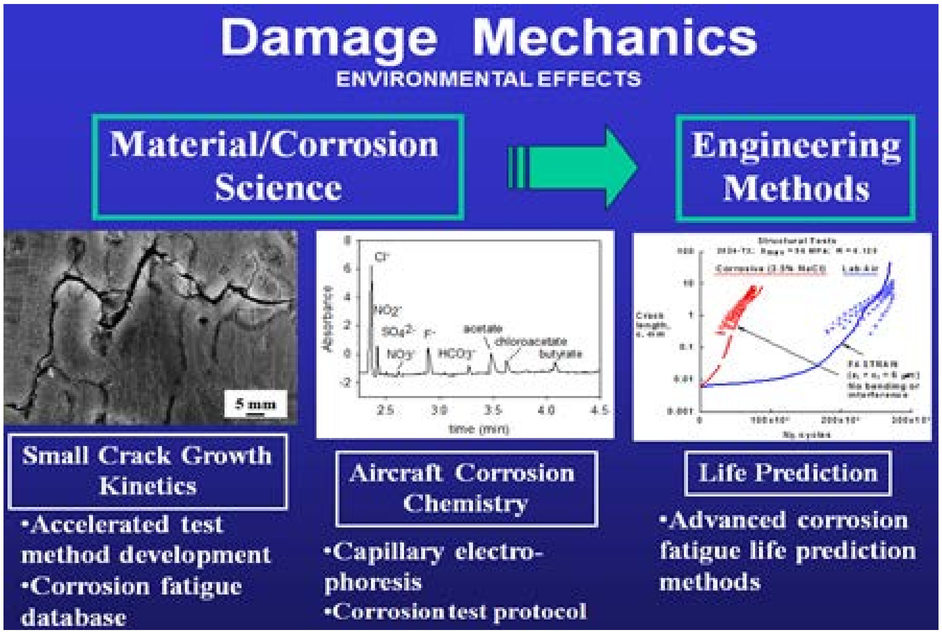


Figure 12.2-8: The Damaging Effect of Lap Splice Corrosive Environment on Fatigue Crack Growth and Fatigue Life.

12.2.3. High-Speed Civil Transport Program

The objective of this work was to understand the effects of environment on fatigue cracking to (1) characterize the high-speed civil transport (HSCT) candidate Ti alloys (Ti 6-22-22 and β-21S), and (2) develop the understanding of critical long-term durability issues associated with titanium airframe structure. Air environment is damaging to titanium alloys, resulting in a factor of 5 to 10 increase in fatigue crack growth rates compared to inert vacuum rates. It is likely that crack-tip damage produced in air is a result of hydrogen embrittlement produced by the dissociation of water vapor at the reactive crack-tip surfaces and rapid transport of atomic hydrogen into the crack-tip process (damage) zone. Little is known about these effects and the damaging effects of the gaseous oxygen in air on titanium alloys, the damaging effects at elevated temperature, and the consequence of long term environmental effects on durability. To simulate air environment and the cumulative damage effect of water vapor in the presence of oxygen, tests were conducted at controlled partial pressures of H_2O and O_2 at HSCT temperature range of 24°C to 177°C. Extensive studies, similar to that shown in **Figure 12.2-9**, revealed that both oxygen and water vapor are the damaging species contained in air; these studies resulted in a model describing the complex environmental fatigue-crack-growth behavior of titanium alloys.[13,14]

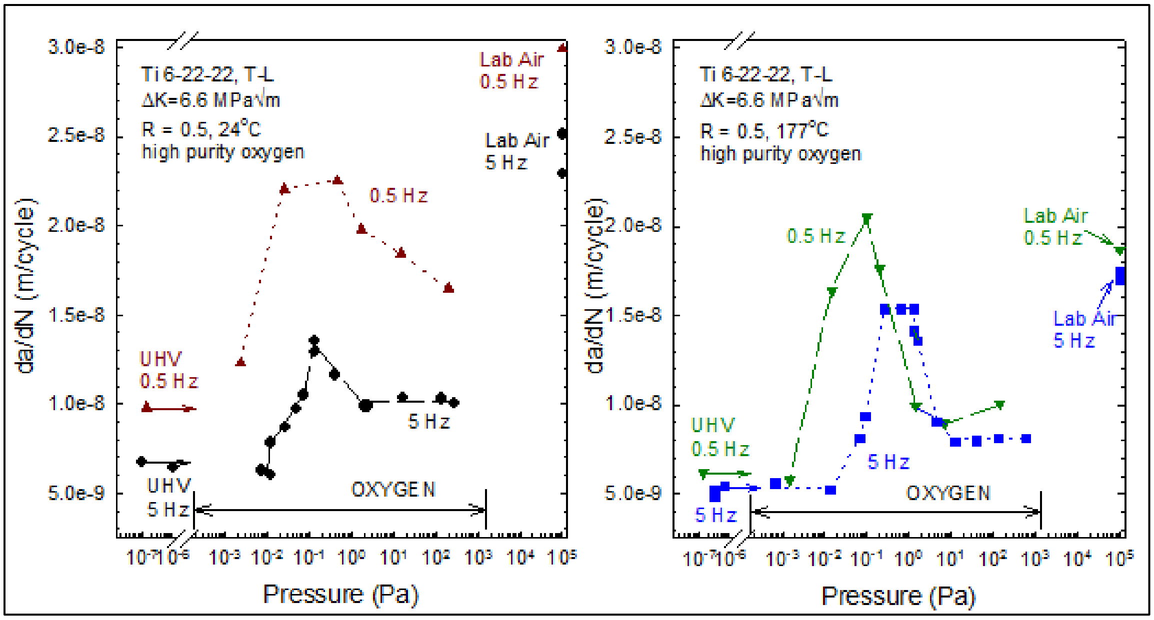


Figure 12.2-9: The Damaging Effect of Frequency and Oxygen Exposure on Fatigue Crack Growth Rate at 12°C (Left) and 177°C (Right).

12.2.4. Aging Shuttle

Dr. Piascik Damage Processes team assisted the Shuttle Orbiter Program to address a number of critical aging issues that required technical expertise in environmentally assisted damage modes.

12.2.4.1. Orbiter Cold-Plate Corrosion

Cold plates are used to dissipate heat from orbiter avionics equipment. Failure of a cold plate in orbit would normally result in immediate return and possible loss of mission. During pre-servicing of a space shuttle (orbiter vehicle, OV-102), helium leak detection of an avionics cold plate identified a leak located in the face sheet oriented towards the support shelf. Subsequent destructive examination of the leaking cold plate revealed that intergranular corrosion had penetrated the 0.017-inch-thick aluminum (AA6061) face sheet. The intergranular attack (IGA) shown in **Figure 12.2-10** was caused by an aggressive crevice environment created by condensation of water vapor between the cold plate and support shelf.

Figure 12.2-10: Cross Section of Cold Plate Outer Wall Showing IGA Corrosion.

Attempts to mitigate the corrosion by various means were not deemed reliable, therefore LaRC's Damage Processes team and nondestructive evaluation (NDE) group, led by Dr. W. Winfree, conducted a study for the early detection of cold-plate corrosion. The study objectives were to (1) develop first-of-a-kind NDE standards that contain IGA similar to that found in the orbiter cold plates and (2) assess advanced NDE techniques for corrosion detection and recommend methods for cold-plate examination.[15] This work resulted in the Orbiter Program modifying cold-plate inspection techniques to ensure cold-plate integrity during flight.

12.2.4.2. Orbiter Main Landing Gear Wheel Corrosion

During a scheduled maintenance inspection of an orbiter, visual inspection of forged aluminum alloy (AA 7050) main landing gear (MLG) wheels revealed small regions of localized corrosion (pitting) in the tie-bolt holes. A common procedure in the aerospace industry is to remove corrosion pitting by grinding. However, if any corrosion damage is still present after assembly, increased local stress at the pits may result in reduced fatigue strength of the component, i.e., fatigue cracking may occur during shuttle roll out, landing, etc. To determine the effect of pitting on shuttle wheel fatigue life, a series of orbiter wheel dynamometer fatigue tests were planned. To simulate local stress concentrations, it was necessary to produce a flaw (artificial pit) in each MLG wheel prior to fatigue testing. However, this approach raised the question of whether the fatigue behavior of MLG wheels containing an electro-discharge machined (EDM) notch is similar to that of corrosion pits.

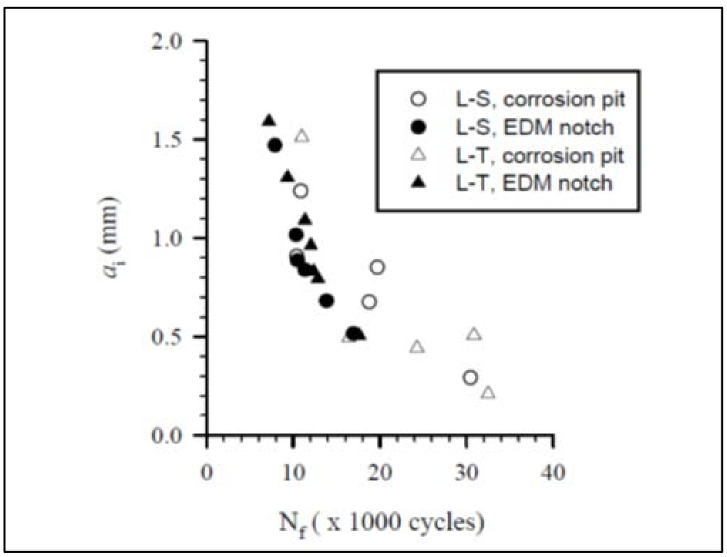


Figure 12.2-11: A Comparison of Corrosion Pits and EDM Notches on Fatigue Life.

The LaRC Damage Process team developed test data, shown in **Figure 12.2-11**, that was used as rationale for conducting dynamometer wheel fatigue testing using artificial flaws. The team designed and conducted uniaxial fatigue tests to compare the fatigue life of laboratory-produced corrosion pits, similar to those observed in the shuttle main landing gear wheel bolt-hole, and EDM flaws. The laboratory test results, shown in **Figure 12.2-11,** demonstrated that the EDM flaw (semi-circular disc shaped) produces a local stress state similar to corrosion pits and can be used to simulate a corrosion pit during the shuttle wheel dynamometer tests.[16]

12.2.5. *Columbia* Accident and Return-to-Flight

Because of the Damage Processes team's unique expertise relative to environmental effects and failure modes, LaRC researchers were directly involved with the *Columbia* accident investigation. Dr. Piascik was assigned to the *Columbia* reconstruction team at the Kennedy Space Center Orbiter debris facility where he and two Boeing materials experts were responsible for technical oversight of the NASA team orbiter-debris root-cause investigation. Drs. Stephen Smith and Andrew Newman were also called upon to investigate and document metallic component failure modes produced during the ballistic break-up of *Columbia*. In addition, the team became a significant Agency resource as the Shuttle Program entered return-to-flight phase to ensure the orbiter fleet was safe for continued operation. The following paragraphs describe a portion of the return-to-flight studies conducted by the Damage Processes team.

12.2.5.1. RCS Thruster Cracking

The Orbiter Reaction Control System (RCS) niobium thrusters were found to contain intergranular cracking (IGC) in the mounting flange relief and counterbore radii. Because of Dr. Stephen Smith's expertise relative to environmental assisted cracking and hydrogen embrittlement (HE), he played a key role relative to the identification of root cause and the assessment of whether thrusters were fit-for-service prior to orbiter return to flight. The LaRC team developed sub-sized specimens and conducted corrosion testing to understand the susceptibility of thruster niobium alloy during exposure to manufacturing and cleaning environments. After considerable test and analysis, it was concluded that the root cause for IGC was a consequence of the hydrofluoric acid (HF) etch used during the original manufacturing, and that conditions for crack propagation, either by environmental or mechanical means, do not exist under current nominal thruster service conditions. It was shown that immersion in the Oakite® rust stripper solution did not significantly compromise the thruster properties, but it is recommended that thruster processing be evaluated for materials that may compromise hardware integrity. These results led to the revised processing procedures to mitigate the occurrence of IGA.[17]

12.2.5.2. RCS Thruster Test Anomaly

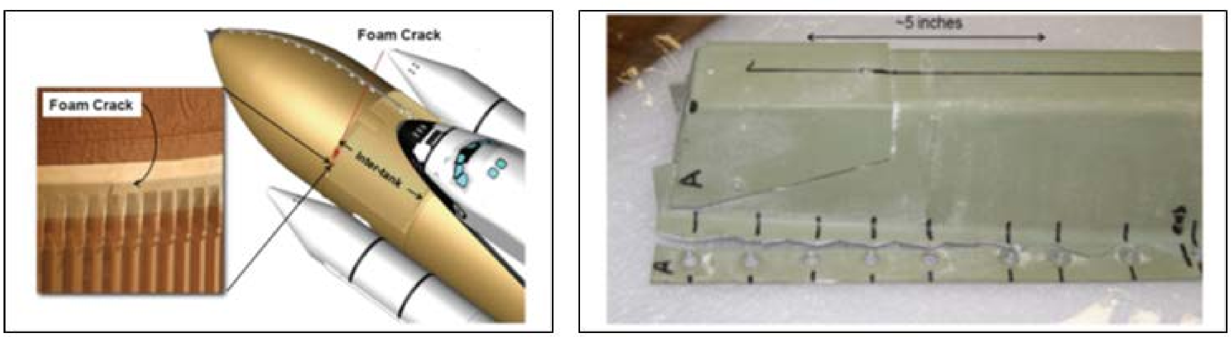
On June 17, 2010, a test firing of a Space Shuttle Program Orbiter Program orbital maneuvering system/reaction control system (OMS/RCS) thruster (serial number 10) at the White Sands Test Facility (WSTF) resulted in a component failure. Subsequent destructive examination of the component and a detailed system evaluation of the events leading to the failure concluded that an over-pressurization of the oxidizer led to the oxidizer bleeding into the fuel passages and ignition of the fuel within the internal surfaces of the fuel manifold. The ignition of the fuel within the manifold resulted in a pressure pulse leading to dynamic/high-strain-rate fracture of the thruster. The destructive analysis revealed a dominant cleavage (brittle) fracture mode in the thruster Niobium (Nb) alloy. The primary goal of this technical assessment was to develop a first-of-a-kind understanding of high-strain-rate cracking in the Nb alloy. The testing effort found that it is extremely difficult to obtain the conditions (i.e., high strain rate and low temperature) required to produce ductile-to-brittle transition behavior in this alloy. Initial testing, using a standard high-strain-rate test technique (i.e., split Hopkinson pressure bar), produced ductile fractures. A second high-strain-rate impact test was developed so that specimens could be tested under a wide temperature range (–310°F to room temperature). These results revealed that the Nb alloy does exhibit a ductile-to-brittle transition consistent with the literature data for commercially pure Nb. These results identified a new brittle fracture failure mode trigger at high strain rates not previously considered for the thruster Nb alloy.[18]

12.2.5.3. Orbiter Flow Liner Cracking

In May 2002, three cracks were found in the downstream flow liner at the gimbal joint in the liquid hydrogen (LH2) feed-line at the interface with the low-pressure fuel turbopump (LPFP) of space shuttle main engine (SSME) #1 of orbiter OV-104. Subsequent inspections of the LH2 feed-line flow liners in the other orbiters revealed the existence of eight additional cracks. No cracks were found in the liquid oxygen feed-line flow liners. After the repair of the high-frequency fatigue cracks, the LaRC Damage Processes team was requested to develop flow-liner inspection method based on small fatigue-crack laboratory methods developed at LaRC. The LaRC surface replication inspection method was modified and demonstrated in the laboratory to be capable of detecting these extremely small cracks in the Inconel 718 flow liner.[19] Dr. Andrew Newman and a research technician were then sent to Kennedy Space Center to train orbiter technicians and oversee proper application of the surface replica. After the replicas were applied to suspect surfaces, each replica was examined by scanning electron microscope by trained small crack experts at LaRC to ensure no small crack indications remained thus clearing the flow liners for flight.

12.2.5.4. Shuttle External Tank Stringer Cracking

Several cracks were detected in stringers located beneath the foam on the external tank following the launch scrub of Space Transportation System (STS)-133 on November 5, 2010, (**Figure 12.2-12**).



a b

Figure 12.2-12: Right (b) Photo Shows Al-Li Stringer End Region Containing a Crack Adjacent Flange Fastener Holes. The Cracked Flange Defection Caused ET Inter-Tank Foam Cracks, Left (a) Photo.

The stringer material was aluminum-lithium (Al-Li) 2090-T87 fabricated from sheets that were nominally 0.064 inches thick. The mechanical properties of the stringer material were known to vary between different material lots, with the stringers from ET-137 (predominately lots 620853 and 620854) having the highest yield and ultimate stresses. Subsequent testing determined that these same lots also had the lowest fracture toughness properties.

The Damage Processes team members assisted this effort by developing a fracture property database that provided validation for structural analysis models, independently confirming test results obtained from other investigators, and determining the root cause of the anomalous low fracture toughness observed in stringer lots 620853 and 620854. The investigation findings revealed that the root cause of the low fracture toughness was a metallurgical process termed “grain recovery” that occurred prior to stringer processing. Grain recovery produced a microstructure in the two affected lots aged differently during nominal stringer processing, producing material with higher yield and ultimate stresses and lower fracture toughness.[20]

References

[1] R.S. Piascik and R.P. Gangloff; “Environmental Fatigue of an Al-Li-Cu Alloy: Part I. Intrinsic Crack Propagation Kinetics in Hydrogenous Environments”, Met. Trans. A, Vol. 22A, pp. 2415-2428, 1991.

[2] R.S. Piascik and R.P. Gangloff; “Microscopic Hydrogen Cracking Processes”, Met. Trans. A, Vol. 24A, pp. 2751–2762, 1993.

[3] R.S. Piascik and R.P. Gangloff; “Modeling Hydrogen Environment-Enhanced Fatigue Crack Growth in Al-Li-Cu-Zr”, Hydrogen Effects in Materials, A.W. Thompson and N.R. Moody, eds., TMS, pp. 409–433, 1996.

[4] R.S. Piascik, J.C. Newman and J.H. Underwood; “The Extended Compact Tension Specimen”, Fatigue Fract. Engng Mater. Struct., Vol. 20, No. 4, pp. 559–563, 1997.

[5] R.S. Piascik and S.A. Willard; “The Growth of Small Corrosion Fatigue Cracks”, Fatigue Fract. Engng Mater. Struct., Vol. 17, No. 11, pp. 1247–1259, 1994.

[6] R.S. Piascik; “The Growth of Small Corrosion Fatigue Cracks in Alloy 7075”, NASA/TM-2015-218672.

[7] R.S. Piascik, S.W. Willard and M. Miller; “The Characterization of Widespread Fatigue Damage in Fuselage Structure”, NASA TM 109142, 1994.

[8] R.S. Piascik and S.W. Willard; “The Characteristics of Fatigue Damage in the Fuselage Riveted Lap Splice Joint”, NASA/TP-97-206257, 1997.

[9] R.S. Piascik and S.W. Willard; “The Growth of Multi-Site Fatigue Damage in Fuselage Lap Joints”, 2nd Joint NASA/FAA/DoD Conf. on Aging Aircraft, C.E. Harris, ed., NASA/CP-1999-208982, pp. 397-–407, 1999.

[10] R.S. Piascik; “The Growth of Small Cracks in Airframe Structure”, Small Fatigue Cracks: Mechanics, Mechanisms and Applications, K.S. Ravichandran, R. O. Ritchie and Y. Murakami, Eds., Pubished by ELSEVIER, Oxford, UK, pp. 457–464, 1999.

[11] R.S. Piascik, J.A. Newman and S.A. Willard; “Characterization of Cracking and Crack Growth Properties of the C5A Airframe Tie-Box Forging, ARL-TR-3046, NASA/TM-2003-211439.

[12] K.S. Lewis, R.G. Kelly and R.S. Piascik; “Determination of Corrosive Conditions Present Within Aircraft Lap-Splice Joints”, 2nd Joint NASA/FAA/DoD Conf. on Aging Aircraft”, C.E. Harris, ed., NASA/CP-1999-208982, pp. 841–852, 1999.

[13] S.W. Smith and R.S. Piascik; "The Effect of O2, H2O, and N2 on the Fatigue Crack Growth Behavior of an $\alpha+\beta$ Titanium Alloy at 24oC and 177oC", NASA/TM-2001-211248.
[14] S.W. Smith and R.S. Piascik; "Fatigue Crack Growth Characteristics of Thin Sheet Titanium Alloy Ti 6-2-2-2-2", NASA/TM-2001-210830.
[15] S.W. Smith, W.P Winfree and R.S. Piascik; "Orbiter Cold Plate Intergranular Corrosion: Development of NDE Standards and Assessment NDE Methods", NASA/TM-2002-211420, 2002.
[16] S.W. Smith, J.A. Newman and R.S. Piascik; "Simulation of Fatigue Crack Initiation at Corrosion Pits with EDM Notches", NASA/TM-2003-212166 ARL-TR-2927.
[17] R.A. MacKay, S.W. Smith, S.R. Shah and R.S. Piascik; "Reaction Control System Thruster Cracking Consultation", NASA/TP-2005-214053
[18] R.S. Piascik and S.W. Smith; "High Strain Rate Fracture of the Space Shuttle Program (SSP) Orbital Maneuvering System/Reaction Control System (OMS/RCS) Thruster", NASA/Tm-2013217970.
[19] J.A. Newman, S.A. Willard, S.W. Smith and R.S. Piascik; "Relpica-based Inspection", Engineering Fracture Mechanics, Vol. 76, pp. 898-910, 2009.
[20] R.S. Piascik; "STS-133/ET-137 External Tank Stringer Cracking Issue and Repair Assessment: Proximate Cause and Material Characterization Sturdy", NASA/TM-2011-217318.

12.3. Future Direction; Computational Materials and Damage Science

The structural response of materials is a result of the aggregation of a myriad of operative microscale and nanoscale mechanisms (damage processes). Current approaches in engineering fracture mechanics do not account for these mechanisms, but rather, rely on continuum fracture parameters (e.g., K_{IC}, CTOA) and an assumed similitude between the coupon-scale test articles used to determine their values and vehicle structures that are being evaluated. Although empirical-based engineering fracture mechanics is an indispensable tool for many applications, NASA is now designing and building fracture-critical components that contain various features that are so small that standard engineering fracture mechanics-based methods are no longer valid. Typically, these component features have length scales that are of similar dimensions to those of the material's microsturcture. Similarly, the development and certification of new materials for structural applications (e.g., nanocrystalline metals, layered metals, and powder metallurgy-formed materials) will be highly dependent on new understanding of their internal damage processes at length scales from less than a nanometer to hundreds of micrometers.

Recognizing that NASA's future human exploration and science missions are dependent on the development of new lightweight materials and efficient structural designs that will require a fundamentally new capability for understanding and quantifying damage processes at their operative length scales, Dr. Piascik initiated an effort in Damage Science at NASA LaRC in 2001. As part of that effort, Dr. E.H. Glaessgen recognized that a computational materials-based research effort was needed; the resulting Damage Science team research activity was led by Dr. Glaessgen (computational group) and Dr. S.W. Smith (experimentalist group).

Figure 12.3-1 presents the characteristic dimensions at which damage may be characterized, the associated physical features and some corresponding methods that may be employed.[1] At the nanoscale, methods such as molecular dynamics are used to determine the most fundamental damage processes.

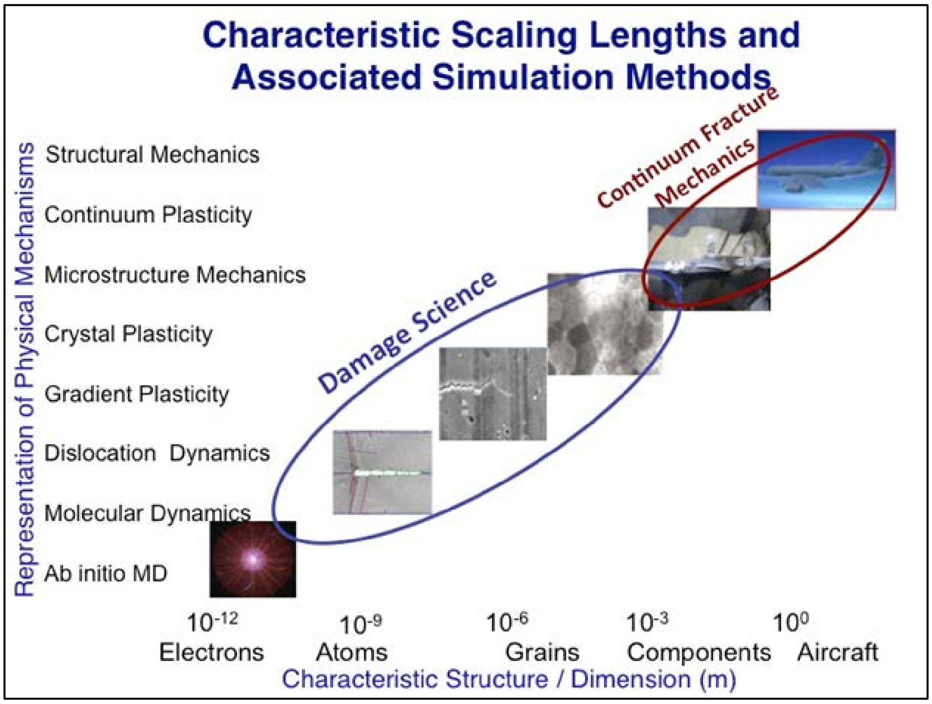


Figure 12.3-1: Characteristic Dimensions and Associated Simulation Methods.

At the mesoscale, methods such as dislocation dynamics are used to model the generation, motion, accumulation and annihilation of relatively large numbers of dislocations within a grain. At the microscale, various small-scale continuum plasticity formulations, cohesive zone models and finite element analyses are used to describe damage processes within individual grains or within polycrystals. Because no single analysis or experimental characterization approach can describe all of the relevant physics of crack growth, approaches that are developed at each length scale should be integrated within a rigorous multiscale modeling framework that spans some or all of these length scales. Additionally, in-situ experimentation is needed to aid in understanding the complexities of damage under realistic conditions, help to validate the nano/micro-scale computational results and provide input for the microscale analyses.

The first several years of damage science (2001–2005) consisted largely of problem formulation and independent computational and experimental efforts whereas work during 2006–2011 focused on multiscale modeling (e.g., the Cohesive Zone Volume Element[2] and Embedded Statistical Coupling Method[3]) and developing close coupling between experimental and computational approaches.[4] The work during this period heavily leveraged university grantees including A.R. Ingraffea (Cornell University), W.A. Curtin (Brown University), D.H. Warner (Cornell University), Y. Mishin (George Mason University), R.G. Kelly (University of Virginia), and M. Sutton (University of South Carolina) to complement the existing in-house capabilities. These relationships proved to be extremely fruitful and led to the hiring of several productive young researchers who are focusing on future development and application of damage science to solve some of NASA’s toughest materials challenges.

Future work will continue to advance the state of the art in both the computational and experimental aspects of damage science needed to address NASA's challenges related to development and certification of new structural and multifunctional materials and components. Computational damage science methods needed for simulation of plastic deformation, prediction of crack growth, multiscale modeling, and quantification of uncertainty in the simulations are being advanced. Similarly, experimental damage science methods including high-resolution measurement techniques used in conjunction with mechanical testing can greatly increase the understanding of the complexities of damage under realistic conditions, help to validate the nano/micro-scale analysis results, and provide input for the microscale analyses.

These and related computational and experimental efforts are the basis for a bold paradigm shift in material science and mechanics of materials that will, for the first time, enable rigorous design and analysis of material microstructures and structural components having small characteristic dimensions. As damage science matures, it will reduce the dependence of material development on heuristic trial-and-error that results in production and evaluation of numerous prototypes of a material before a suitable one is found. Similarly, the work will reduce reliance on empiricism in engineering design and development, particularly for structures that are too small to be analyzed using current engineering approaches.

References

[1] Glaessgen, E.H., Saether, E., Smith, S.W., Hochhalter, J.D., Yamakov, V.I. and Gupta, V; "Modeling and Characterization of Damage Processes in Metallic Materials", Proceedings of the 52nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, AIAA, Denver, CO, April 4–7, 2011.

[2] Yamakov, V., Saether, E., Phillips, D.R. and Glaessgen, E.H.; "Asymmetric Inter-granular Crack Growth Along Grain Boundary in Aluminum by Molecular Dynamics and Finite Element Simulations", Journal of the Mechanics and Physics of Solids, Vol. 54, 2006, pp. 1899–1928.

[3] Saether, E., Yamakov, V. and Glaessgen, E.H.; "An Embedded Statistical Method for Coupling Molecular Dynamics and Finite Element Analysis", International Journal for Numerical Methods in Engineering, DOI: 10.1002/nme.2529, 2009.

[4] Glaessgen, E.H., Saether, E., Smith, S.W., Hochhalter, J.D., Yamakov, V.I. and Gupta, V.; "Modeling and Characterization of Damage Processes in Metallic Materials", Proceedings of the 52nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, AIAA, Denver, CO, April 4–7, 2011.

13. NONDESTRUCTIVE ANALYSES

13.1. NDE Research at NASA Langley

Nondestructive evaluation techniques are currently used during component design/testing, manufacturing, design certification, maintenance, inspection, and repair. **Table 13.1-1** summarizes the state-of-the-art NDE/I technology. While visual inspection methods remain the method of choice for most airlines, nondestructive inspection (NDI) methods are routinely used in manufacturing and are required in flight operations environments. Each NDI method, including thermal, ultrasonic, electromagnetic, radiography, and optical, has strengths and weaknesses, depending on the specific inspection requirement. The NDI methods listed in **Table 13.1-1** include their technology readiness levels (TRL) for applicability to metallic and composite structures with simple and complex configurations. (The comparative summary given in **Table 13.1-1** was prepared by the NASA NDE Working Group.) Referring to this table, a TRL of 9 means that the technology is mature and is part of the industry standard practices. The gray boxes without a number mean that the corresponding NDI methods are not being developed for the specific application. The other colored boxes help to identify similar TRL levels. The distinction between "conventional" and "advanced" systems refers to the sophistication of the system and user.

Table 13.1-1: The State-of-the-art of NDE/I Technology

NDE TECHNOLOGY	BASIC METAL STRUCTURES	BASIC COMPOSITE STRUCTURES	COMPLEX METAL STRUCTURES	COMPLEX COMPOSITE STRUCTURES
	Planar, slight curvature	Planar, slight curvature B-2, B-777	Irregular, curved, hybrid, bonded, honeycomb, built-up structure	Irregular, curved, hybrid, bonded, honeycomb, built-up structure, X-33, X-34
Conventional thermography	9			
Advanced thermography	9	9	4	4
Conventional ultrasonics	9			
Advanced ultrasonics	9	9	3	3
Conventional X-radiography	9	9		
Reverse geometry X-ray	6	5	4	3
Computed tomography	9	9	9	6
Backscattered X-ray	5			
Conventional eddy current	9			
Advanced eddy current	9		4	3
Optical shearography	6	4	3	3
Microwave	3	4	3	3
Conventional acoustic emissions	9	6		
Advanced acoustic emissions	9	6	3	3
Visual	9			
Penetrants (surface defects)	9		9	
Magnetic particle (surface defects)	9		9	
In-Situ vehicle health monitoring			3	3

Numbers in the table are TRL's

Current research explores the role of advanced sensors coupled to computer simulations to revolutionize the traditional NDE role (**Figure 13.1-1**). It is generally understood that NDE issues that are not addressed during the component design stage must be addressed later in the manufacturing stage. This staging of the use of NDE procedures can be, potentially, at a much higher cost as maintenance and repair considerations increase with component age. If validated and robust NDE simulations are available during the initial design stage, then component configurations may be adjusted in "real-time" to lower the overall life cycle costs while maintaining optimized system level benefits. Furthermore, these benefits are enhanced when manufacturing simulations make use of NDE process control simulations. Validated NDE for process control during manufacturing can reduce or eliminate manufacturing process steps, including conventional inspections, while further optimizing the yield of the manufacturing process.

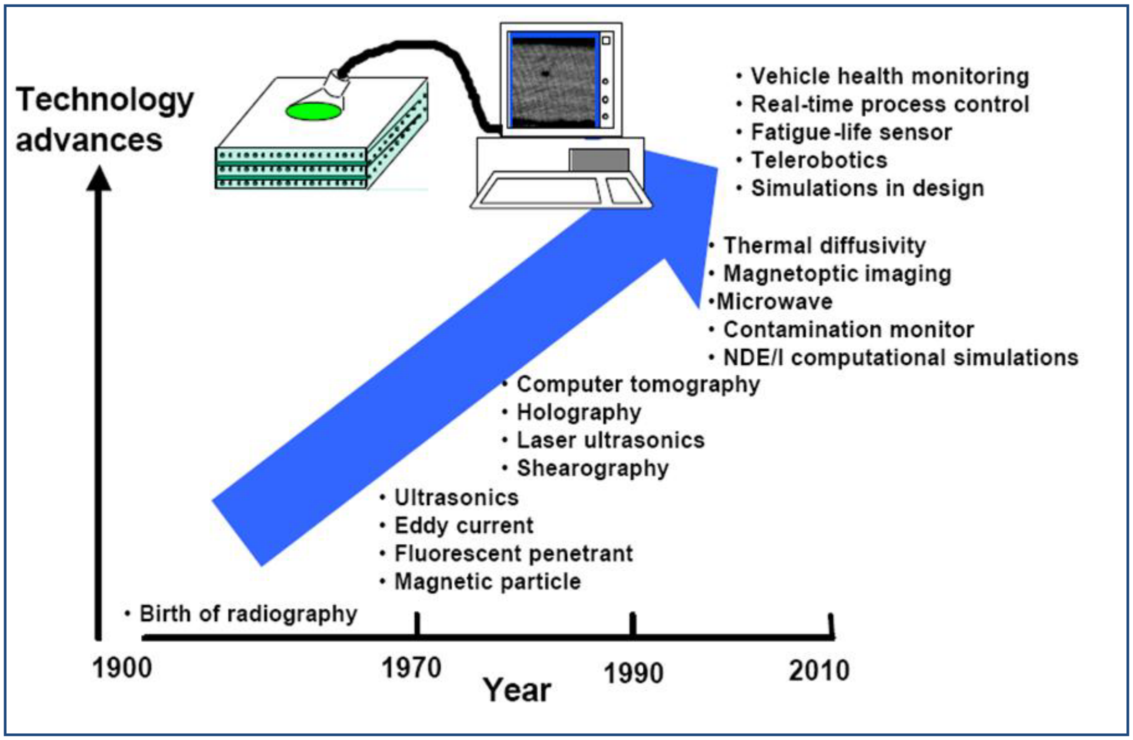


Figure 13.1-1: Evolution of Composite Materials NDE Technology

For the foreseeable future, structural components will continue to incur operational service-induced damage and degradation. The requirement to evaluate component integrity and repair or replace damaged components will continue to challenge the NDE community. In the future, NDE simulations may be optimized to the point that they may be used to generate the plans for in-service maintainability and repair. Issues such as component design and functional specifications, work space geometry and component access, and accept/reject criteria or retirement-for-cause criteria will need to be incorporated into these NDE simulations. It is anticipated that NDE technology will evolve to a state-of-the-art where virtual reality NDE simulations in design, smart health monitoring systems, and telerobotic inspection and repair are commonplace. The challenge for the NDE community is to develop and validate virtual reality simulations that are robust and adaptable enough to function smoothly and autonomously.

13.2. NDE Methods Development for Metallic Structure

Dr. Joseph Heyman	Dr. William Winfree	Dr. John Cantrell	Dr. Buzz Wincheski
1964-2001	1980 –	1979 –	1990 –
1st Leader of NESB	Developed:	World-Class Expert:	Developed:
4 IR-100 Awards	Dynamic CAT Scanner	Nonlinear Acoustics	Flux Nulling Probe
3 NASA Metals	Thermoelasticity	Elasticity Physics	Eddy Current Models
Silver Snoopy Award	Diffusivity Imaging	Fatigue Damage	Field Instrumentation
33 Patents	NDE Lead for ASIP, AAP, NTSB AA597	Fellow IP, APS, ASA	IR-100 Award
110 Papers/Talks	2 NASA Metals	NASA Metal	Silver Snoopy Award
JANNAF NDE Chair	9 Patents	IR-100 Award	13 Patents
AGARD NDE	90 Papers/Talks	27 Patents	94 Papers/Talks
		250 Papers/Talks	

13.2.1. History at Langley

LaRC traditionally is the core research center for the Agency in materials and structures. As such, the Center developed and applied supporting technologies for information required by the materials and structures programs. In the 1960s and early 1970s, the NDE support came from within the Fabrication Division, providing state-of-the-art X-ray, ultrasonics and other off-the-shelf NDE technologies. Perhaps one of the most advanced systems of that time was an immersion c-scan ultrasonics tank able to scan large parts up to 15 square feet.

The NDE research program that created the Nondestructive Evaluation Sciences Branch (NESB) began at LaRC through several interesting events. Dr. Joseph Heyman had just returned to LaRC in 1975 with his Ph.D. from Washington University, where he had studied solid-state physics under the Agency's graduate program. He was examining II-VI semiconductor materials in high magnetic fields in his Instrument Research Division lab to improve sensor technology. His specialty was physical acoustics with emphasis in ultrasonics. Events on the opposite coast were to forever change his career.

In 1975, the Ames Research Center 3.5-Foot Hypersonics Wind Tunnel had a serious accident. The tunnel used high-pressure gas to create hypersonic flow over a vehicle model to test reentry dynamics. The gas had to be heated prior to its expansion into the wind tunnel. The heater used zirconium oxide pebbles raised to 3000ºF contained in a steel vessel 8 inches thick. A flange between the nozzle and heater failed, blowing incendiary pebbles and hot steel in the surrounding area. Heyman was asked to serve on the accident review panel.

Returning to LaRC after the investigation, Heyman was intrigued by the NDE technologies that were common and practiced at that time. One of the contributing accident factors was a flange failure caused by improperly loaded fasteners. Within three weeks of his return to the Center, Heyman had developed and validated an instrument concept for an ultrasonic bolt tension monitor able to achieve accurate preloading of flat-and-parallel critical fasteners. More importantly, the incident gave him the opportunity to look at the NDE big picture. He recognized that the Agency needed advanced NDE science research to provide quantitative information for mission assurance and for materials and structures research. That began a 36-year period building one of the world's greatest NDE labs, NESB. LaRC recognized that NDE should be at a peer level with materials and structures as a research profession. During the 1980s, the environment at NESB allowed a rich influx of students, both undergraduate and graduate, to work within the branch along with post-docs and visiting professors. Many of the staff were adjunct professors at prestigious universities, giving LaRC great exposure to multidiscipline thinking. The outreach also resulted in hiring many of the experts now leading their fields currently working at NESB.

Another big-picture lesson came from this experience. Although the first bolt monitor worked after just three weeks of development, it required a rack of big, heavy electronics and only worked on fasteners that were prepared to have flat and parallel end faces. It took nearly seven years of advances to produce a field-ready instrument for NASA's critical applications.[1−2] In parallel with developments for aerospace, the NASA technologies solved problems in other application areas. The bolt monitor, for example, provided a procedure by which the mining industry can assess the tension in roof bolts that enhance mine stability (**Figure 13.2-1**).

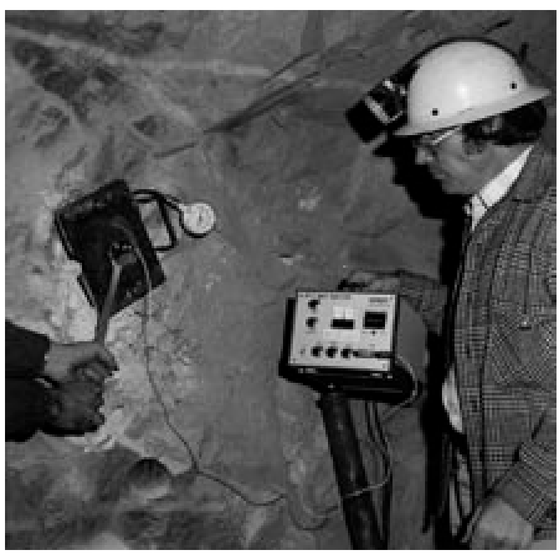


Figure 13.2-1: Heyman Shown in a Bureau of Mines Test of the Bolt Monitor for a Mine Bolt.

Other applications based on similar NASA technology include the detection of compartment syndrome, a painful and potentially life-threatening condition occurring to trauma patients. The lessons learned in these projects helped shaped the future of NESB in many ways.

Creativity and innovation are the backbone of moving a technology area forward. Total immersion in the physics and mechanics of the problem is necessary, along with ample time to explore, and, yes, to fail at several approaches. In fact, quick failure, working with the owner of the problem, often produced insights leading to lasting advances in the field. Having an organization rich in discipline depth, coupled with experts in the supporting technologies, was the foundation for many of the decades of success coming from NESB. For that branch, physics was the core, coupled with electronics and software enabling innovative advances necessary for both materials and structures research, and program mission assurance.

13.2.2. A Sampling of Some of the NESB NDE Disciplines

Advanced NDE is the application of quantitative measurement physics to materials and structures providing information for making decisions. The outcome of this practice is an understanding of the material state. This is far beyond defining the size of a flaw, even though that information is part of the answer. A simple example is a crack in a flat plate: will the crack grow? The answer depends on more than the crack size. It also depends on the material properties and the stresses at the crack tip. Often, to answer tough questions, one has to perform several measurements based on different physics and fuse the data to assess the performance of the material. To that end, NDE brings different technologies together, where needed, to generate a robust answer.

13.2.3. Ultrasonics

In ultrasonics, an acoustic wave is used to probe a material. Pulse-echo is the common testing approach where an impulse (broad band) wave enters the object and reflects off of any discontinuity such as a crack or a boundary. The time of flight gives the location of the discontinuity. Attenuation of the wave may also indicate damage caused by scattering of energy by distributed discontinuities such as issues in metal matrix materials. LaRC greatly expanded the practical measurement technologies for the Agency exploring both broad-band and narrow-band approaches with higher resolution.[3,4]

An example application is a steel sample bonded to insulation similar to the shuttle solid rocket motor (SRM). In this test example, a deep disbond was layered in the sample that could not be detected with pulse echo. Instead, a narrow band system, shown in **Figure 13.2-2**, was used to scan the part. **Figure 13.2-3** shows a model prediction that was used to determine what ultrasonic frequencies are most sensitive for defect detection.

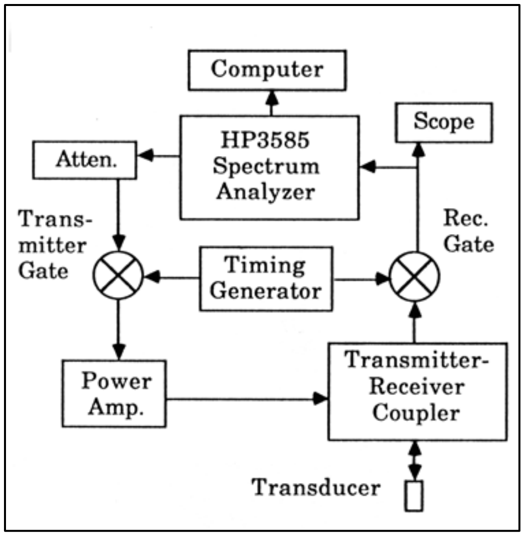


Figure 13.2-2: Block Diagram of the Broad Band Ultrasonic Testing System.

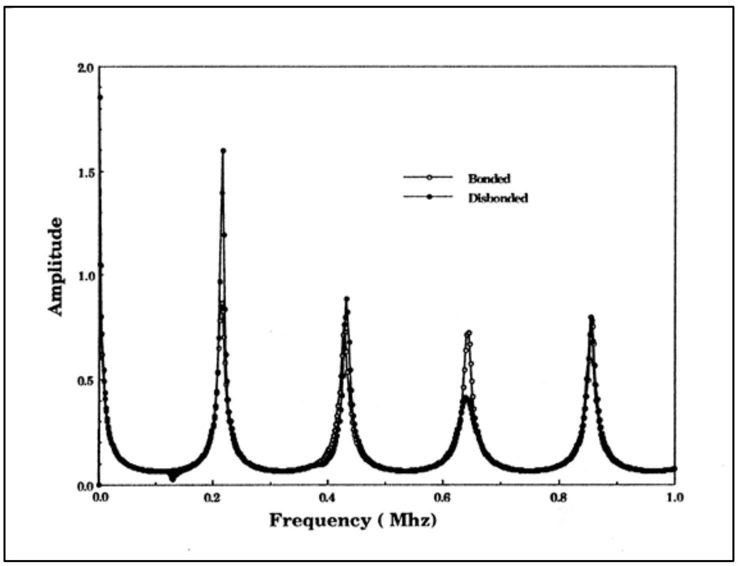


Figure 13.2-3: Calculated Spectral Response of the Layered Geometry for a Bonded and Unbonded Specimen.

A fundamental scientific advance is often a result of special insight brought to bear on an important problem. Working within NESB, Dr. John Cantrell has provided a physics model of material damage using nonlinear acoustics as a probing energy.[5] Working closely with Dr. Tom Yost, performing precise, high-resolution laboratory procedures, these two scientists were the first to validate that fatigue in practical metals could be quantitatively measured using acoustic harmonic generation to assess dislocation dipole density generated by fatigue, as shown in **Figure 13.2-4**.

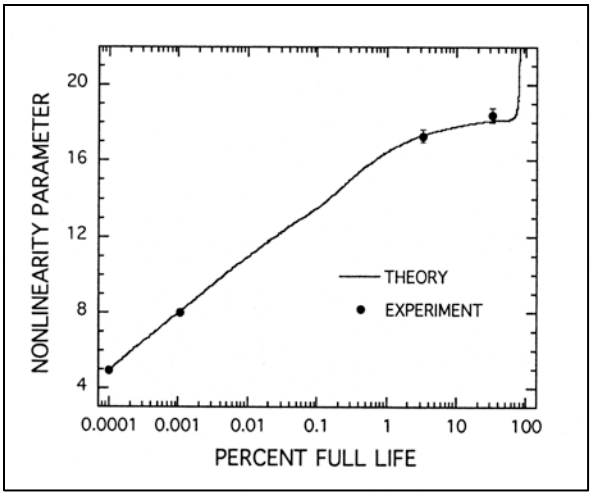


Figure 13.2-4: Graph of Nonlinearity Parameter of Aluminum Alloy 2024-T4 Fatigued in stress-controlled loading at 276 MPa plotted as a function of percent full fatigue life.

Professor L. M. Brown, a highly respected scientist in the field of metal fatigue from Cambridge University, England, called the work "a triumph." Dominion Power Corporation has incorporated the patented[6, 7] technology into their inspection protocol for the company's electric power generators. Wyle-Advanced NDI, Inc. obtained exclusive license from NASA for commercial marketing of the technology. Dr. Cantrell has published over 33 papers in this topic area out of the 172 papers he has written. In a recent plenary paper, Dr. Cantrell reviewed the history of the LaRC advances leading to technology for an unambiguous quantitative assessment of metal fatigue damage accumulation.[8]

NDE of metal wires has direct applications for assessing the health of electrical and mechanical components that use wire assemblies. Dr. Eric Madaras has shown that physics models coupled with advanced ultrasonic techniques can assess wire integrity.[9,10] Other guided wave techniques were developed with Dr. Patrick H. Johnson to examine corrosion in aircraft skins. These Lamb waves follow the surface of the structure with their energy transformed by geometric irregularities such as corrosion.[11] The resulting detected signals are indications of internal damage. In a related area, members of NESB under the leadership of William T. Yost developed and patented a new NDE device to assess the quality of wire crimp connections. The device is built directly into the crimp tool providing the user with direct measurement of the wire condition during crimping.[12]

13.2.4. Acoustic Emission (AE)

Acoustic emission (AE) is the study of energy released as an acoustic wave during the onset of material failure, the propagation of such waves, and their interpretation to assess material integrity. Traditionally, several very sensitive piezoelectric transducers were attached to a monitored structure to vector to the site of the emission where other NDE technology would be used to inspect the site. Dr. William Prosser and his team recognized that AE sensors were, by their sensitive design, very narrow-band monitors of the wave frequencies. Using physics models of wave propagation in plates, they saw that broad-band sensors would provide a much richer picture of the damage source.[13] Working with Professor Michael R. Gorman, a new approach to

AE was born using more of the available frequency bandwidth of the AE waves and models of wave propagation for quantitative analysis of the severity of the recorded event.[14]

13.2.5. Thermography

Thermography NDE utilizes thermal information, usually images, combined with heating techniques and physical models, to assess the integrity of a structure. LaRC is one of the birthplaces of this new and very successful NDE technology.

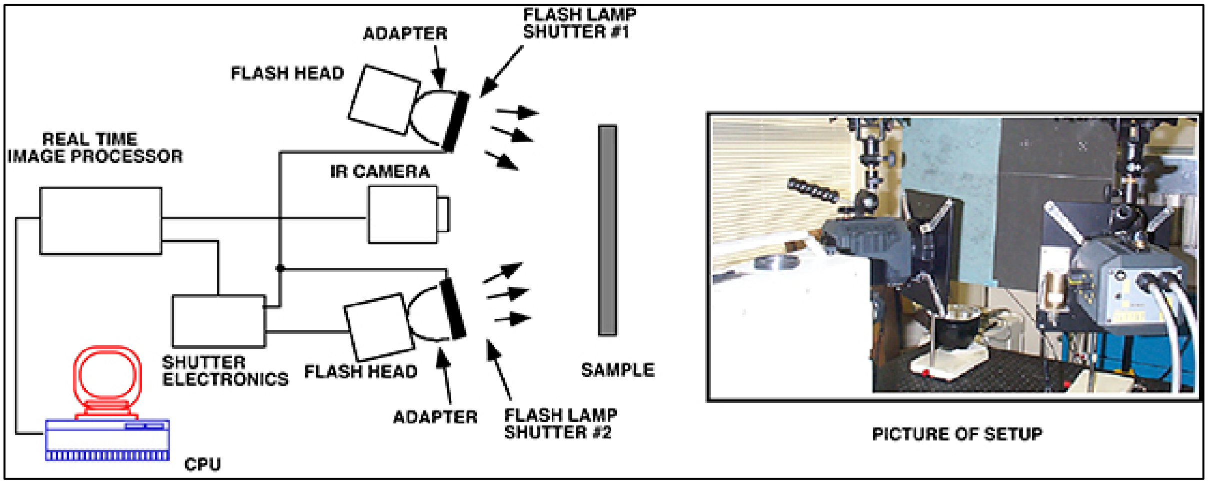


Figure 13.2-5: Typical NESB Thermography System Set Up With Thermal Source, Camera, System and Inspection Sample. (NASA/TM-2004-213235).

Some of the early developments were in the field of physical modeling, with results that directly impacted experimental approaches. Dr. William Winfree and his team quickly saw that one of the early limitations of infrared (IR) imaging was that the emissivity of the material was convoluted with the thermal history. He created diffusivity imaging to circumvent the problem, concentrating on the heat diffusion equations and their inversion. As such, his work provided some of the most quantitative evaluations of sub-surface conditions including lack of bonding and hidden corrosion.[15,16,17,18,19] Dr. Elliott Cramer continued the development of the thermal technology inventing an approach called line scanning that has become one of the standard field applications.[20]

The line scanner system was a technology transfer success showing how new aerospace developments benefit the U.S. industry. The geometry of the system was ideal for application to steam boiler inspections in the power industry. **Figure 13.2-6** shows an industrial thermal line scanner inspecting a power plant boiler.

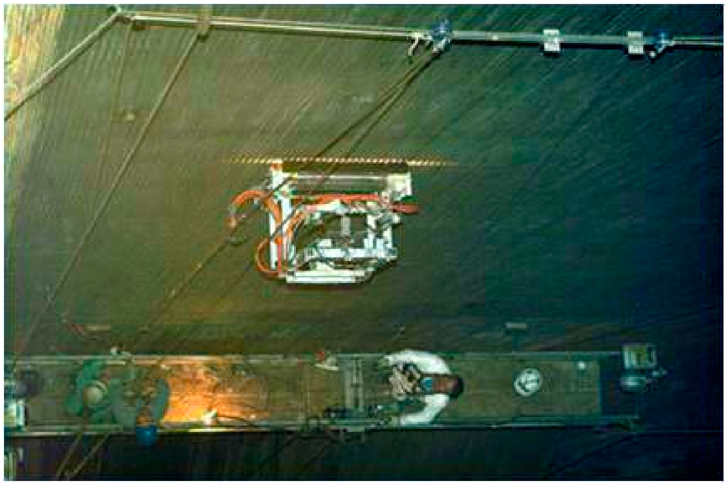


Figure 13.2-6: Inspectors on a scaffold watch the LaRC patented thermal line scanner they implemented for boiling water power plant NDE.

13.2.6. Eddy Current & Dynamic Magnetic NDE

Eddy current NDE is used to find cracks in conducting materials. Dr. Min Namkung studied the behavior of ferromagnetic material to characterize the onset of tensile stresses in critical assembles. Built-in compressive stresses are an important element in extending the life of steel wheels. Loss of that condition can lead to wheel failures. The Federal Research Administration-funded research was conducted at LaRC while Dr. Namkung was a Research Associate at the College of William and Mary. This important study led to the discovery of a technique for the unambiguous detection of residual compressive stresses in iron-like ferromagnets, which was otherwise impossible.[21,22] This research led Dr. Namkung, several years later at NESB, to develop the magnetoacoustic emission (MAE) method to characterize embrittlement in high-strength steel.[23].

These studies provided the background for one of the most significant developments in eddy current NDE, the flux focusing[24] rotating probe[25] (**Figure 13.2-7**) invented by Dr. Russell "Buzz" Wincheski, who continues to pioneer in that field. Dr. Wincheski recognized that typical eddy current probes were measuring a small change in signal (induced impedance) on a large background signal. In his invention, the magnetic flux from the probe is nulled by the unique probe design. As such, a crack that changes the impedance of the system is now seen against a zero signal background, with significantly superior signal-to-noise. This work and its applications/advances received the IR-100 award in 1994.

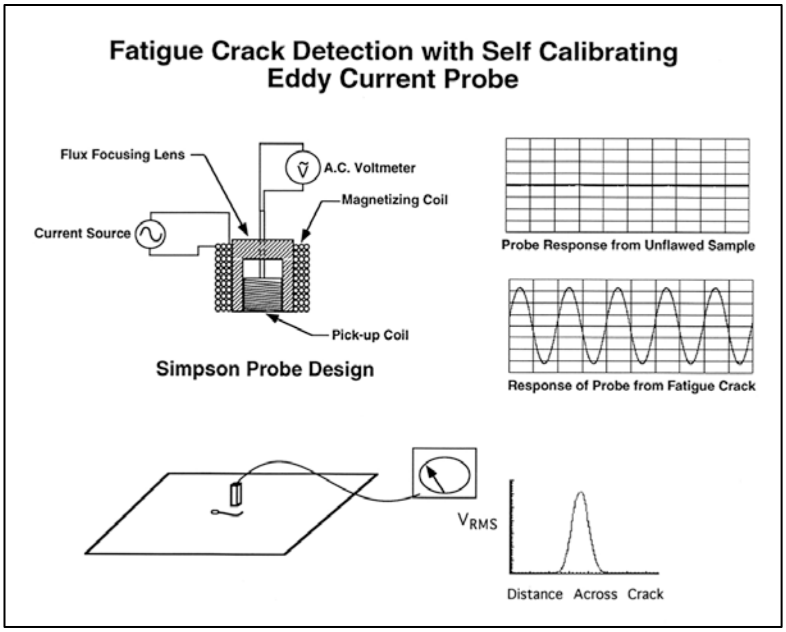


Figure 13.2-7: Design of the Flux-Focusing or Nulling Probe for improved crack detection in conductors. Note that the output of the device is zero, except over a crack.

As with many of the technology developments at NESB, this work was a combination of advanced physical modeling (conformal mapping[26] of magnetization) and practical instrument invention/design/implementation. Many field devices followed from this work and have been used on aircraft (**Figure 13.2-8**) and on the shuttle.[27]

Figure 13.2-8: Electromagnetic Flux Nulling Probe Inspecting an area near a lap joint on an aircraft.

13.2.7. Radiography and CT Imaging

In radiography, ionizing radiation is used to penetrate otherwise opaque materials to image their interior. Dr. William Winfree created a unique research instrument, called Quantitative Experimental Stress Tomography (QUEST) (**Figure 13.2-9**) that was capable of three-dimensional imaging of materials while they were experiencing strains and fatigue. With this system, internal deformation was imaged as a material was loaded to failure. A focused study produced the first image of a rivet's expansion in an airframe skin joint. The system was composed of a microfocus X-ray source, a fatigue load frame and a unique rotating grip system able to maintain high positional accuracy.

NESB experimented with an advanced X-ray system called Reverse Geometry X-ray invented by Dr. Richard D. Albert of Digiray®. In this system, the X-ray source is in close proximity to the object and is electronically scanned while the detector(s) is fixed and usually separated from the imaged object.[28] When several detectors are used, the system can produce slices through the object similar to CT, as shown in **Figure 13.2-10**. This approach is called laminography and was used and further developed for corrosion inspection research at NESB (**Figure 13.2-11**).

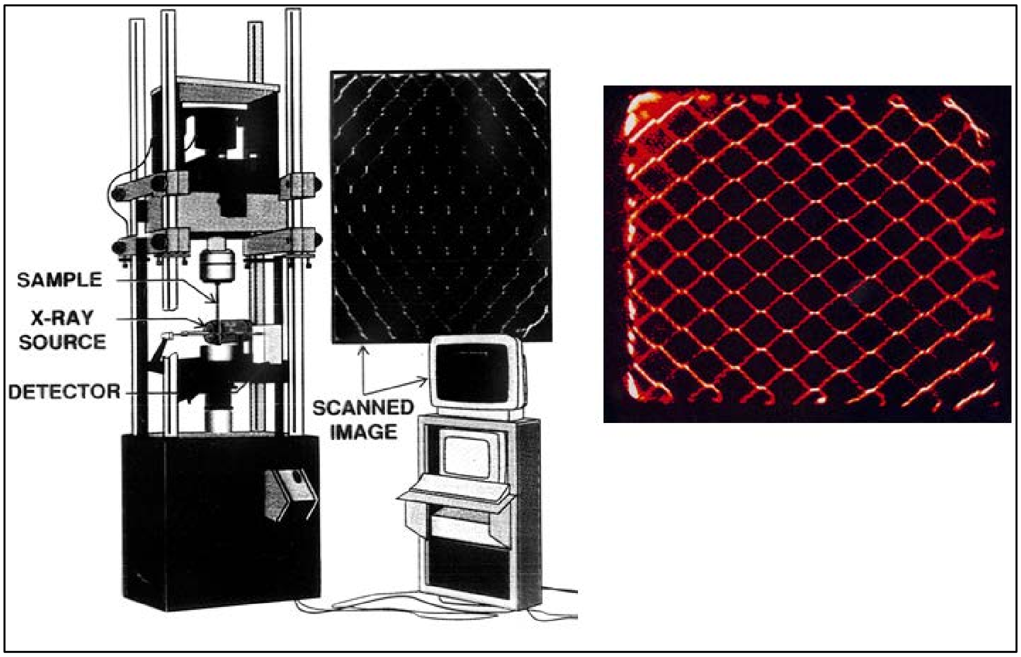


Figure 13.2-9: Block Diagram of QUEST Microfocus CT System Built on a Fatigue Load Frame. This system produced the first CT images of internal deformation in NDE. The insert image shows internal damage in a slice through a honeycomb structure under loading.

Figure 13.2-10: X-ray Images Showing Conventional (Left) and Laminography with Reverse Geometry X-ray (Center and Right) Capabilities. Note that the laminography can produce slice images similar to CT. [Image is from Digiray®.]

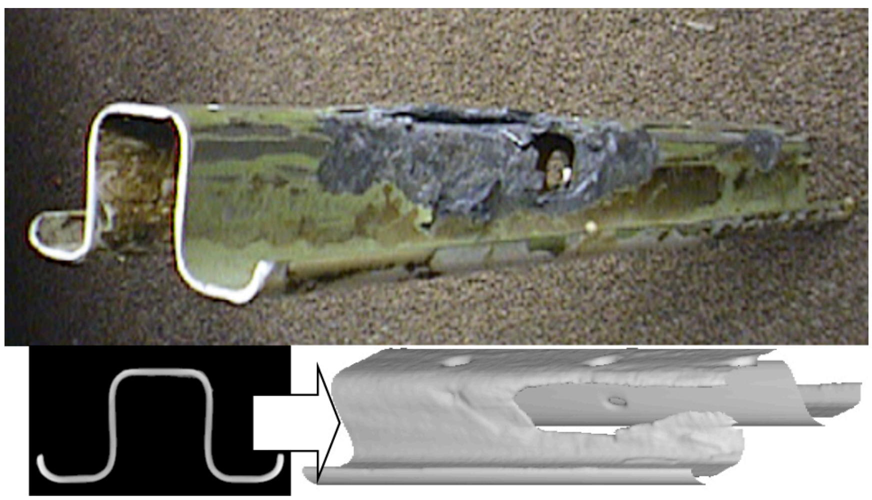


**Figure 13.2-11: An Aircraft Part Examined with the Reverse Geometry X-ray System and the reconstruction of the 3-D image created from the scanned data.
Note the fidelity of the identified corrosion.**

More recently, NESB has focused on applications of CT for X-ray inspection of experimental and research articles. F. Ray Parker and Patty Howell have worked on system assessments such as valves, wire crimps, and structures. One test of a dome structure examined the impact damage showing honeycomb crushing. The test set up is shown in **Figure 13.2-12**.

Figure 13.2-12: Microfocus X-ray System at NESB.

Figure 13.2-13 presents CT images at three magnifications of internal damage caused by impact on a honeycomb domed structure. Note the internal crushed core. NESB CT systems image components up to 25 × 25 cm with a resolution of 200 microns or a 10 micron resolution on 1.5 cm samples. Software developed by the branch images curved components as if they were curved slices, enabling materials analysis of specific damage planes within the structure.

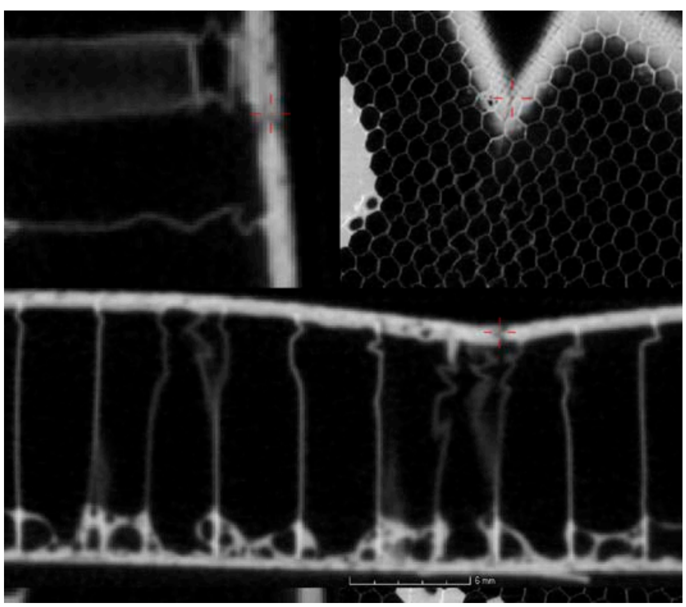


Figure 13.2-13: CT Image of Impacted Crushed Honeycomb at Three Different Magnifications.

13.2.8. Terahertz NDE (T-Ray)

Recent developments in electromagnetic sources and detectors have opened a new radiation band for NDE. Terahertz waves (frequency of 1012), called T-Rays, propagate through most materials except for water and metal. As systems became available, NESB experimented with T-Rays to inspect the sprayed-on foam insulation (**Figure 13.2-14**) on the shuttle external tank.[29] Successful tests at NESB lab demonstrated the value of T-Rays for the Shuttle Program (**Figure 13.2-15**). A T-Ray commercial system was installed to inspect the ET. It has also been used for corrosion detection and metallic surface roughness assessment.[30]

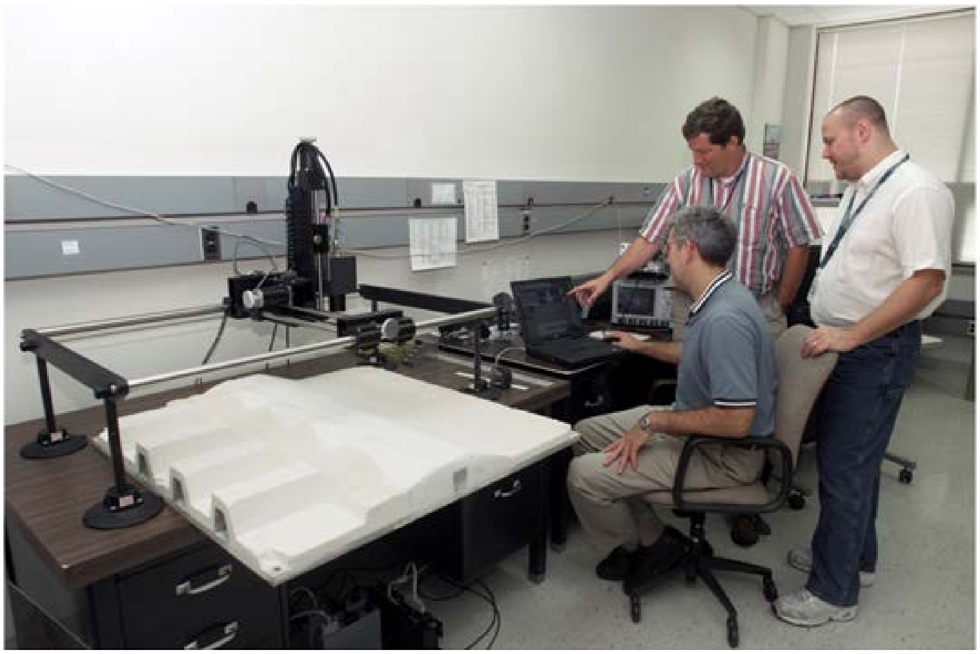


Figure 13.2-14: Research on T-Ray System at NESB for Application to Shuttle External Tank Foam Inspection.

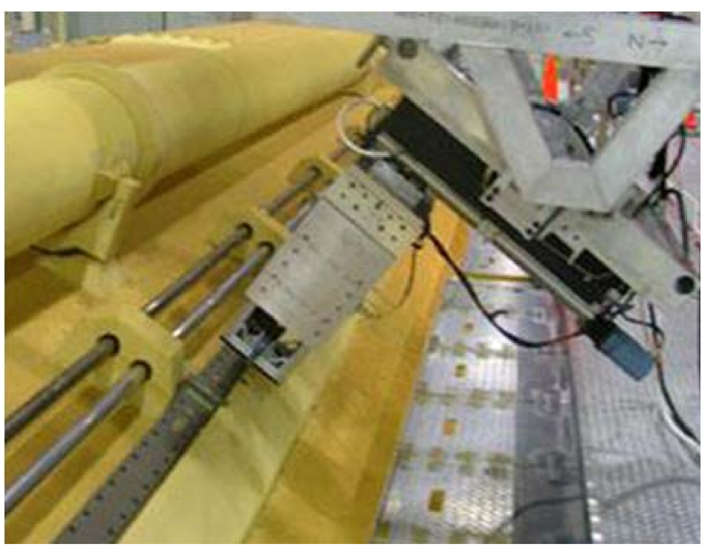


Figure 13.2-15: Large Scale Terahertz Inspection System for Space Shuttle.

References

[1] Heyman, J.S.; “Pulsed Phase Locked Loop Strain Monitor”, United States Patent 4,363,242, Dec. 14, 1982.

[2] Yost, William T.; Cantrell, John H.; and Kushnick, Peter W.; “Constant Frequency Pulsed Phase-Locked Loop Instrument for Measuring Ultrasonic Velocity of Condensed Matter”, Rev. Sci. Instrum. 62, 2451–2456 (1991).

[3] Heyman, Joseph S. and Miller, James G.; “Verification of Sensitivity Enhancement Factors for CW Ultrasonic Resonators”, JAP, Vol. 44, No. 8, August 1973 (3398).

[4] Cantrell, John H., Jr. and Heyman, Joseph S.; “Ultrasonic Spectrum Analysis Using Frequency-Tracked Gated rf Pulses”, J. Acoust. Soc. Am. 67, 1623-1628 (1980).

[5] Cantrell, John H.; “Ultrasonic Harmonic Generation from Fatigue-Induced Dislocation Substructures in Planar Slip Metals and Assessment of Remaining Fatigue Life”, J, Appl. Phys. 106, 093516 (2009).

[6] Cantrell, John H.; U.S. Patent No. 5,736,642, granted April 7, 1998: “Nonlinear Ultrasonic Scanning to Detect Material Defects”,(with Yost, William T.)

[7] Cantrell, John H. and Yost, William T.; “Improved Non- Destructive Evaluation Method Employing Dielectric Electrostatic Ultrasonic Transducers”, U. S. Patent No 6,584,848, granted July 1, 2003.

[8] Cantrell, John H.; “Nondestructive Evaluation of Metal Fatigue Using Nonlinear Acoustics”, Reviews of Progress in Quantitative Nondestructive Evaluation, Vol. 28, edited by D. O. Thompson and D. E. Chimenti (AIP, Melville, 2009), pp. 19–32.

[9] E. I. Madaras, T. W. Kohl, W. P. Rogers; “Measurement and Modeling of Dispersive Pulse Propagation in Drawn Wire Waveguides”, Journal of Acoustical Society of America, Vol. 97, n. 1, pp. 252–261 (1995).

[10] R.F. Anastasi and E. I. Madaras; “Application of Ultrasonic Guided Waves for Aging Wire Insulation Assessment”, Materials Evaluation, ASNT, Inc., Feb. 2005, Vol. 63, n. 2, pp. 143–147.

[11] Keun J. Sun, Doron Kishoni, Patrick H. Johnson; “Feasability of Using Lamb Waves for Corrosion Detection in Layered Aluminum Aircraft Structures”, Proc. 1993 IEEE Symposium, IEEE Cat. No. 93 CH 3301-9, pp. 733-736, (1993).

[12] William T. Yost, Daniel F. Perey and K. Elliott Cramer; “Assessment and Calibration of a Crimp Tool Equipped with Ultrasonic Analysis Features”, U.S. Patent 7,181,942.

[13] William H. Prosser; “The Propagation Characteristics of the Plate Modes of Acoustic Emission Waves in Thin Aluminum Plates and Thin Graphite/Epoxy Composite Plates and Tubes”, NASA TM 104187, (November, 1991).

[14] M. R. Gorman, W. H. Prosser; “Application of Normal Mode Expansion to AE Waves in Finite Plates”, Transaction of the ASME: Journal of Applied Mechanics, Vol. 63(2), 1996, pp. 555–557.

[15] Welch, C. S.; Heath, D.M.; and Winfree, W. P.: “Remote Determination of the Two-Dimensional Diffusivity Tensor in Thin Plates”, 1985 IEEE Ultrasonics Symposium Proceedings, p. 1139.

[16] Welch, C. S.; Heath, D. M.; and Winfree, W. P.; “Remote Measurement of In-Plane Diffusivity Components in Plates”, J. Appl. Phys, 61(3), p. 895, 1987.

[17] P. A.; Winfree, W. P.; Crews, B. S.; and Cramer, E.; "Parametric Studies of Thermographic Detection of Disbonds in Laminated Structures Using Computational Simulations", Review of Progress in Quantitative Nondestructive Evaluation,9, p. 1263, 1989.

[18] Heyman, Joseph S.; Winfree, William P.; Cramer, K. Elliott; and Zalameda, Joseph N.; "Method and Apparatus for Thermographically and Quantitatively Analyzing a Structure, for Disbonds and/or Inclusions", U.S. Patent 5,562,345, October 8, 1996.

[19] Zalameda; Joseph N., Winfree; William P.; "Synchronized electronic shutter system and method for thermal nondestructive evaluation", U.S. Patent 6,712,502, March 30, 2004.

[20] K. Elliot Cramer and William P. Winfree; "Method and apparatus for the portable identification of material thickness and defects using spatially controlled heat application", U.S. Patent 6,000,844; March 4, 1997.

[21] Method of Characterizing Residual Stress in Ferromagnetic Materials a Pulse Histogram of Acoustic Emission Signals, Min Namkung, Peter Kushnick, William T. Yost and John L. Grainger; U.S. Patent 5,164,669, 11/17/92.

[22] M. Namkung and J. S. Heyman; "Residual Stress Characterization with an Ultrasonic/Magnetic Technique", Nondest. Test. Comm., Vol. 1, 175 (1984).

[23] Magneto Acoustic Emission Method for Testing Materials for Embrittlement, Sidney,G. Allison, Min Namkung, William T. Yost and John H. Cantrell; 5,109,195, 4/28/92.

[24] John W. Simpson, C. Gerald Clendenin, James P. Fulton, Russell A. Wincheski, Ronald G. Todhunter, Min Namkung, and Shridhar Nath; Flux-Focusing Eddy Current Probe, U.S. Patent 5,617,024, 4/1/97.

[25] Russell A. Wincheski, James P. Fulton, Shridhar Nath, John W. Simpson, and Min Namkung; Rotating Flux-Focusing Probe for Flaw Detection, 5,648,721, 7/15/97.

[26] B. Wincheski, J.P. Fulton, S. Nath, and M. Namkung; "Analysis of Eddy Current Distribution and Resulting Flaw Detection Mechanism for Self-Nulling Probe", Reviews of Progress in Quantitative NDE, Vol. 14A, D.O. Thompson, and D.E. Chimenti, Ed., Plenum Press, 291-298, 1995.

[27] R. Wincheski, J.W. Simpson, and A. Koshti; "Development of Eddy Current Techniques for the Detection of Cracking in Space Shuttle Primary Reaction Control Thrusters", NASA/TP-2007-214878, 2007.

[28] William P. Winfree, F. R. Parker, and N.A. Cmar-Mascis; "Imaging Corrosion in Aircraft Structures With Reverse Geometry X-Ray", Presented at 43rd International SAMPE Symposium, Vol. 43, Book 2, pp. 1438–1447, 1998.

[29] D. Zimdars, J. A. Valdmanis, J.S. White, G. Stuk, S. Williamson, W. P. Winfree, E. I. Madaras; "Technology Applications of Terahertz Imaging Non-Destructive Examinations: Inspection of Space Shuttle Sprayed on Foam Insulation", 31st Annual Review of Progress in QNDE, 2004, Golden, CO, vol. 24B, pp. 570–577.

[30] Robert F. Anastasi, Eric I. Madaras; "Terahertz NDE for Metallic Surface Roughness Evaluation", SPIE 11th Annual International Symposium on Nondestructive Evaluation for Health Monitoring and Diagnostics, 2/26/2006, San Diego, CA.

13.3. Applications to the Aging A/C Program

NESB explored new technology programs for the aging airfleet. When the world saw Aloha Airlines accident images, where unexpected flaw growth occurred in a Boeing 737, NASA was ready with well thought out plans to address this critical event. In fact, an NDE proposal from LaRC had been sent up for review just months before the fuselage had ripped open on a 737 (**Figure 13.3-1**) from multi-site fatigue damage (MSD).

Figure 13.3-1: The photograph from the NTSB Report (NTSB number: AAR-89-03) shows the explosive decompression of the fuselage.

In very short order, a significant research team was involved in understanding and reducing the risk of such accidents in the future. The team approach brought together scientists and engineers from three major disciplines, fatigue and fracture, structural analysis, and nondestructive evaluation. The close interdisciplinary activities conducted in the LaRC laboratories were key to the success of this program. Research interplay occurred at the modeling, experimental, and analysis stages for this multi-year multi-million dollar program that helped rewrite airframe safety practices of the day.

An excellent example of the NDE developments created by this team is one of the thermal NDE technology systems. **Figure 13.3-2** shows an actual data image from a lap-joint tested by NESB for a 747.

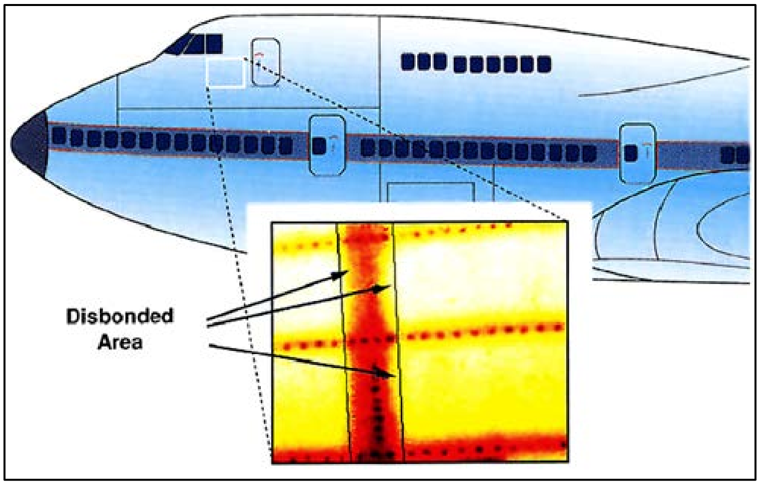


Figure 13.3-2: Thermal Diffusivity Data using the NESB developed system to inspect lap joints on an aircraft. The data clearly shows regions of disbonds that may be the precursor to MSD.

The necessary technical disciplines worked closely together: physicists, materials scientists, structural scientists, electrical engineers, software experts, and program leadership. The technology moved from ideas to models to lab testing, and finally to field-capable systems to demonstrate for the stakeholders. **Figure 13.3-3** shows a complete system test at an aircraft rework facility. In this image we see a thermal system scanning the lap joint band on a 737.

Figure 13.3-3: Demonstration by NESB of the Thermal Diffusivity System on an airframe undergoing a D-Check.

The NESB flux-nulling probe is another example of a technology that moved from a research technology readiness level to a fieldable system. One of the key problems in airframe inspection is the detection of cracks in rivet and bolt holes. Often the cracks are not only found on the surface, but also in buried layers of aluminum in regions built-up for higher loads. The history of this device is quite interesting. The probe was invented by a technician team and a Ph.D. physicist working together, moving from a theoretical model of magnetic flux to a real probe to test in a lab. As with the development of the bolt monitor, the flux nulling probe was a success immediately, but it’s more visible accomplishment was to come next.

To inspect holes for cracks, one has to move the inspection device around the hole. It required an additional technique and patent to bring this to success. An enhanced capability to inspect holes was invented by developing a rotational probe with the advanced flux model. This science capability has led to new inventions and practical probes for the inspection of tubes and for buried layer crack detection.

13.4. Structural Health Monitoring (SHM)

Structural health monitoring (SHM) is the integration of sensor data, structural information, and physics/engineering models into a predictive capability of integrity. With such a broad definition, SHM systems can utilize any appropriate sensor and especially a fusion of different sensors, each representing unique physical/engineering properties. The human nervous system is an excellent example upon which to model a SHM system (**Figure 13.4-1**). For example, our skin can detect temperature, vibration, displacement, and roughness. A thermal protection system would benefit if it could report back data related to its surface temperature (or heat flux), unusual vibrations (acoustic emission related to internal damage growth), movement (a gap opening between protective elements), or erosion at the surface. A SHM system must be cost effective, must have a unique power source, must not significantly alter the operational properties of the monitored structure, must be dependable, and fit within the fabrication time frame. Not an easy task!

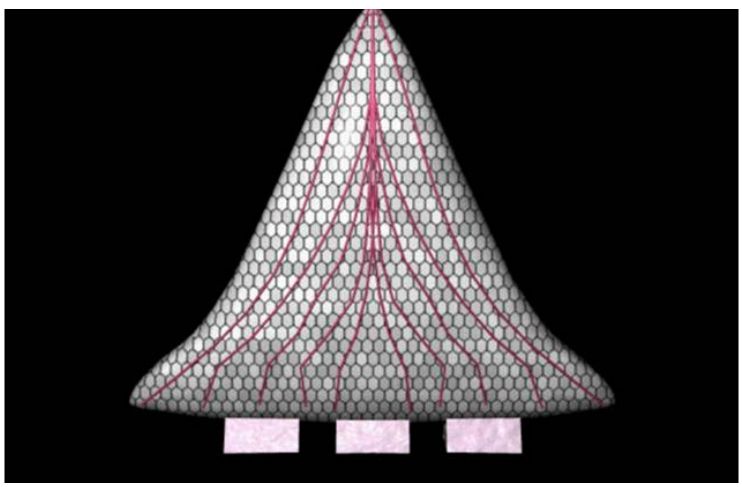


Figure 13.4-1: Artist’s Rendition of a SHM System Built into a Hot Structure.

Yet today, we are integrating many more sensors into critical structures, and they are providing information that would otherwise require costly structural dismantling. An acoustic emission sensor system was flown on the shuttle to detect impact on the RCC structures. A device for testing has been prepared and is being evaluated for wireless installation on sensitive structural sites (**Figure 13.4-2**).

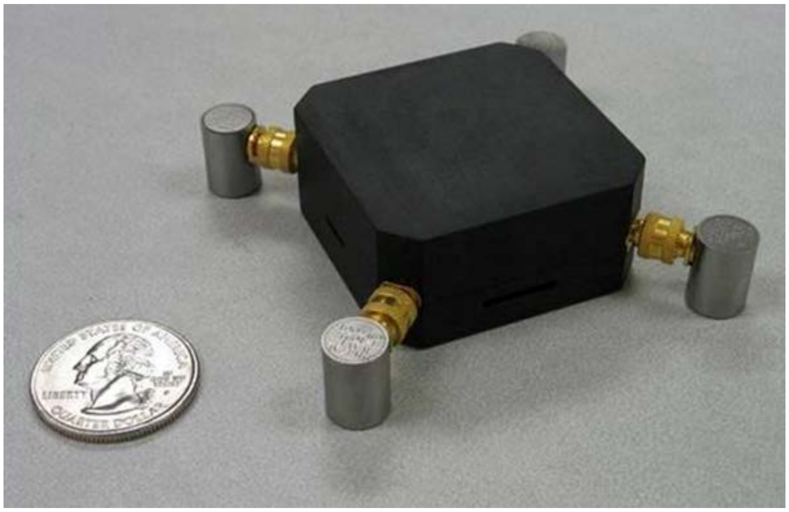


Figure 13.4-2: Prototype Impact Damage Detection Sensor Array.

Fiber optic (FO) sensors have been used in many situations to sense acoustic emission, strain and vibration. NESB, working with Professor Rick Claus, then at VPI, developed a FO sensor for ultrasonics that resulted in applications for SHM.[1] In other studies, structural modal vibrations were measured using a single fiber optic line with the intent of recording wing modes and their amplitudes during flight to develop a vibratory spectral life history of a flying structure. NESB integrated FO lines into composite tubes to monitor space structures working with the Air Force Astronautics Laboratory to provide a feedback control loop for structural stability.[2] Luna Innovations has developed a sensing fiber that can report the structural strain (~1.0 μstrain) and temperature (~0.1ºC) at any point (~1 cm) along the fiber up to 70 m in length. This FO product was inspired by research at NESB to provide sensors for the X-33 launch vehicle project. 10,000 sensors were needed but could not add appreciably to the vehicle test weight. NASA researchers invented an optical Fiber Bragg Grating sensor system to meet this challenge.[3]. Another Luna development is a shape-sensing fiber with applications that include medical robotic surgery as well as monitoring complex structural systems.[4].

References

[1] R. O. Claus and J. H. Cantrell; “Detection of Ultrasonic Wave in Solid by an Optical Fiber Interferometer”, IEEE Ultrasonics Symposium, pp. 719-721, 1980.

[2] R. S. Rogowski. J. S. Heyman, M. S. Holben, Jr., C. Egalon, D. W. Dehart, T. Doederlein, J. Koury; “Fiber Optic Strain Measurements in Fillament-Wound Graphite-Epoxy Tubes Containing Embedded Fibers”; SPIE Vol. 986, Fiber Optic Smart Structures and Skins (1988).

[3] Mark Froggatt; “Apparatus and Method for Measuring Strain in Bragg Gratings”, U.S. Patent 5,798,521, August 25, 1998.

[4] Dr. Brian Soller and Trevor Rice; “Fiber Sensors Go 3-D”, Photonics Spectra, page 63, December 2008.

13.5. Lessons Learned and Future Direction

A major lesson learned over the past few decades is the importance of risk analysis and setting quantitative mechanisms to measure and project mission assurance. Part of that advancement is a more complete understanding of the concept of probability of detection (POD) of flaws in structures and how the existence of a flaw affects structural life. Prior to the Aloha 737 accident, engineers were confident that failures in aircraft structures could be managed by understanding isolated flaw growth. We now know that multiple flaw sites must be modeled together to predict failures. Similarly, only looking at flaw size and not including changing material properties around the flaw site may not accurately reflect lifetime outcomes. These factors coupled with validation procedures for NDE measurements move prediction technology forward. An example of important work in the area of POD is the paper of Dr. Ed Generazio looking at the design of experiments to properly determine risk factors in NDE.[1].

To look to the future, it is necessary to step away from the present and think beyond incrementalism. The "Development and Evaluation of Sensor Concepts for Ageless Aerospace Vehicles"[2] is an excellent examination looking over the horizon for what is possible. This study was initiated by Dr. Generazio to explore the future of NDE and integrated health management (IHM). First looking at biological systems, the review asks the question, "How can a structure become self-healing and self-sensing?" Coupled with these properties is communications from the structure to an autonomous monitor able to gather, process, and act on information. The report ends with a proposal for a demonstration project to verify at the concept level properties of such a system. A more recent review of self-healing polymers was published by Elsevier in 2008.[3] Dr. Mia Siochi at LaRC has been exploring advanced technologies to implement practical materials with necessary capabilities ranging from energy harvesting structures to materials with enhanced engineering performance.[4]

At some time in the future, there will be advanced structural entities that come close to having their own reflexive systems. They will not only know their condition, but they will also be able to perform repairs on many classes of damage. This advanced state is a product of great innovation and discovery, working at the molecular level. Today's investments in long-term research provide the palate necessary to paint this future vision. Here are some of the foundational works in this category, and they start small.

This class of SHM is at the nano-size. It is possible to integrate nano particles within a structure, even to produce an alloy of such particles. The properties of the particles offer the potential of being passive sensors to the material condition such as fatigue, strain, or thermal history. As such, these particles become their own data system, storing information that can be assessed for SHM. NESB has been experimenting with such ideas, led by Buzz Wincheski, using carbon nanotubes (CNT). Prior to the actual step of fabricating the CNT sensors, extensive preprocessing of CNTs is necessary as summarized below;

1. As-produced CNTs are bundles of tangled mess, and they need to be dispersed down to individual single tubes to enable any device fabrication. The effort resulted in perfect dispersion that is either the first or second time in the world to accomplish such. The dielectrophoresis method was extensively used in this work.
2. It is also important to characterize the distribution of CNT morphology (side wall geometry) that is directly related to the electrical properties of a batch of CNTs. This required the direct comparison of Raman scattering and optical absorption spectroscopy

results of a batch of CNTs. The effort, led by Dr. Min Namkung, is the first time anyone implemented this method.

3. Individual CNTs are either semi-conducting or metallic depending on the side-wall geometry. It was imperative to separate them for specific applications. A dielectrophoresis method was used to separate the two types of CNTs.

These advances in processing CNT are the early steps in advancing the technology for their application to both sensor-based IHM and enhanced performance materials that will be the core of future systems.

Another future vision may introduce new methods of healing materials exposed to complex thermal and fatigue environments. Glass must be thermally annealed after forming to prevent residual stress fracture. Holding glass at several annealing temperature/time periods permits stresses to relax. Thermal annealing is a form of chaotic molecular vibration, similar to random ultrasonic vibration. In the 1970s, high-power ultrasonics was used to make metal flow,[5] not unlike high-temperature processing of metals. The connection between heat and ultrasonics is that both involve the vibration of the material, with ultrasonics acting at controlled phase and frequencies. Therefore, it should not be too surprising in the future to see ultrasonics and other aspects of acoustics used in the healing of materials that have suffered fatigue, strains, or thermal cycles. Dr. Cantrell visualizes a time when diagnostic nonlinear acoustics will include a capability to rejuvenate materials to increase remaining life. These projections follow from a more fundamental understanding of internal material damage and fatigue “memory.”

It may be some time before the vision of these studies mature, but the progress toward the vision and the environment to seek beyond what are guaranteed research outcomes will bring the future visions into focus and practice.

References

[1] E.R. Generazio; “Validating Design of Experiments for Determining Probability of Detection Capability for Fracture Critical Applications”, Materials Evaluation, Vol. 69, No. 12, pp. 1399–1407, 2011.

[2] David Abbott et. al.; “Development and Evaluation of Sensor Concepts for Ageless Aerospace Vehicles”, NASA/CR – 2002-211773, Commonwealth Scientific Industrial Research organization, Lindfield, New South Wales, Australia, July 2002.

[3] Dong Yang Wu, Sam Meure, David Solomon; “Self-healing Polymeric Materials: A Review of Recent Developments”, Elsevier, Progress in Polymer Science Volume 33, Issue 5, May 2008, pp. 479–522.

[4] Emilie J Siochi, Dennis C Working, Cheol Park, Peter T Lillehei, Jason H Rouse, Crystal C Topping, Arup R Bhattacharyya, Satish Kuma; “Melt Processing of SWCNT-Polyimide Nanocomposite Fibers”, Elsevier, Composites Part B: Engineering Volume 35, Issue 5, July 2004, pp. 439–446.

[5] Robert C. McMaster et. al.; “Metal Working Apparatus and Process”, US Patent 3,609,851, October 5, 1971.

14. Failure Analyses: Examples and Methodologies

14.1. Selected Case Studies

Langley Research Center has been a premier aeronautics and space research center for more than nine decades. At times, Langley was referred to as the heavy metal center because of the many wind tunnels and supporting infrastructure. Even though Langley has an outstanding safety record, there have been many equipment failures and some rather spectacular facility failures. Many of these failures involved structural materials and, in most cases, were metallic components. Failure investigation boards were formed to find the cause of the failure and to recommend repair procedures and steps to prevent similar future failures. Researchers from the Metals Branch, the Fatigue and Fracture Branch, and/or the Structural Mechanics Branch were often assigned to these investigation boards to perform failure analyses to establish the probable cause of failure.

The failure analysis capabilities of the Langley metals experts combined with the metallurgical analysis capabilities of the Light Alloy Laboratory is a national asset. These resources have supported over 200 failure investigations for NASA Centers, other government, and Department of Defense (DoD) organizations and private industry.

Failure analyses work was essential to restoring wind-tunnel operations at Langley following failure of a tunnel component or system and/or failure of a test model in the tunnel. Support was also provided to the Navy on a forging failure on an A6 aircraft, the Army on a helicopter failure, and to past space projects like the very successful Viking Project (Viking Parachute Swivel Failure, during development testing).

Examination of past failure analyses reports shows that frequent names among the technical experts ask to serve on these investigation boards included W. Barry Lisagor, Tomas T. Bales, Dr. Harvey Herring, Dr. Bland Stein, Dr. Jim Newman, Dr. Jim Starnes, Mike Hudson, Marcia Domack, John Wagner, and key people from the Nondestructive Inspection Branch. Lisagor was an expert in performing failure analyses and in mentoring younger engineers in the “science of failure analyses.” When a failure occurred at Langley, Barry Lisagor was almost always the first person requested to examine the accident site and either perform the investigation or make a recommendation on who should be on the investigation board.

The results of failure analyses investigations were briefed to mishap boards typically formed to uncover the cause(s) of the failure and corrective actions to be taken to prevent similar future failures. A selection of the investigation titles are presented to illustrate the type of failure analyses performed and to recognize the breath of topics addressed and the importance of their work to the continued safe operation of the highly specialized test equipment operated by Langley. The files from these investigations are archived in the library of the Light Alloy Laboratory.

Four example failure investigations were briefly discussed in section 2.10 of chapter 2 as part of the success stories on the metals program at Langley.

14.1.1. Investigations in Support of LaRC Facilities

1. W.B. Lisagor, T.T. Bales: Air Supply Pipeline at 8’ HTST, 1968.
2. W.B. Lisagor, B.A. Stein: Helicopter Gyro Damping Rod, 1968.
3. W.B. Lisagor, B.A. Stein, T.T. Bales: Cooling Tower Fan Blades, 1968–1969.
4. B.A. Stein: Microcircuit, 1969.
5. B.A. Stein: P-1127 VTOL Flap, 1969.
6. T.T. Bales: Accelerator Tubes-HGRF, 1969.
7. T.T. Bales, W.B. Lisagor: Boiler Tubes, 1969.
8. W.B. Lisagor, T.T. Bales: Shape Program, Shear Rivets, 1969.
9. W.B. Lisagor, D.R. Rummler, B. A. Stein: High Pressure He Line, Coupling Nut, 1969.
10. T.T. Bales: Solis Rocket Motor Case, 1969.
11. W.B. Lisagor: Commutation Bar, Wind Tunnel Motor, 1969.
12. W.B. Lisagor: Brazed Joints in Heat Exchanger, 1070.
13. W.B. Lisagor: High Voltage Power Cable, 1970.
14. B.A. Stein: Cd Plated Fasteners, 1970.
15. W.B. Lisagor: Electromagnetic Coil, 1970.
16. B.A. Stein: Impact Damage to HRE Model, 1970.
17. B.A. Stein: H-11 Bolts on Supercritical Wing Test, 1970.
18. B.A. Stein: Corrosion in M-6 Tunnel, 1971.
19. B.A. Stein: Micrometeoroid Simulation Hole Morphology, 1971.
20. H.W. Herring, B.A. Stein, J.E. Gardner, W. B. Lisagor, T.T. Bales: 9 X 6 TST Bottle field Explosion, NASA-Special Committee, 1971–1972.
21. W.B. Lisagor, B.A. Stein: Wall Cracks in Continuous Flow Hypersonic Tunnel, 1971.
22. B.A. Stein: Materials for High Velocity Flywheels, 1972.
23. W.B. Lisagor: Fan Blade Attachment Pins for 8’ Transonic Tunnel, 1972.
24. D.R. Tenney, W.B. Lisagor: Wall of Low-Turbulence Pressure Tunnel, 1974.
25. D.R. Tenney, B.A. Stein, D.R. Rummler, M.D. Bhandarkar: Landing Load Track Carriage, 1974.
26. D.M. Royster: 8’ HTST Combustor, 1975.
27. W.B. Lisagor, M.D. Bhandarkar: 8’ TPT Model Balance Arm, 1975.
28. W.B. Lisagor, M.D. Bhandarkar: NASA Beech C23 Aircraft Landing Gear, 1975.
29. W.B. Lisagor: B1247D Vacuum Line Filter Residue, 1975.
30. W.B. Lisagor, M.D. Bhandarkar: Material Selection for NTF Balance Assemblies, 1975.
31. M.D. Bhandarkar, B.A. Stein: Screw Failures on Model in 16 Ft Transverse Tunnel, 1975.
32. S.S. Tompkins: Better Insulation for NTF, 1976.
33. W.B. Lisagor: Deposits in CF4 Tunnel, 1976.
34. W.B. Lisagor, B.A. Stein: Corrosion in Beech Sundowner, 1976
35. W.B. Lisagor, B.A. Stein: Compressor Failures in B1247D, 1976.
36. W.B. Lisagor, B.A. Stein: T38 Trainer Rudder H.C. Panel Disbrd, 1976.
37. W.B. Lisagor: UPWT Cooling Motor Fan Blade, 1978.
38. W.B. Lisagor: High Reynolds No. Tunnel Particulate Contaminants, 1978.

39. Bales, T. T.; Wagner, J. A.; Lisagor, W. B.; Illg, E. D.; and Kiss, J. J.: "Failure Analysis Report on Lockheed Propfan Model During Testing in the 16-Foot Transonic Tunnel on October 28, 1985," May 1986.
40. Domack, Marcia S.; Wallace, Terryl A.; and Lisagor, W. Barry: Aircraft Landing Dynamics Facility Stroloy 5C Carriage Tube, Presented to the ALDF Engineering Review Board, April 3, 1987.
41. Domack, Marcia S. and Bales, Thomas T.: 16-foot Tunnel Main Drive System Bolts, December 1988.
42. Domack, Marcia S., Edahl, Robert A., Van Orden, Ann C., Drummond, William T., Lisagor, W. Barry: Metallurgical Analysis of NTF Main Drive System External Thermal Barrier Components, March 1989.
43. Domack, Marcia S.: Materials Evaluation Report - 8-foot High Temperature Tunnel Welded 304 SS Tubing, June 1989.
44. Domack, Marcia S., Hoffman, Eric K., Bales, Thomas T., Birt, Michael J. and Drummond, William T.: 20-inch Supersonic Wind Tunnel Upper Flexible Nozzle Plate, October 1989.
45. Domack, Marcia S.: Qualification Testing of Replacement Bolts for the National Transonic Facility. Critical Design Review of Replacement LN2 Injector Fairings, June 27, 1990.
46. Domack, Marcia S.: Fracture of Wing Flap Support Ping, 8 Foot Transonic Dynamics Tunnel, January 1991.
47. Domack, Marcia S. and Lisagor, W. Barry: 8-Foot High Temperature Nozzle Platelet Failure, June 1991.
48. Domack, Marcia S., Crooks, R., Shenoy, R.: Failure analysis of WRATS Model in the TDT Tunnel, Nov. 2000.
49. Smith, S.W.; Wagner, J.A.; Davila, C.G.; Crooks, R.E.; and Baughman, J.M.: "Investigation of the SAMPSON F-15 Inlet Model Mishap in the 16-Foot Transonic Wind Tunnel," Appendix D.4. NASA-LaRC, May 2001.
50. Domack, Marcia S.: NTF Heat Exchanger Copper Tubing, August 2001.
51. Domack, Marcia S.: NTF Heat Exchanger Expansion Joint, October 2001.
52. R. Edahl and M. Domack, Failure Analysis of NTF Ball Screw, March, 13, 2007.
53. M. Domack, R. Edahl, R. Shenoy, S. Sankaran, and J. Baughman, NTF Cooling Coil Investigation, April 18, 2007.
54. M. Domack, R. Edahl, R. Shenoy, S. Sankaran, and J. Baughman, Materials Analysis Summary, NTF Cooling Coil Replacement Operational Readiness review, January 24, 2008.
55. Edahl, Domack, "31 Inch Mach 10 Tunnel Filter Failure Analysis," November 2011.
56. Domack, Edahl, Gordon, Sankaran, Baughman, "Failure Analysis Report: 8-Foot High Temperature Tunnel Air Line Debris," February, 2013.
57. Edahl, Domack, Gordon, Bird, Baughman, Sankaran, Shenoy; "Analysis of Debris and New Piston Ring Material for the Compressor Station," April, 2015.

14.1.2. Investigations in Support of Programs and Missions

58. B.A. Stein, "Electrical Breakdown of Microcircuits," NASA-Lunar Orbiter, 1966.
59. C.R. Manning, W.B. Lisagor, T.T. Bales: Stress Corrosion of N2O4 Tanks, 1968.
60. W.B. Lisagor, T.T. Bales: Machining Error in Apollo Service Propulsion Tank, 1968.
61. W.B. Lisagor: Hydrogen Peroxide Tanks, NASA-Pressure Vessel Safety Committee, 1968.

62. W.B. Lisagor: Stress Corrosion of Ti Methanol Tanks, 1969.
63. B.A. Stein: Catalyst Material NASA-Life Support, 1969.
64. W.B. Lisagor: Bacteria Surface Analysis, 1970.
65. T.T. Bales: OMPRA Pressure Supply Tube, 1970.
66. B.A. Stein: Viking Heat Shield-Ablator Material Analysis, 1970.
67. B.A. Stein: Earth Orbital Experiments, LaRC-Adv. Aero. Stud. Br., 1970.
68. W.B. Lisagor, B.A. Stein: Gaseous H2 Storage Pressure Vessels, LaRC-Viking Program Office, 1970.
69. B.A. Stein: Viking Lander Expt. Mortar Transducer, 1971.
70. B.A. Stein: Pioneer F&G Meteoroid Penetration Panel, 1971.
71. H.W. Herring:Analysis of Coating on Micron-size Powder Particles, 1971.
72. B.A. Stein: Viking, Electronic Packaging Materials, 1972.
73. H.W. Herring: Electron Microscopy of Stainless Steels, 1972.
74. W.B. Lisagor: Analysis of Upper Stratosphere Particulates, 1972.
75. B.A. Stein: Stainless Steel Surfaces, 1972.
76. B.A. Stein, W.B. Lisagor, D.R. Rummler: Viking Parachute Swivel, 1972.
77. W.B. Lisagor: Particulate Analysis of Apollo Launch Products, 1972.
78. W.B. Lisagor: TPSTF Brazed Joints, 1972.
79. D.M. Royster, B.A. Stein, T.T. Bales: Viking Thermal Switch Sensor Plate, 1972.
80. W.B. Lisagor: Materials for Helicopter Mufflers, 1972.
81. H.W. Herring, W.B. Lisagor: Skylab Isolation Mounts, 1972.
82. B.A. Stein, W.B. Lisagor: FAR Diffusion Bonds on Snap 19 RTG Electrical Receptacle for Viking, 1973.
83. W.B. Lisagor: FAR Vacuum Tight Brazed Electrical Feed Throughs for Viking Lander Scientific Experiment, 1973.
84. W.B. Lisagor: Viking Instrumentation Vacuum Feed-Throughs, 1973.
85. B.A. Stein, W.B. Lisagor, D.R. Rummler: Viking RTG Diffusion Bonds, 1973.
86. H.W. Herring: Aluminum Alloy Components-In-service Failures, 1973.
87. W.B. Lisagor, B.A. Stein: Viking Computer Bank Word Straps, 1973.
88. W.B. Lisagor: Properties of Hastalloy X, 1973.
89. H.W. Herring: High Strength Steel Bolts in HRE Cowls, 1973.
90. W.B. Lisagor: TPSTF-Intergranular Corrosion Brazed Joints, 1973.
91. B.A. Stein, A.R. Saunders: Surfaces of Thin Films, 1973.
92. B.A. Stein, W.B. Lisagor: CdS &GaAs Crystal Surfaces, 1973.
93. H.W. Herring, W.B. Lisagor, B.A. Stein: Viking Mass Spectrometer Filaments, 1973.
94. W.B. Lisagor, B.A. Stein: Electromyography Needles, 1973.
95. W.B. Lisagor: Lubricant of DHC-6 Propeller Shank Bearing, 1973.
96. W.B. Lisagor, B.A. Stein: Tantalum Capacitor Micro deposits, 1973.
97. W.B. Lisagor: Viking Computer Memory Wires, 1973.
98. W.B. Lisagor, B.A. Stein: Flex Leads on Initial Ref. Unit Gyro for Viking, 1973.
99. W.B. Lisagor: TPSTF Brazed Joints, 1973.
100. W.B. Lisagor, B.A. Stein: Viking IRU Cryo Ceramic End Plates, 1974.
101. D.R. Tenney, W.B. Lisagor: Viking Gyro Flex Lead Wires, 1974.
102. B.A. Stein: Galling of Magnetic Tape in Viking Data Recorder, 1974.
103. W.B. Lisagor: Surgical Implant Information, NASA-TU Office, 1975.

104. Domack, Marcia S.; Bales, Thomas T.; Lisagor, W. Barry; and Edahl, Robert A., Jr.: 7049 Aluminum Drag Brace Support Fitting, July 1987.
105. Domack, Marcia S.: Robot Arm Bearing Retainer, August 1989.
106. Domack, Hafley, Edahl, Shenoy, Sankaran, Baughman, Claytor, Bryant, "CERES Flexible Circuit Tape Analysis," November 2011.

14.1.3. Investigations in Support of Other NASA Centers

107. Domack, Marcia S., Bales, Thomas T., Lisagor, W. Barry, Edahl, Robert A.: NASA (DFRF) F-18 Aircraft, December 1988.

14.1.4. Investigations in Support of Other Government and DoD Organizations

108. B.A. Stein, L.R. Jackson: Overheated Fuselage Ring on F106, USAF, 1967.
109. B.A. Stein: F-111 DAG, USAF, 1968.
110. B.A. Stein: F-106 Rack Ejection Tester, USAF, 1969.
111. T.T. Bales, B.A. Stein: U8F Aircraft Landing Gear Actuator, Army, 1969.
112. B.A. Stein: Fracture Surfaces in Fiberglass/Epoxy, Army-AvLabs, 1970.
113. W.B. Lisagor: Scanning Electron Microscope Capabilities, Norfolk Naval Shipyard, 1971.
114. W.B. Lisagor: Chain Hoist Gear Assembly Welds, Norfolk Naval Shipyard, 1971.
115. R.L. Cain: Generator Turbine Bearing, Norfolk Naval Shipyard, 1971.
116. W.B. Lisagor, B.A. Stein: Hawk Missile Fittings, Army, 1971.
117. W.B. Lisagor: Navy Mine Suspension Lug, Naval Weapons Station, Yorktown, 1971.
118. W.B. Lisagor: Particulate Air Pollutants, Va. Commonwealth Attorney, Yorktown, 1971.
119. T.T. Bales, B.A. Stein: Welds in Aluminum Alloy Reaction Wheels, US DOT, 1972.
120. W.B. Lisagor, B.A. Stein: Surface Replication Features, Norfolk Naval Shipyard, 1972.
121. H.W. Herring: Fatigue Fractures in Titanium Alloy Tubes, Army, 1972.
122. W.B. Lisagor: Navy C2/E2 Aircraft Materials, Navy, 1972.
123. W.B. Lisagor: Corrosion in CH47 Helicopter Blades, Army, 1972.
124. H.W. Herring, D.R. Rummler: Review of SCC Proposal, Army, 1973.
125. W.B. Lisagor, B.A. Stein: FAR Interconnection Wire and Printed Circuit Board Resistor in Air Force Univac 1050 Computer, USAF, 1973.
126. B.A. Stein, D.R. Rummler: Heavy Lift Helicopter Components, Army, 1974.
127. W.B. Lisagor, H.W. Herring: Univac Computer Wires & Resistor, USAF-TAC, 1974.
128. B.A. Stein, D.R. Rummler: Air Particulate Pollutants, Va. State Env. Control Bd., 1974.
129. B.A. Stein, W.B. Lisagor: Al Corrosion Under Pencil Lines on Aircraft, Army Transportation School, Ft. Eustis, 1974.
130. W.B. Lisagor: USS Kennedy Turbogenerator, Norfolk Naval Shipyard, 1974.
131. M.D. Bhandarkar, W.B. Lisagor, B. A. Stein: Paint Smears on T29 & Cessna Aircraft which Collided, USAF & NTSB, 1974.
132. W.B. Lisagor, B.A. Stein: Embrittlement of Ti by Cd, USAF, 1975.
133. W.B. Lisagor: Flakes in F106 Engine Fuel Line, USAF, 1976.
134. W.B. Lisagor: Huey Cobra Drive Train Assy-Norfolk Crash, ARMY-Ft. Eustis, 1976.
135. W.B. Lisagor, W. Illg: F106 Magnesium Casting, USAF-48th FIS, 1976.
136. D.R. Tenney: Rotor in TF-30 Engine, Portsmouth Naval Rework Facility, 1977.
137. W.B. Lisagor: F-15 Canopy Actuators, USAF, 1977.
138. D.R. Tenney, W.B. Lisagor: F-106 Main Landing Gear Door Failure, USAF-48th FIS, 1978.

139. B.A. Stein, W.B. Lisagor, E.P. Phillips, G.L. Roderick, D.J. Progar, M.L. Walton: CH53E Helicopter Blade Failures, NAVY, Naval Air Test Center, Pax River, 1978–1979.
140. Wagner, J. A.; Lisagor, W. B.; Bales, T. T.; and Edahl, R. A., Jr.: "Failure Analysis on MD20 MOD7 Rockeye Missile Tail Cone Screw Failures', July 25, 1986.
141. Wagner, J. A.; Lisagor, W. B.; Bales, T. T.; and Edahl, R. A., Jr.: "Failure Analysis Report on F-15 Wheel Assembly Bolt," August 20, 1986.
142. Domack, Marcia S.; Lisagor, W. Barry; Bales, Thomas T.; and Edahl, Robert A., Jr.: 305 Stainless Steel Mine Sweeper Cable, October 1986.
143. Domack, Marcia S.; Wallace, Terryl A.; Bales, Thomas T.; Lisagor, W. Barry; and Edahl, Robert A., Jr.: Mine MK 60 CAPTOR Mine Strongback End Fitting and Release Arm, Report to the Yorktown naval Weapons Station, July 1987.
144. Wagner, J. A.; Bales, T. T.; and Edahl, JR. A., Jr.: "Failure Analysis Report on Cracking of MD20 MOD7 Rockeye Missile Tail Cone Sections," November 4, 1987
145. Domack, Marcia S. and Lisagor, W. Barry: Beechcraft King Air Main Landing Gear Failure, Report to the Federal Aviation Administration, April 1991.
146. Domack, Marcia S. and Lisagor, W. Barry: Lake 250 Wing Spar Cap, Report to the Federal Aviation Administration, July 2002.

14.1.5. Investigations in Support of Industry and Private Organizations

147. W.B. Lisagor: High Temperature Valve, Newport News Shipbuilding and Dry Dock Co., 1970.
148. B.A. Stein, W.B. Lisagor: Parasitic Organisms in Sea Water, Virginia Institute of Marine Science (VIMS), 1971.
149. W.B. Lisagor, B.A. Stein: Analysis of Pollutants, Newport News Shipbuilding and Dry Dock Company, 1971.
150. J. Wagner, M. Domack, and S. Shah, Assessment of Pratt & Whitney Rocketdyne Advanced Aluminum Alloy, May 17, 2007.
151. W.B. Lisagor: Surgical Implant Failures, LaRC-TU Office and Univ. of Miami, 1972–1973.
152. B.A. Stein, W.B. Lisagor: Bone Marrow Venting Instruments, NASA-TU Office & RTI, North Carolina, 1973.

14.2. F-111 Failure Investigation

The F-111 airframe utilized a significant amount of high-strength D6AC steel in the wing carry-through structure. This component was heat treated to a tensile strength of 220,000 psi and designed for –3 g to 7.33 g with design flight life goals of 4000 hr and 10 years of service. However, a full-scale static test program that was conducted over a 6-year period encountered several failures, including a failure at the wing-pivot fitting. Various modifications, including the first use of an advanced boron-reinforced composite doubler to reduce stress levels, coupled with an extension of the structural tests to 40,000 hr, were believed to have provided for 10,000 hr of safe operations.

In December 1969, an F-111 experienced a catastrophic wing failure during a pull-up from a simulated bombing run at Nellis Air Force Base. This aircraft only had about 100 hr of flight time when the wing failed. The failure originated from a fatigue crack, which had emanated from a sharp-edged forging defect in the wing-pivot fitting. As a result of the accident, the Air Force convened several special committees to investigate the failure and recommend a recovery program. James C. Newman, Jr. and Herbert F. Hardrath represented Langley[1] on the recovery team deliberations, and, along with Charles M. Hudson and Wolf Elber, they conducted fatigue-crack-growth and fracture tests on specimens made from the D6AC steel used in the aircraft. These tests were conducted in the Langley Fatigue and Fracture Laboratory under conditions that simulated aircraft operations. The original material had low fracture toughness due to the heat-treatment process. The committee recommended that every F-111 be subjected to a low-temperature proof test. This proof-test concept had been developed and successfully used in the Apollo Program, as well as other missile and space efforts. To screen out the smallest possible flaw size, the F-111 full-scale proof tests were conducted at temperatures of about –40°F, where the fracture toughness of the D6AC steel was lower than the fracture toughness at room temperature. The heat-treatment process was also corrected to provide improved toughness for the D6AC material in newer aircraft. A decade later, the same material with improved toughness was also successfully used in the space shuttle solid rocket boosters. As a result of the revised proof-test approach and the improved toughness material, there were no F-111 aircraft lost due to structural failure in almost 30 years of operations before the aircraft was retired from service in 1996.

The F-111 failure was most responsible for the U.S. Air Force developing the damage-tolerant design concept, where flaws, such as a 0.05 in crack, are assumed to exist in critical aircraft components. The structural components must then be tolerant of these defects during flight conditions. This concept relies on fatigue-crack growth and fracture criteria to establish an inspection interval to insure the safety and reliability of the aircraft.

References

[1] Chambers, J. R.; "Partners in Freedom: Contributions of the Langley Research Center to U.S. Military Aircraft of the 1990s", NASA/SP-2000-4519; NAS 1.21:4519; L-17965.

15. Emerging New Materials and Structural Concepts

Advanced materials are a prerequisite for all major research and development areas and for all key technologies ranging from information and communication, health and medicine, energy and environment, to transport and space exploration. Sophisticated materials and materials systems with novel properties and unheard of performance will have to be conceived and designed in the decades to come. [1] The laboratories, engineers and scientists at NASA Langley are well positioned to aid in the development and applications of these advanced materials. This section covers new and emerging materials that will be important in current and future aircraft and space systems.

In this section we have attempted to identify emerging new research areas in metallic materials and structures that may offer significant advantages over conventional aerospace materials. We have also highlighted materials systems that have the potential to be used on aircraft, spacecraft, launch vehicles, or other aerospace applications that fit within the NASA Charter.

During NASA's 50th anniversary conference, October 28, 2008, the then-NASA Administrator Michael D. Griffin made these comments:[2]

> It is too easy to become mired in the day-to-day tactics of budget defense or program execution, too easy to lose sight of the larger goal. A look back at history can provide the context to look forward at what we are doing and why. When I consider NASA and the Nation's space program in this way, I am drawn again and again to the overriding need for constancy of purpose in our enterprise, if we are to obtain anything useful from it.

Following the theme of his comments, we have looked at some of the many past accomplishments and lessons learned, and in this chapter we will look forward to the future. NASA Langley is well positioned to maintain the purpose of developing lightweight and durable material solutions for future NASA flight vehicles and spacecraft.

This section builds off accomplishments and contributions presented in earlier sections. Potentially high-payoff new research opportunities in metallic materials that take advantage of existing Langley test capabilities and expertise have been identified. In addition, new research opportunities have been identified that will likely require new skills to fully exploit and will require retraining of personnel or hiring of new employees with specialized skills not currently in the existing staff. Maintaining scientific excellence in core areas while at the same time developing new areas of research with due diligence to scientific excellence is critical to having a world class materials and structures research program that will position Langley to support future NASA missions. We must have boldness and the will to use it to press beyond today's limits and craft a future of lighter, more durable and robust, less expensive, and more capable aerospace systems that contribute to our society.

We have attempted to identify possible new s-curve for advancing metallic materials for future aerospace applications. Each challenge contains a discussion of actions required for Langley to develop this area of research including training, special technical courses, acquiring critical equipment, and/or developing new computational capabilities.

Before launching into a discussion of new materials development, it is useful to keep in mind that the development cycle can range from a few years to 20–30 years, as illustrated in **Table 14.2-1**.

Table 14.2-1: Typical Development Times for New Materials.

Development Phase	Development Time
Modification of an existing material for a noncritical component	2 to 3 years
Modification of an existing material for a critical structural component	Up to 4 years
New material within a system for which there is experience	Up to 10 years. Includes time to define the material's composition and processing parameters.
New material class	20 to 30 years. Includes time to develop design practices that fully exploit the performance of the material and establish a viable industrial base (two or more sources and a viable cost).
SOURCE: R Schafrik, GE Aircraft Engines, briefing presented at the National Research Council Workshop on Accelerating Technology Transition, Washington, D.C., November 24, 2003.	

References

[1] GENESIS; White Paper on Nanomaterials, Editors, H. Dosch and M.H. Van de Voorde, Max-Plank-Institut für Metallforschung, Stuttgart, Germany, February, 2009.
[2] http://www.epubbud.com/read.php?g=J778ZEU2&p=8

15.1. Amorphous Materials

Amorphous metal is an emerging new class of structural materials that have found diverse applications such as those shown in **Figure 15.1-1**.

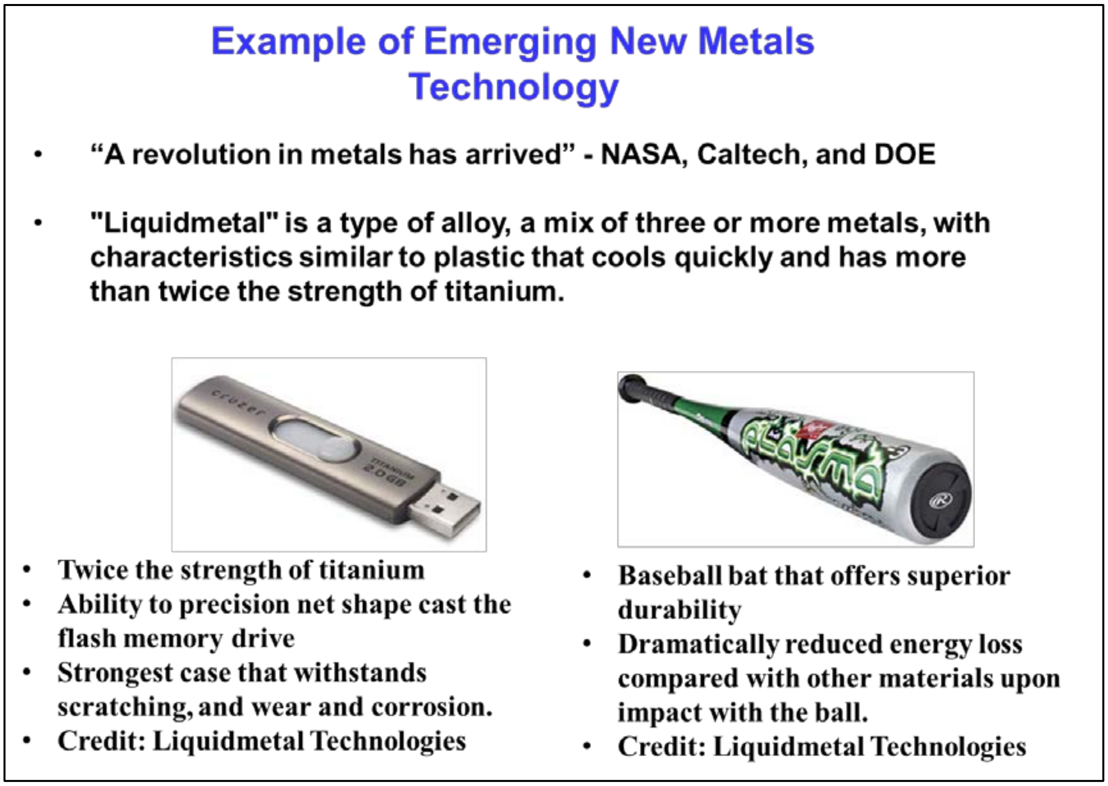


Figure 15.1-1: Example of Emerging New Metals Technology.

An amorphous metal is a metallic material with a disordered atomic-scale structure (**Figure 15.1-2**). These materials have a non-equilibrium microstructure. In contrast to most metals, which are crystalline and therefore have a highly ordered arrangement of atoms, amorphous alloys are non-crystalline.

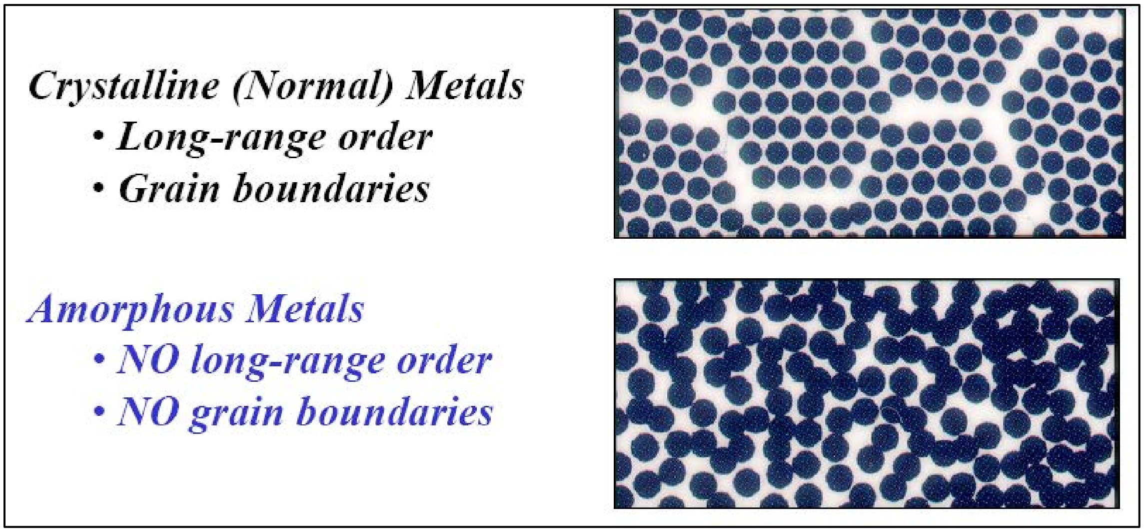


Figure 15.1-2: Atomic Structure of Amorphous Metals and Crystalline Structure of Normal Metals.

Nonetheless, the systems have metallic conductivity, whereas the usual glasses, i.e., window-glasses etc., would be isolating. Materials in which such a disordered structure is produced directly from the liquid state during cooling are called “glasses,” even if they have metallic conductivity, and so amorphous alloys with metals as basic ingredients are commonly referred to as “metallic glasses” or “glassy metals.” However, there are several ways besides extremely rapid cooling in which amorphous metals can be produced, including physical vapor deposition, solid-state reaction, ion irradiation, and mechanical alloying. Some scientists do not consider amorphous metals produced by these techniques to be glasses; however, materials scientists commonly consider amorphous alloys to be a single class of materials, regardless of how they are prepared.

Amorphous metal is usually an alloy rather than a pure metal. The alloys contain atoms of significantly different sizes, leading to low free volume (and therefore up to orders of magnitude higher viscosity than other metals and alloys) in molten state. The viscosity prevents the atoms moving enough to form an ordered lattice. The material structure also results in low shrinkage during cooling, and resistance to plastic deformation. The absence of grain boundaries, the weak spots of crystalline materials, leads to better resistance to wear and corrosion. Amorphous metals, while technically glasses, are also much tougher and less brittle than oxide glasses and ceramics.

Amorphous metals exhibit unique properties, as shown in **Figure 15.1-1** and **Figure** 15.1-3. Conventional metals exhibit long range order and have grain boundaries. Amorphous metals exhibit no long range order and have no grain boundaries. In crystalline metals, the atoms are arranged on atomic planes in a crystalline structure, but, in amorphous metals, there is a random arrangement of atoms. In conventional metals, the intersection of grains (grain boundaries) can be considered as “amorphous.” Volume fraction of grain boundaries ranges from zero for single crystals to very large for nano crystalline metals.

Figure 15.1-3 shows some representative properties of amorphous steel compared with some typical crystalline steels.[1] In addition to having attractive hardness, strength, and fracture toughness properties, they also have very attractive dynamic toughness, as shown in **Figure 15.1-4**. This behavior makes amorphous metals attractive candidates for armor applications on military vehicles. They also exhibit good corrosion resistance, high wear-resistance, unique acoustical properties, low melting temperature, net-shape casting, and fabrication process similar to plastics and are non-magnetic. Because of this combination of properties, DARPA has been sponsoring research on these materials for military applications. These materials are of high interest for kinetic energy penetrator (KEP) rods. The KEP, the key component of the highly effective armor piercing ammunition system, currently utilizes depleted uranium (DU) because of its density and self-sharpening behavior. Ballistic tests conducted by the Army have proven that the amorphous metal composites exhibit self-sharpening similar to the DU KEP, but are environmentally benign, unlike KEP rods. These alloys are also of interest for missile components, fins, nosecones, gimbals, and bodies.

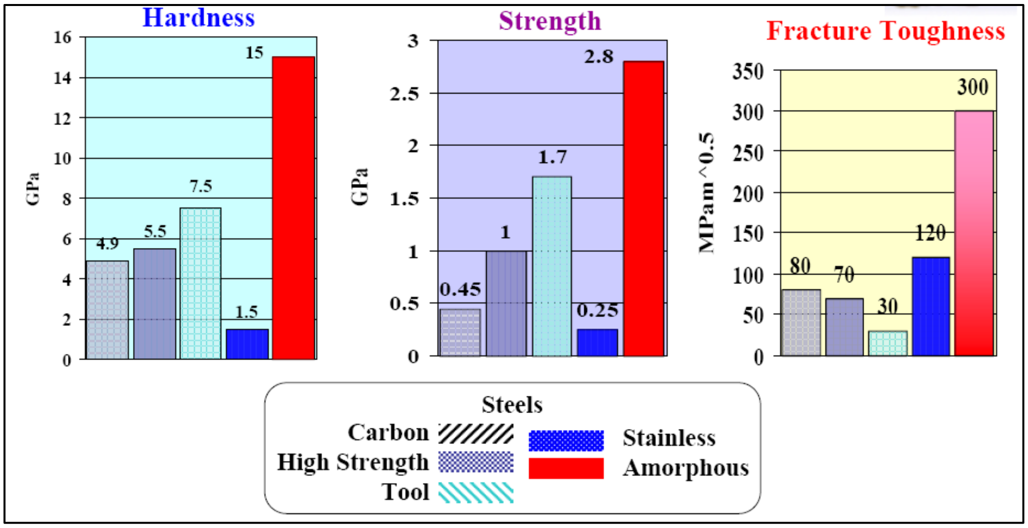


Figure 15.1-3: Typical Properties of Amorphous Metals Compared to Conventional Alloys.

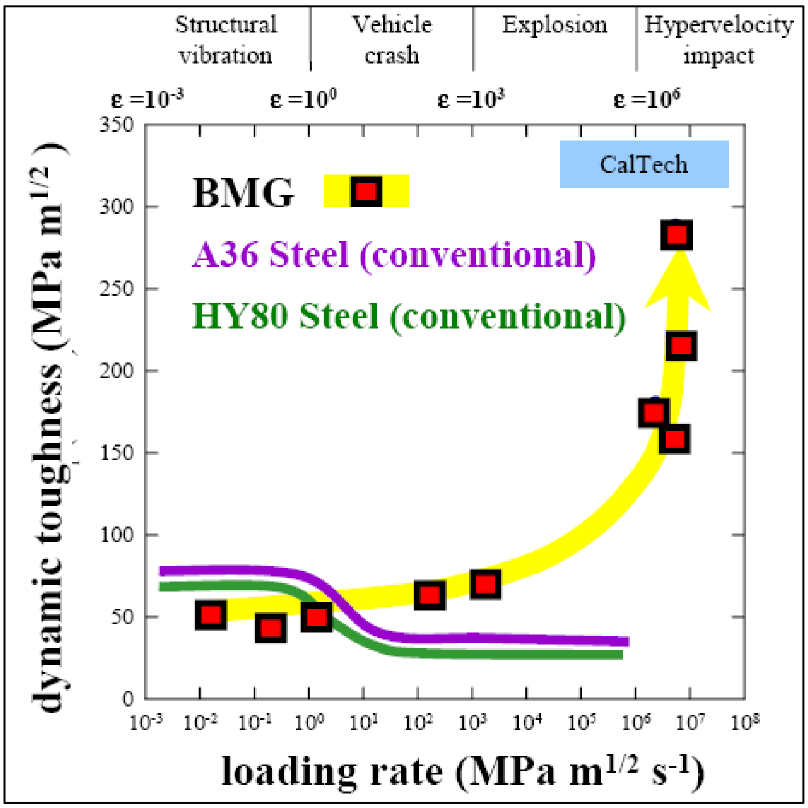


Figure 15.1-4: Dynamic Toughness of Amorphous Steel Compared with Conventional Steels.

These materials are also attractive for sports and high-performance products. An amorphous metal golf club head is shown in **Figure 15.1-5**. Liquidmetal also has a visible point of difference with scratch resistant surface finishes that can be satin blasted, highly polished, or molded with intricate designs and shapes not possible with other materials. This is truly a design-engineers' dream to be able to create the most innovative, unique, and exciting designs that out-perform other popular high-performance metal.

Figure 15.1-5: High Performance Sporting Goods Made From Amorphous Metals.

An attractive property of amorphous metals is the ability to exploit near-net-shape processing characteristics for the fabrication of highly sophisticated and complex structures while eliminating most secondary machining and processing. Although, metallic glasses provide very high strengths and other impressive properties, their weak link is damage tolerance and producibility. Getting the massive cooling rates needed to stop crystallization during solidification isn't practical at a large scale, and introducing secondary particles or phases in the glass to get around brittleness is easier said than done.

Like metallic glasses, getting a high-strength nanoscale crystalline metal is limited by practical considerations for the various production routes such as the solidification cooling rate, the massive pressures needed to deform and refine the metal structure, or getting a near-perfect consolidation of nano-dimensioned powdered metals and the high cost of powder production. Getting a second toughening phase into these nanostructured metals, which is needed to match the durability and damage tolerance of traditional metals, proves challenging as well.

Bulk metallic glasses and exotic nanostructured metals have the potential to provide increases in both strength and damage tolerance, but scaling production seems to be a major roadblock. It's a roadblock, though, that researchers may be able clear with explosives. A new paper describes how a clever manipulation of thermodynamics and solidification theory, along with a healthy dose of explosive chemistry, can produce a nanostructured alloy with a truly impressive mix of properties.

As noted above BMGs typically display more than double the yield strength and up to four times the elastic limit compared to their crystalline counterparts. However, due to the lack of crystal structure, deformation by dislocation movement is not possible and monolithic samples fail on a single or few shear bands, leading to a brittle fracture behavior. This has hindered the technological breakthrough of these alloys as a structural material. A major research challenge for these materials is to improve the plastic strain of BMGs and further tailor their mechanical and tribological properties.

One approach for increasing the plasticity and, in general, tailoring the mechanical properties of BMGs is the development of foreign-particle-reinforced composites. The reinforcement particles interact with the shear bands, arresting them and also aid the initiation of multiple shear bands due to local stress concentrations in the material. This allows deformation on multiple shear bands leading to a significant increase in plastic strain because the deformation energy is distributed over more sample volume. Such composites can be produced either by means of melt processing or powder consolidation.

Graphite-reinforced Vit 105 was developed by Marco E. Siegrist and Prof. Dr. Jörg F. Löffier[2] with the aim of increasing the plastic strain of the amorphous alloy. Vit 105 powder was produced by mechanical amorphization of crystalline pre-alloys. These composites, produced by melt processing, were shown to display a maximal plastic strain of up to 18.5% combined with yield strength of 1.85 GPa. This is perhaps the highest combination of yield strength and plasticity ever reported for foreign-particle reinforced BMGs. Further, the mechanical properties of theses composites can be tailored by transforming part of the graphite to ZrC during processing. Higher carbide content leads to an increase in hardness accompanied by a decrease in plasticity of the composite.

The graphite-reinforced composites also display very interesting microtribological properties. Graphite, with its self-lubricating properties and ZrC reinforcement, leads to a significant decrease of the coefficient of friction of the glassy alloy when paired against bearing steel.

In the past, small batches of amorphous metals have been produced through a variety of quick-cooling methods. For instance, amorphous metal wires have been produced by sputtering molten metal onto a spinning metal disk (melt spinning). (**Figure 15.1-6**). The rapid cooling, on the order of millions of degrees a second, is too fast for crystals to form and the material is "locked in" a glassy state.

Figure 15.1-6: Melt Spinning to Produce Metallic Glass.

More recently, a number of alloys with critical cooling rates low enough to allow formation of amorphous structure in thick layers (over 1 millimeter) had been produced; these are known as bulk metallic glasses (BMG). Liquidmetal sells a number of titanium-based BMGs, developed in studies originally carried out at Caltech. More recently, batches of amorphous steel have been produced that demonstrate strengths much greater than conventional steel alloys.

Liquidmetal and Vitreloy are commercial names of a series of amorphous metal alloys developed by a California Institute of Technology research team, now marketed by a firm that the team organized called Liquidmetal Technologies. Despite the name, they are not liquid, but solid at room temperature, and the maker claims they are hard-wearing and withstand thermal cycling. Liquidmetal alloys combine a number of desirable material features, including high tensile strength, excellent corrosion resistance, very high coefficient of restitution, and excellent anti-wearing characteristics, while also being able to be heat-formed in processes similar to thermoplastics. Liquidmetal was introduced for commercial applications in 2003. It is used for, among other things, golf clubs, watches, and covers of cell phones.

Thermal conductivity of amorphous materials is lower than that of crystals. As formation of amorphous structure relies on fast cooling, this limits the maximum achievable thickness of amorphous structures.

To achieve formation of amorphous structure, even during slower cooling, the alloy has to be made of three or more components, leading to complex crystal units with higher potential energy and lower chance of formation. The atomic radius of the components has to be significantly different (over 12%), to achieve high packing density and low free volume. The combination of components should have negative heat of mixing, inhibiting crystal nucleation and prolonging the time the molten metal stays in supercooled state.

The alloys of boron, silicon, phosphorus, and other glass formers with magnetic metals (iron, cobalt, or nickel) are magnetic with low coercivity and high electrical resistance. The high resistance leads to low losses by eddy currents when subjected to alternating magnetic fields, a property useful for transformer magnetic cores.

15.1.1. Properties and Applications of Metallic Glasses

Comparisons of properties published by Liquidmetal Technologies[3] are shown in **Figure 15.1-1** and **Table 15.1-2**. The properties of a liquidmetal alloy produced by Liquidmetal Technologies are compared with magnesium AZ-91, aluminum 380-series alloy, titanium Ti-6Al-4V, and stainless 17-4 PH condition H 1150 steel. Liquidmetal's main production alloy is a Zr/Ti based alloy ($Zr_{47}Ti_8Cu_8Ni_{10}Be_{27}$). Joining these alloys is an area that requires additional work. Laserwelding and electron beam welding are technically possible with some materials, however, welding or soldering are not certified production processes at this point in the development of this class of materials.

Table 15.1-1: Comparison of Mechanical and Physical Properties

	Mechanical and Physical Properties				
	Liquidmetal® Alloy	Mg AZ-91	Al 380 Series	Ti 6Al-4V	Stainless 17-4
Yield Strength, σ_y *ksi* *(MPa)*	**270 (1900)**	22 (150)	23 (159)	115 (790)	126 (870)
Hardness *Vickers*	**550**	71	100	340	325
Density, ρ *lb/in³* *(g/cm³)*	**0.222 (6.1)**	0.065 (1.8)	0.099 (2.8)	0.160 (4.4)	0.283 (7.8)
Impact Strength *ft-lb* *(J)*	**5.9 (8)**	1.9 (2.7)	3.0 (4)	17.7 (24)	55.3 (75)
Elasticity, e *(% of Original Shape)*	**2.00%**	0.35%	0.10%	0.69%	0.44%
Young's Modulus, E *Msi* *(GPa)*	**13.5 (93)**	6.5 (45)	10 (71)	16.5 (114)	28.6 (198)
Specific Strength, σ/ρ *ksi* *(MPa)*	**45 (311)**	13 (83)	8 (58)	26 (178)	16 (111)
Poisson's Ratio, ν	**0.39**	0.35	0.33	0.34	0.27

Table 15.1-2: Comparison of Electrical and Thermal Properties

	Electrical and Thermal Properties				
	Liquidmetal® Alloy	Mg AZ-91	Al 380 Series	Ti 6Al-4V	Stainless 17-4
Heat Capacity, cp *BTU/lb°F* *(J/Kg°K)*	**0.10 (420)**	0.25 (1050)	0.23 (963)	0.13 (526)	0.10 (419)
Thermal Expansion, α *µin/in°F* *(µm/m°K)*	**5.5 (10.1)**	14.0 (26.0)	12.0 (21.2)	4.8 (8.6)	6.7 (12.0)
Thermal Conductivity, k *BTU/ft hr°F* *(W/m°K)*	**3.5 (6)**	42.1 (73)	62.9 (109)	3.8 (7)	10.3 (18)
Electrical Resistivity, R *µ Ω in* *(µ Ω cm)*	**75 (190)**	6.7 (17)	2.5 (6.4)	70 (178)	30.3 (77)

The lack of long-range periodicity in metallic glasses precludes the plastic deformation mechanisms that are operative in crystalline materials. The mechanical properties of metallic glasses are characterized by a large elastic limit of about 2%—compared with about 0.2% for crystalline metallic materials—and yield strength values that are about 1.5 to twice those of their crystalline counterparts. For example, tensile strength levels were reported for Al-based metallic glasses of up to 1500 MPa compared to about 750 MPa for the strongest crystalline Al alloys. Co-based bulk metallic glasses were measured with yield strengths of about 5 GPa. These strength levels, however, only occur in compression. In tension, much lower strength levels are observed. The lack of tensile strength follows from the deformation mechanism of metallic glasses that is based on shear bands. During deformation at room temperature, metallic glasses slide internally along bands with thicknesses of about 10–20 nm that can propagate through the entire sample if they are not impeded, for example, by precipitates. The challenge will remain for the foreseeable future to design metallic glasses with improved ductility but without loss in strength and elastic limit.[4] **Figure 15.1-7** shows the elastic limit against density for different metals, alloys, metal matrix composites, and metallic glasses.[5] **Figure 15.1-8** shows Fracture toughness and Young's modulus for metals, alloys, ceramic, glasses, polymers, and metallic glasses. The contours show the toughness Gc in kJ m–2.[6]

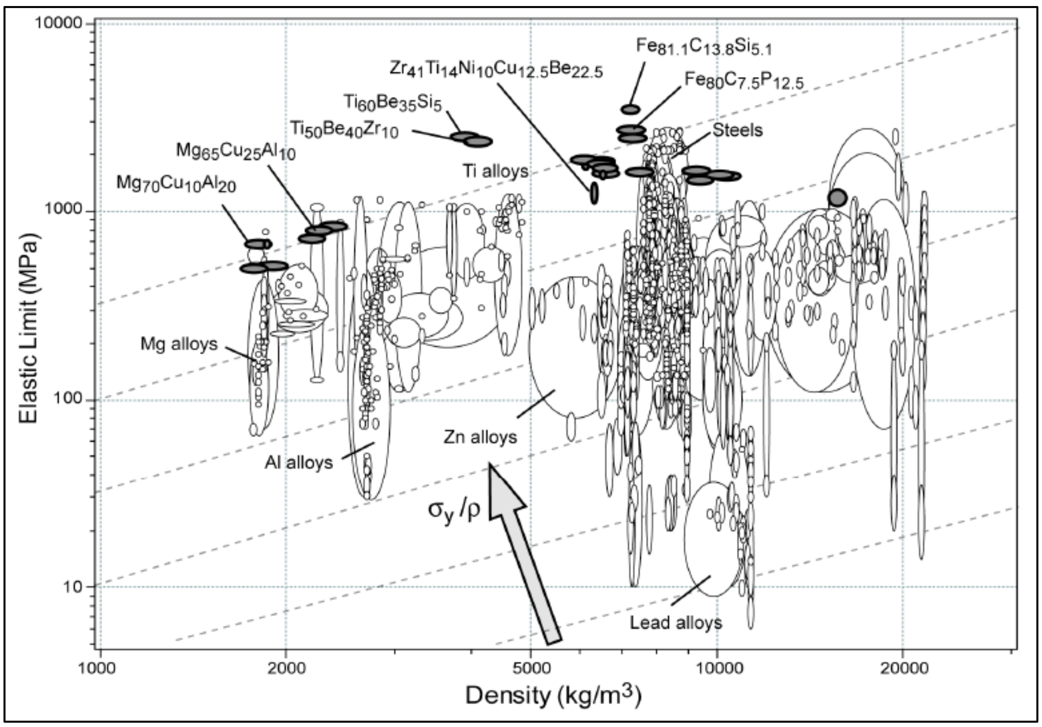


Figure 15.1-7: Properties of Selected Metallic Glasses (M.F. Ashby & A.L. Greer: Scripta Materialia 54 (2006) 321. (Viewpoint set on Mechanical Behavior of Metallic Glasses, edited by T.C. Hufnagel).

Amorphous alloys have a variety of potentially useful properties. In particular, they tend to be stronger than crystalline alloys of similar chemical composition, and they can sustain larger reversible ("elastic") deformations than crystalline alloys. Amorphous metals derive their strength directly from their non-crystalline structure, which does not have any of the defects (such as dislocations) that limit the strength of crystalline alloys. One modern amorphous metal, known as Vitreloy, has a tensile strength that is almost twice that of high-grade titanium. However, metallic glasses at room temperature are not ductile and tend to fail suddenly when loaded in tension, which limits the material applicability in reliability-critical applications, as the impending failure is not evident. Therefore, there is considerable interest in producing metal matrix composite materials consisting of a metallic glass matrix containing dendritic particles or fibers of a ductile crystalline metal.

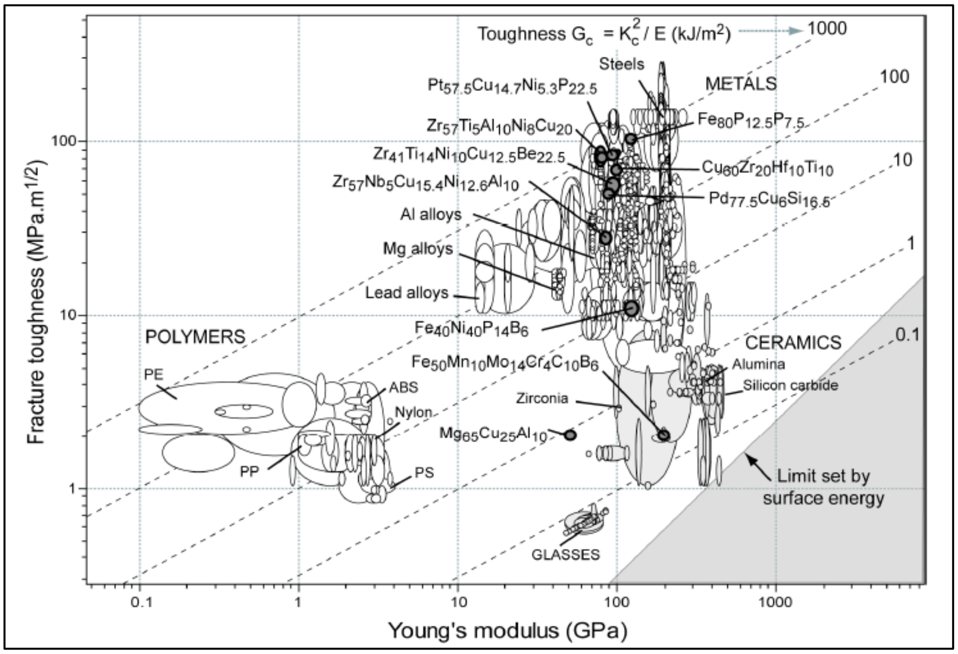


Figure 15.1-8: Fracture Toughness and Young's Modulus for Metals, Alloys, Ceramic, Glasses, Polymers and Metallic Glasses. The contours show the toughness Gc in kJ m–2. http://www.admin.cam.ac.uk/offices/research/documents/local/events/downloads/mh/1.1_Greer.pdf.

Although at high temperatures, plastic deformation occurs easily, almost none occurs at temperature before onset of catastrophic failure. The material is also susceptible to metal fatigue with crack growth; a two-phase composite structure with amorphous matrix and a ductile dendritic crystalline-phase reinforcement, or a metal matrix composite reinforced with fibers of other material can reduce or eliminate this disadvantage.

Perhaps the most useful property of bulk amorphous alloys is that they are true glasses, which means that they soften and flow upon heating. This allows for easy processing, such as by injection molding, in much the same way as polymers. As a result, amorphous alloys have been commercialized for use in sports equipment, medical devices, and as cases for electronic equipment.

Metallic glasses differ greatly in their solute content compared with engineering alloys. The solute content in metallic glasses is typically on the order of tens of percent and thus far exceeds the solute content of conventional engineering alloys. At the same time, fully amorphous alloys are homogeneous. The combination of homogeneity, lack of grain boundaries, and concentrated solute content can play out very favorably for corrosion properties.

The unique properties of metallic glasses appeal to a range of applications. Structural applications include sporting goods such as baseball bats or tennis rackets, where metallic glasses excel with their high-elastic limits, micro-meter sized gears and springs that reveal exceptional wear resistance, biomedical applications such as tooth implants, or casings for electronic devices. Metallic glasses have been used since the late 1960s for magnetic applications, for example, as transformer core materials. With an ever expanding range of glass-forming systems, processing improvements, and a better understanding of fundamental properties the number of applications continues to increase. Once thought of as a lab curiosity, metallic glasses have come a long way, but still provide ample opportunities for new discoveries.

Thin films of amorphous metals can be deposited via high velocity oxygen fuel technique as protective coatings.

References

[1]http://archive.darpa.mil/DARPATech2000/Presentations/dso_pdf/5ChristodoulouSAMB&W.pdf

[2] http://e-collection.library.ethz.ch/eserv/eth:29366/eth-29366-02.pdf

[3] http://www.liquidmetal.com/userfiles/file/Prop-Comparison9803.pdf

[4] http://www.azom.com/article.aspx?ArticleID=5566

[5]http://www.admin.cam.ac.uk/offices/research/documents/local/events/downloads/mh/1.1_Greer.pdf

[6] M.F. Ashby & A.L. Greer; *Scripta Materialia* **54** (2006) 321. (Viewpoint Set on *Mechanical Behavior of Metallic Glasses*, edited by T.C. Hufnagel)

15.2. Metallic Foams

Metallic foams create a relatively new class of structural materials possessing enormous application potential in lightweight construction. Highly porous metallic foams by themselves or as the cores of ultralight metal structures have significant practical interest because of unique combinations of properties.[1] As noted in the paper by Sypeck et al.,[2] the properties can include high energy absorption and acoustic damping during impact, high electrical conductivity and electromagnetic shielding capability, as well as good thermal insulating and fire resistance potential. Common fluids like air and oil readily permeate foams having open cells, while aluminum foams having closed cells exhibit enhanced corrosion resistance and are buoyant in water. Furthermore, when used as the cores of tubes, sandwich plates and shells, the excellent specific stiffness and damage tolerance of such members allows for the construction of efficient load bearing structures with considerable shakedown potential.[2] Aluminum foams[3] have also been utilized in the automobile industry for their crashworthy properties. Nickel foams have been used to improve the performance in high-power batteries. Foam-based nickel metal hydride batteries currently compete with the more expensive lithium ion batteries for lightweight cordless electronics.[4]

The development of metallic foams and cellular structures were driven by the desire for greater performance. Features in metallic foams and cellular structures consist of metallic areas and open spaces, i.e., holes. Fleck, Deshpande, and Ashby have reviewed the current and future micro-architecture of these materials.[5] They state that one approach to filling voids in material property space is that of manipulating chemistry, developing new metal alloys, new polymer formulations and new compositions of glass and ceramic, which extends the populated areas of the Ashby property charts. A second is that of manipulating microstructure, using thermomechanical processing to control the distribution of phases and defects within materials. Both have been exploited systematically, leaving little room for further gains, which tend to be incremental rather than step like. A third approach is that of controlling architecture to create hybrid materials—combinations of materials or of material and space in configurations and with connectivities that offer enhanced performance. The success of carbon and glass-fiber-reinforced composites at one extreme, and that of foamed materials at another, in filling previously empty areas of the property charts is encouragement enough to explore this route in greater depth.

There are many methods for manufacturing foams and cellular metals and the various processes have been covered in an extensive review by Wadley from which the following is taken.[6] These foams and cellular materials are normally classified by the size of the cells, the cell type (open or closed), and the relative density of the structure. **Figure 15.2-1** summarizes the range of cell size and relative density for many of the manufacturing methods. Manufacturing methods based upon the foaming of a liquid metal either by injecting a gas (the CYMAT process) or by the decomposition of gas releasing particles (e.g., the Alporus or Alulight materials) are the most widely used processes for the manufacture of cellular metals. Both result in closed cell foams with cell sizes in the 0.5 to 15 mm range and relative densities of 0.04–0.4. Significant efforts are also being directed at the development of processes based upon the consolidation of hollow spheres and the infiltration of metals into sacrificial (e.g., water soluble salt) spheroidal particle aggregates.[6] Metals and alloys can also be foamed in the solid state by entrapping gas within the intraparticle voids during powder consolidation. If this is followed by heating, the gas pressure within the voids increases, and when it exceeds the resistance to plastic flow, the component expands by either plasticity or creep. The low density core (LDC) process for Ti-6Al-4V is an example of such a solid-state foaming process.[7] The manufacturing routs are summarized in **Figure 15.2-2** together with the names of the products associated with each.[4]

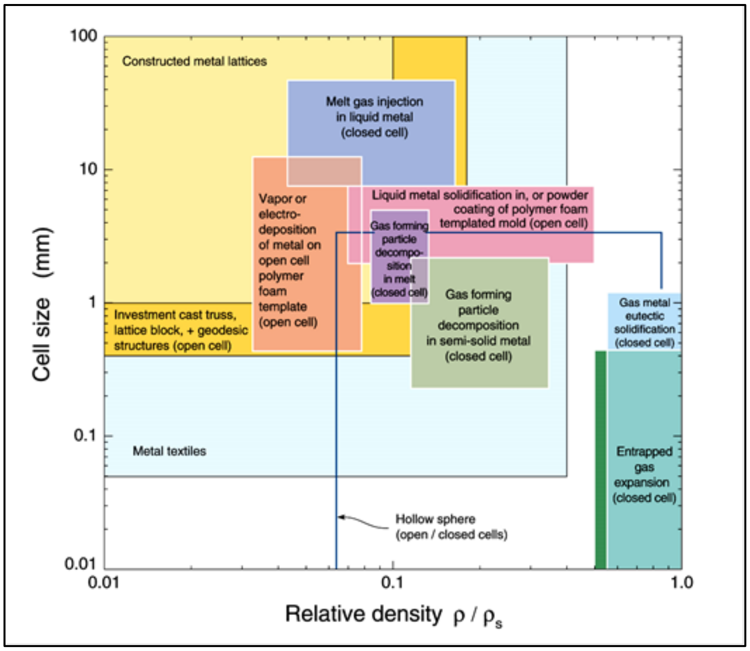


Figure 15.2-1: Many cellular metal manufacturing processes have been developed. Each covers a part of the cell-size relative density space. Figure courtesy of Haydn Wadley.

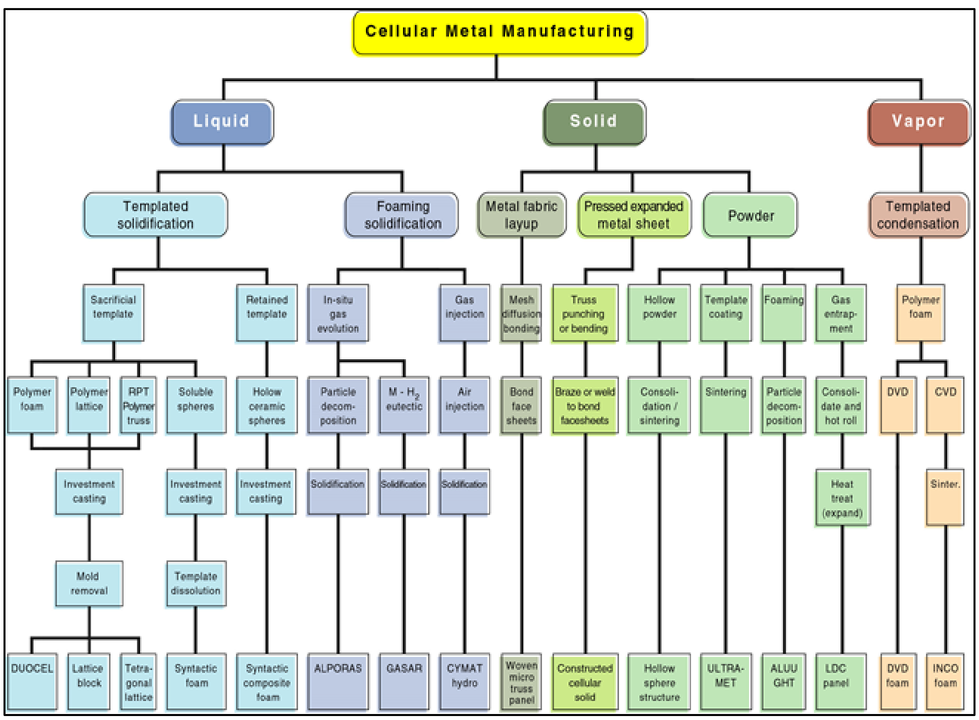


Figure 15.2-2: A Taxonomy of Cellular Metal Manufacturing Processes. They exploit liquid solid and vapor phase processing routes. Courtesy of Haydn Wadley.

The properties, and therefore potential applications, of cellular metals and foams are usually a sensitive function of relative density, cell type (open/closed), and cell size distribution. Applications for acoustic damping, catalyst support and perhaps impact energy absorption are well served by stochastic materials. **Figure 15.2-3** gives a comparison of the mechanical properties of a variety of cellular metals as a function of relative density. Applications where load support or thermal management dominates are optimized by a periodic truss structure. However, as Wadley has pointed out, it is not yet clear if the increased cost of the periodic cellular manufacturing process under development today can be compensated for by the reduction in weight. Also, ongoing improvements in foaming processes may, overtime, reduce the discrepancies in performance and further lessen the impact of the periodic materials.[6] A review on this topic can be found in the publication by Ashby et al.[8]

Cellular structures may be useful for many NASA aerospace applications, including low-density paneling and shields. Although conventional cellular structures exhibit high specific strength, their porous structures make them challenging to fabricate. In particular, metal cellular structures are extremely difficult to fabricate due to their high processing temperatures. Aluminum honeycomb sandwich panels, for example, are used widely as spacecraft shields due to their low density and ease of fabrication, but suffer from low strength. A desirable metal cellular structure is one with high strength, combined with low density and simple fabrication.

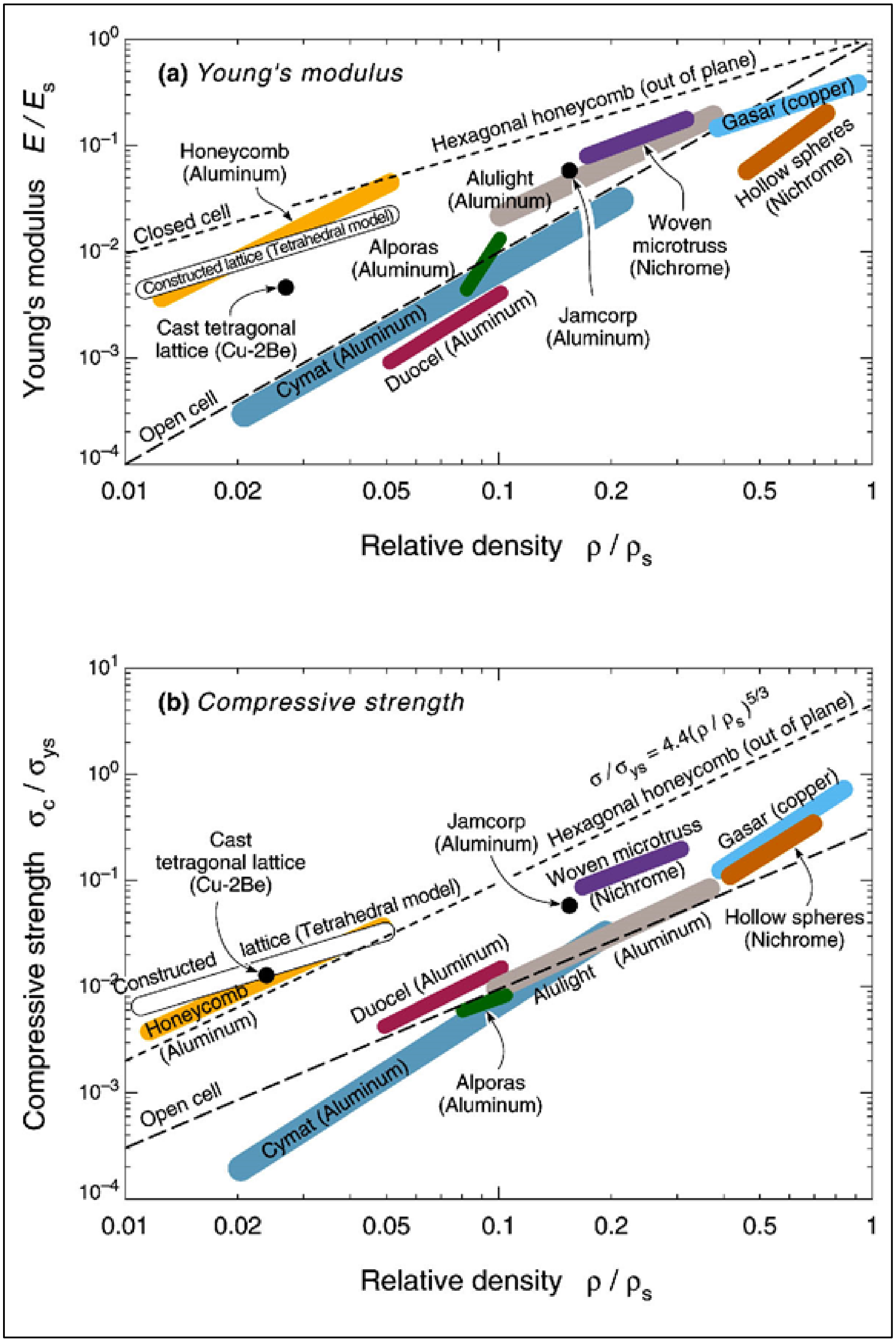


Figure 15.2-3: A Comparison of the Mechanical Properties of Cellular Metals. At low relative density, periodic systems have superior properties to their stochastic counterparts. The differences can be large. At 2% relative density a tetrahedral cored material can be as much as 30 times stronger than a closed cell stochastic foam.
Figure courtesy of Haydn Wadley.

New product forms, such as those shown in **Figure 15.2-4**,[9,10] are emerging that offer some unique characteristics for aerospace applications. One potential new application for metallic foams is in future space habitat cabins, such as the Nautilus-X (**Figure 15.2-5**).[11] For the past 50 years, the protection of manned spacecraft against micrometeoroids and orbital debris (MMOD) has, for the most part, been performed by the Whipple shield or derivatives thereof. Although highly capable, the installation of Whipple-based shielding configurations requires a significant amount of non-ballistic mass for installation (e.g., stiffeners, fasteners, etc.) that can consume up to 35% of the total shielding mass. As NASA's vehicle design focus shifts from large pressurized modules operating for extended durations in relatively debris-polluted low-Earth orbits, to small-volume lower-duration craft, new protective concepts are being designed and evaluated to address the new threats.[12] The performance of a dual-wall protective spacecraft structure against the impact of MMOD particles is generally considered to be degraded by the presence of a honeycomb core. For impacts that penetrate the shield outer wall (bumper or front face sheet), fragmented projectile and bumper fragments disperse radially as they propagate through the shield interior, distributing the load over an area that is significantly larger than that of the original projectile diameter. The presence of honeycomb cell walls acts to restrict expansion, effectively channeling the fragments within a limited number of honeycomb cells for a more concentrated impact on the rear face sheet. However, mission requirements often prevent the inclusion of a dedicated MMOD shielding structure, and, as such, structural panels (i.e., honeycomb sandwich panels) also commonly serve as the protective system.

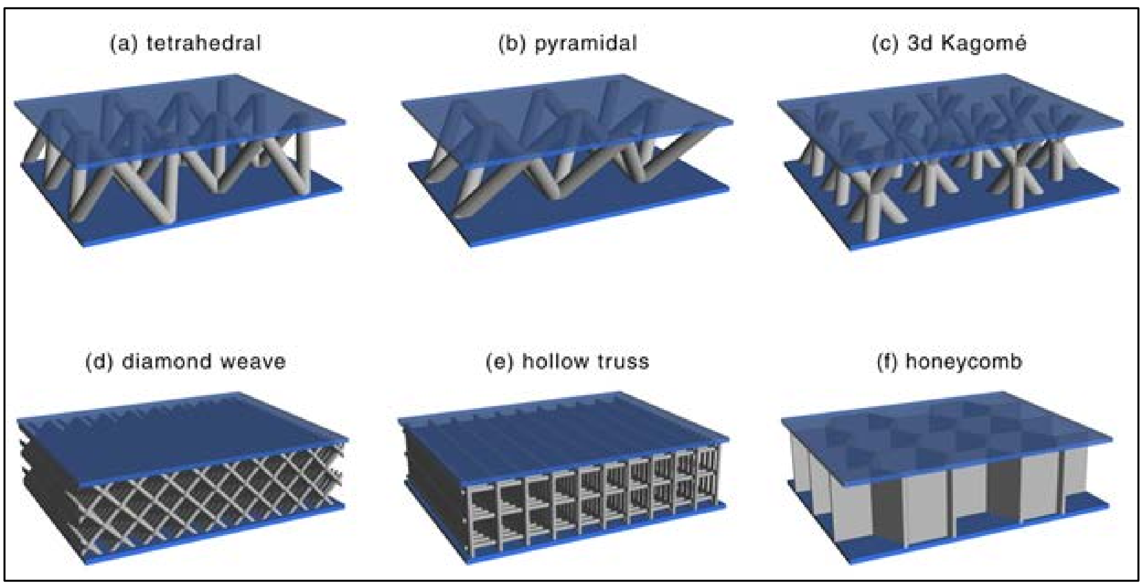


Figure 15.2-4: Schematic Illustrations of Several Lattice Topologies: (a) Tetrahedral, (b) Pyramidal, (c) 3D Kagome, (d) Diamond Weave, (e) Hollow Truss and (f) Egg Box. Figure Provided by Haydn Wadley.

Figure 15.2-5: Artist Concept of Multi-Mission Space Exploration Vehicle.

Metallic foams are a promising alternative to honeycomb structures as they offer comparable structural and thermal performance without the presence of MMOD shielding-detrimental channeling cells. In a recent paper by Ryan, Hedman, and Christiansen[13] hypervelocity impact tests on the double-layer honeycomb and double-layer foam configurations showed that for comparable mechanical and thermal performance, the foam modifications provided a 15% improvement in critical projectile diameter at low velocities (i.e., 3 km/s) and a 3% increase at high velocities (i.e., 7 km/s) for normal impact. With increasing obliquity, the performance enhancement was predicted to increase, up to a 29% improvement at 60º (low velocity). Ballistic limit equations have been developed for the new configuration, and consider the mass of each individual shield component to maintain validity in the event of minor configuration modifications. Previously identified weaknesses of open cell foams for hypervelocity impact shielding such as large projectile diameters, low velocities, and high degrees of impact obliquity have all been investigated and found to be negligible for the double-layer configuration. **Figure 15.2-6** shows a comparison of the damage to a honeycomb core and an open-cell foam core.[12]

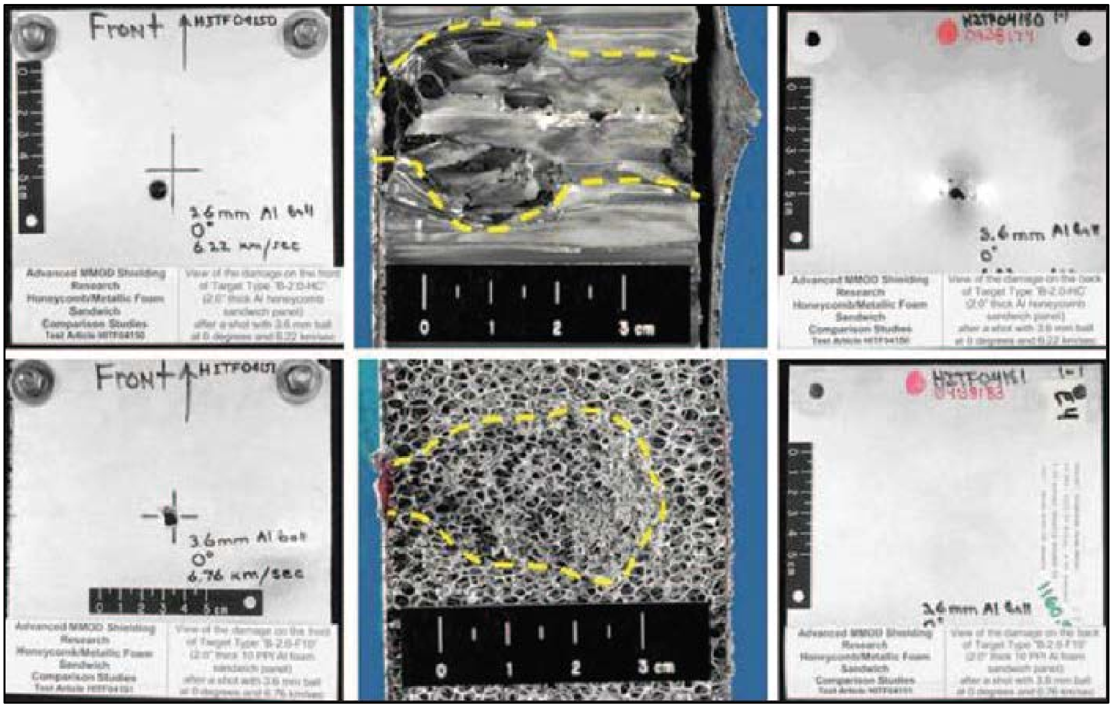


Figure 15.2-6: Comparison of Damages in a Honeycomb Core (Top) and Open-Cell Foam Core (Bottom) Sandwich Panel Impacted by 3.6 mm Diameter Aluminum Spheres at 6.22 km/s (Honeycomb) and 6.76 km/s (Foam) With Normal Incidence (0°). From Left to Right: Bumper (Front View); Core Cross Section (Emphasis Added); and Rear Wall (Rear View).

Researchers at NASA Langley have also evaluated metallic foams [14] for thermal protection systems (TPS) for aerospace applications. Metallic foam has been considered as the insulating material of the TPS on reusable launch vehicles. Another application is to use the metallic foam as part of an integrated structure that serves as the launch vehicle's primary structure and thermal protection system. The metallic nickel foam used in this study was commercially available. It was manufactured in bulk for use in a variety of applications. In the manufacturing process, polyurethane foam is used as a template. A proprietary chemical vapor decomposition process coats the surface of the template with nickel. The material is annealed at around 1800°C, causing evaporation of the polyurethane core. The authors measured the effective thermal conductivity of high-porosity, open-cell nickel foam samples over a wide range of temperatures and pressures using a standard steady-state technique. They also developed a numerical model to predict the behavior of the effective thermal conductivity at various temperatures and pressures.

Revolutionary materials and structures are high-payoff research areas for NASA to continue funding. A unified approach of basic research and synthesis of new metallic material product forms (e.g., porous and direct deposited metals) should be pursued in order to establish processing-structure-property correlations, in order to develop design methodology using physical models that link structural function with material characteristics, and to conduct environmental durability studies under extreme environment conditions expected during vehicle service life.

References

[1] L.J. Gibson and M.F. Ashby; "Cellular Solids Structure and Properties – Second Edition", Cambridge University Press, Cambridge, 1997.

[2] David J. Sypeck, Haydn N.G. Wadley, Hilary Bart-Smith, Stephan Koehler and Anthony G. Evans; "Structure and Deformation of Aluminum Foams Through Computed Tomography", Review of Progress in Quantitative Nondestructive Evaluation, Vol. 17, Edited by D.O. Thompson and D.E. Chimenti, Plenum Press, New York, 1998, pp. 1443–1450.

[3] Fuganti, A., Lorenzi, L., Hanssen, A. G. and Langseth, M.; "Aluminum Foams for Automotive Applications Metal Foams and Porous Metal Structures", ed. by Banhart, J., Ashby, M.F., and Fleck, N.A., Verlag MIT Publishing, 1999.

[4] Ettel, V.A.; "New Inco Powders and Foams for Nickel Batteries", NiCad 98, Prague, Sept. 21–22, 1998.

[5] N.A. Fleck, V.S. Deshpande and M.F. Ashby; "Micro-architectured materials: past, present and future", Proceedings of The Royal Society A; Mathematical Physical and Engineering Sciences, Vol. 466, June 2010.

[6] H.N.G. Wadley; "Cellular metals manufacturing: an overview of stochastic and periodic concepts", in Cellular Metals and Metals Forming Technology (Metform 2001) Editors J. Barnhard, M.F. Ashby and N.A. Fleck, MIT-Verlag, Bremen; pp. 137–146. Also in Advanced Engineering Materials, Vol. 4, No. 10, 2002, pp. 726–733.

[7] D.M. Elzey and H.N.G. Wadley; "The Limits of Solid State Foaming", Acta Mater. Vol. 49, 2001, pp. 849–859.

[8] M.F. Ashby, A.G. Evans, N.A. Fleck, L.J. Gipson, J.W. Hutchinson, and H.N.G. Wadley; "Metal Foams: A Design Guide", Butterworth-Heinemann, Woburn, MA (2000).

[9] Haydn N.G. Wadley, Norman A. Fleck and Anothony G. Evans; "Fabrication and structural performance of periodic cellular metal sandwich structures", Composites Science and Technology, Vol. 63, 2003, pp. 2331–2343.

[10] Douglas T. Queheillalt and Haydn N.G. Wadley; "Hollow pyramidal lattice truss structures" , Int. Mat. Res. (formerly /z. Metallkunde) Vol. 102, 2011, p. 389.

[11] Edward M. Hendersan and Mark L. Holderman; "Technology Applications that Support Space Exploration", 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 31 July–3 August 2011, San Diego, California.

[12] Shannon Ryan, Eric L. Christiansen and Dana Lear; "Shielding Against Micrometeoroid and Orbital Debris Impact with Metallic Foams", NASA, Space and Ground Operations, pp. 267–269.

[13] Shannon Ryan, Troy Hedman and Eric L. Christiansen; "Honeycomb vs. Foam: Evaluating a potential Upgrade to International Space Station Module Shielding for Micrometeoroids and Orbital Debris", NASA/TM-2009-214793, September 2009.

[14] Daryabeigi, Kamran, and Sullins, Alan D.; "Effective Thermal Conductivity of High Porosity Open Cell Nickel Foam", AIAA 2001-281 9, 35 th. AIAA Thermophysics Conference, 11–14 June 2001, Anaheim, CA.

15.3. Ultra-Light Alloys (Advanced Al-Li and +)

A high-potential approach for alloy performance improvements over the past several years has been in the optimization of Al-Cu-Li-(Mg-Ag-Zn) alloys where every weight percent of lithium in the alloy results in a 3% reduction in density and a 6% increase in elastic modulus of the metal. This third generation of lithiu- bearing alloys has been developed as damage-tolerant variants of military and space metals in order to meet the demands of future commercial airframes. AA2198 and AA2050 are typical of these damage tolerance alloys. Material performance improvements are only part of the potential developments of metallic solutions for airframes, however, with gains of similar magnitude in component weight and cost achievable by applying new technologies and new design solutions to metallic structures.[1]

To continue to make advancements in lightweight air vehicle structures, it is essential material development, process, and product design be worked together as a whole. It is impossible to take action in one of these factors without the others being affected, or to optimize one in isolation. Nowhere is this more evident than at the interface between aluminum and carbon in hybrid composite/metallic structures.

The electrochemistry of the aluminum/carbon pairing is a detriment to hybrid structures; the difference in electronegativity between these two elements is sufficient to create a battery or, in the presence of an electrolyte, accelerated galvanic corrosion. However, the addition of lithium as an alloying element, itself well known as an electrochemically active material, provides lower corrosion potential through the formation of nanoscale dendritic microstructures. Because of these specific nanoparticulates, corrosion is mainly due to pitting and is intergranular in nature. By creating dendrites within the microstructure that are actually nanomaterials, and by looking at these alloys in a wider context than just corrosion, it has been possible to alter performance at two levels: at macro and nanoscales. In tests with these new alloys, some 30% improvement in corrosion potential is seen compared with standard 7000 series alloys. This eases an already tight situation in joint design but does not eliminate the corrosion problem for designers and aircraft operators. Additional R&D is needed to address this problem if the full potential of aluminum/CFRP hybrids is to be realized.

Having created the majority of aviation alloys flying today, Alcoa is developing and introducing next-generation products that continue to offer optimum solutions for manufacturability, weight savings, structural integrity, damage tolerance, corrosion resistance, and recyclability.

One focus at Alcoa has been on evolving a portfolio of new aluminum plate offerings for use in aircraft internal structures such as ribs, frames, and bulkheads. These products include two new 7XXX alloys: 7085-T7451, developed for very thick applications (4–7 inches), which provides significant improvements in both strength and toughness, with excellent corrosion resistance; and C85T-T7651/-T7451 plate, developed for a range of thicknesses (1–6 inches), with substantially higher strength with similar or better toughness over incumbent 7050 plate in a given temper. Among the company's third-generation aluminum-lithium alloys is Al-Li 2099 (also designated C460), which is tailored for extruded products in high-strength applications requiring low density, high stiffness, superior damage tolerance, excellent corrosion resistance, and weldability.

Alcoa has followed NASA Langley's lead in the development of integrally stiffened panels (ISP) for possible use of extruded ISPs for the wings and wing box of large commercial aircraft. As mentioned earlier in the section on near-net-shape manufacturing, using ISPs both the skin and the stiffeners are one continuous part made from the same piece of raw stock. As such, they are an effective method of producing high-strength, lightweight structures and are well suited for the highly loaded, long panels of a commercial aircraft wing.[2] Examples of extruded ISPs are shown in **Figure 15.3-1**.[2]

Figure 15.3-1: Extrudes ISPs Can Be Made in a Variety of Shapes, Thicknesses, and Widths. Straightness and Flatness Tolerances are Very Good After the Standard Stretching Operation. Figure Courtesy of Alcoa.

ISPs can be joined by high-quality friction stir welds, and panels can be formed by a variety of methods including age forming. Original equipment manufacturers (OEMs) can realize saving in assembly time and costs by capitalizing on these advanced manufacturing operations. An example of a curved, age-formed and friction-stir-welded IPS is shown in **Figure 15.3-2**.[2]

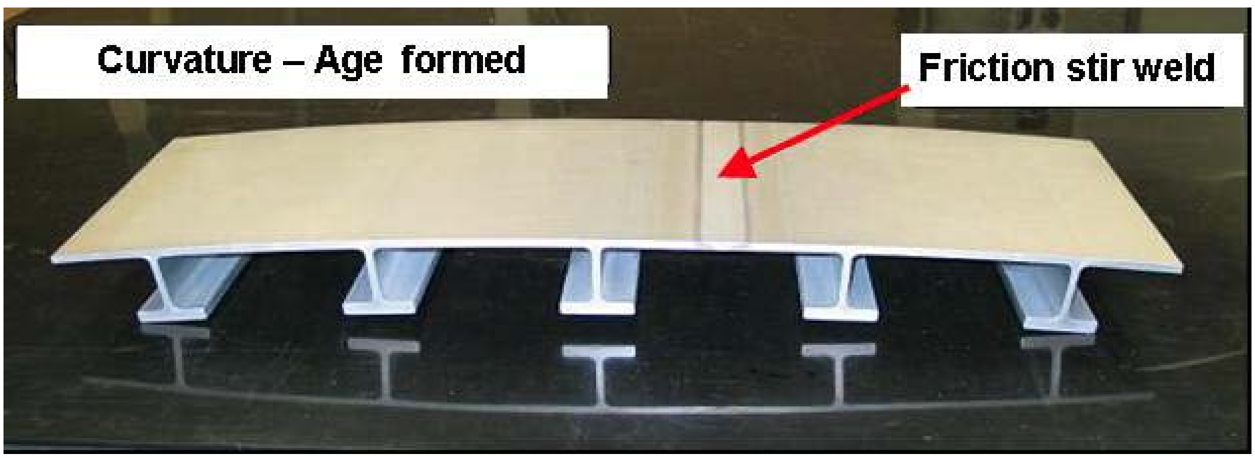


Figure 15.3-2: Example of a Curved, Age Formed and Friction Stir Welded IPS. Figure Courtesy of Alcoa.

Extrusions made with alloy 2099 exhibit very good machining, forming, fastening, and surface finishing behavior in production. Such extrusions can replace 2XXX, 6XXX, and 7XXX aluminum alloys for applications such as statically- and dynamically-loaded fuselage structures, lower wing stringers and stiffness-dominated designs. Alcoa's 2099 alloy is commercially available and already has been adopted for structural applications on jetliners.

Aluminum-lithium solutions from Alcoa also include the 2199 alloy, which is tailored for use in sheet and plate on aircraft fuselages and in lower wing skin applications. Weight savings of nearly 20% can be realized with Al-Li 2199 due to its higher modulus, strength, lower density, and lower spectrum fatigue-crack-growth rates (**Figure 15.3-3**).[3]

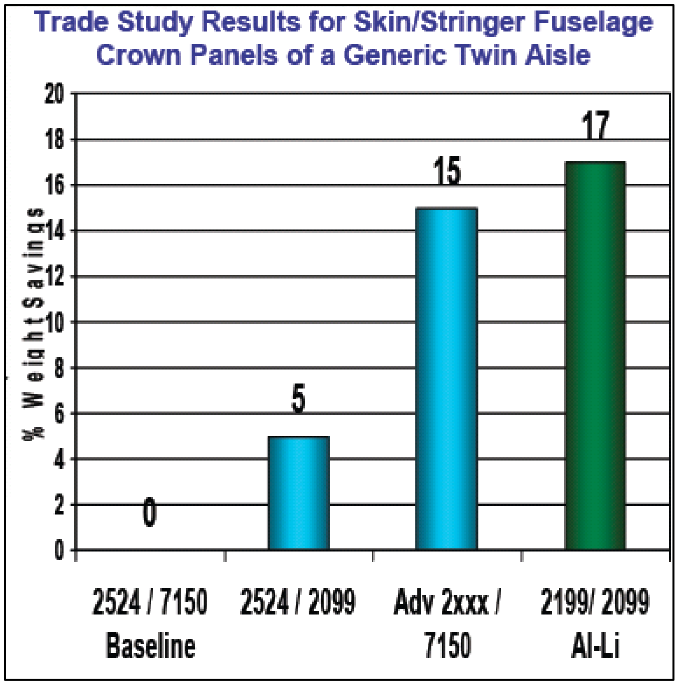


Figure 15.3-3: Computed Weight Savings Using 2199-T8E74 Sheet and 2099-T83 Extrusions on Crown Panels for a Twin-Aisle Aircraft. Figure Courtesy of Alcoa.

Alcoa has made significant production quantities of the Al-Li 2199 alloy, including full-sized samples, and material specifications exist for final evaluation by aircraft manufacturers for their future production applications. As part of Alcoa's capability to provide a portfolio of solutions, the Al-Li 2199 and Al-Li 2099 alloys can be combined for innovative lower wing applications on new aircraft, including the use on the successors to today's single-aisle jetliners.

The demand for lighter structures and advanced manufacturing technologies has led to the recent development of Al-Mg-Sc alloys, which have a density similar to the latest aluminum-lithium alloys. They offer excellent fatigue and damage tolerance properties, good corrosion resistance and very good weldability.[4] A basic patent for Al-Sc alloys was filed by Alcoa in 1971,[5] and since that time significant advances have been made in understanding the metallurgical principles and processing requirements for their development. Process technologies like melt spinning can produce a very stable microstructure in Al-Mg-Sc alloys compared to other aerospace aluminum alloys. One such alloy, ScaLA®, has been developed through a cooperative program of seven Austrian and two German companies.[6] Strength properties of this second generation Al-Mg-Sc alloys are adjustable by the amount of Sc added to the alloy. Appropriate processing generates a very dense network of nano-scaled Al_3ScZr precipitates responsible for high strength (up to 600 MPa) and good notch toughness. Aleris has developed two high-performance 5XXX Al-Mg-Sc alloys, which they designate as KO8242/KO8542, that are age-creep formable, have low density, midrange strength, and excellent fatigue-crack-growth resistance and good toughness.[7] As with other Al-Mg-Sc alloys, these alloys are amenable to laser-beam and friction stir welding and have been considered by Airbus for use in future fuselage shells and high-lift components.[6]

Alcoa[8] has been developing a weldable Al-Mg-Sc alloy intended for use as thin section fuselage components, both sheet and extrusions. The claimed advantages include improved corrosion resistance and lower density when compared with current 2XXX alloys. They have also been developing a modified 2XXX with minimal recrystallization for thin (and thick) extruded applications to replace 2024/2224. They claim higher strength, minimal machining, and improved damage tolerance.

Scientists of the former Soviet Union developed several Sc-containing Al alloys during the 1980s and 1990s. Much of the alloy development that took place was for aerospace applications. One Sc-containing Al-Li alloy, 1421, was used for fuselage stringers of large cargo aircraft and some parts of the MiG 29 military aircraft. It is also believed that some parts of the International Space Station are made from alloys with Sc.[9] The effect of Sc on the strength of a variety of aluminum alloys may be seen from data in the literature, assembled by Royset and presented in paper by Röyset.[9]

Table 15.3-1: Literature Data on the Effect of Sc on the Strength of the Various Classes of Wrought Aluminum Alloys.[9]

Alloy system	Ref.	Alloy	R_{p02} [Mpa]	R_m [Mpa]	Comment
1xxx	47	Al	15	48	Cold rolled material (89%), aged 288°C/8 h
		Al-0.23Sc	198	208	
		Al-0.38Sc	240	264	
2xxx	50	2618	~ 260	~ 330	Rolled sheet, solution heat treated, aged to peak hardness at 200°C (16-20h)
		2618 + Sc,Zr	~ 340	~ 390	
3xxx	53	Al-0.5Mn-0.2Mg-0.15Zr	87	140	As-extruded flat bar
		Al-0.5Mn-0.2Mg-0.15Zr-0.11Sc	119	173	
		Al-0.5Mn-0.2Mg-0.15Zr-0.21Sc	152	198	
		Al-0.5Mn-0.2Mg-0.15Zr-0.26Sc	168	207	
5xxx	54	Al-1Mg	50	120	As hot worked or annealed condition
		Al-1Mg- Sc (1515)	160	250	
		Al-2Mg-Mn	90	190	
		Al-2Mg-Sc (1523)	200	270	
		Al-4Mg-Mn	140	270	
		Al-4Mg-Sc (1535)	280	360	
		Al-5Mg-Mn	170	300	
		Al-5Mg-Sc (1545)	290	380	
		Al-6Mg-Mn	180	340	
		Al-6Mg-Sc (1570)	300	400	
	47	Al-5.3Mg	147	259	Cold rolled material (50%) w/intermediate anneals at 343°C, aged 288°C/8 h
		Al-5.3Mg- 0.3Sc	368	401	
6xxx	61	6082	333 / 338	351 / 357	Extruded rods, T5 age hardening at 185°C/ 4h (1st value) and 165°C/24h (2nd value)
		6082 + Sc,Zr	329 / 333	362 / 366	
	62	6060 + Zr	81	163	Extruded rods, T1 condition
		6060 + Zr,Sc	182	247	
	63	1370	380	430	Rolled sheet, T6 condition
7xxx	68	7017	400	475	Hot rolled plate, solution heat treated + aged to max. hardness at 120°C
		7017 + 0.25Sc	415	490	
	69	Al-8.6Zn-2.6Mg-2.4Cu-0.1Zr	649	672	Extruded rod, T6 condition
		Al-8.6Zn-2.6Mg-2.4Cu-0.1Zr-0.2Sc	689	715	
Al-Li	77	1420 (= 1421 without Sc)	270 / 280	440 / 450	Rolled sheet. Strength in longitudinal direction (1st value) and transverse direction (2nd value)
		1421	320 / 340	460 / 480	
		1423	350 / 330	460 / 460	
		1424	320 / 320	475 / 425	

NASA has examined aluminum-scandium alloys for air frame applications and fuel tanks that are chemically compatible with hydrogen peroxide (H_2O_2) propellant for possible use in NASA's Hypersonic-X vehicles[10] (**Figure 15.3-4**).

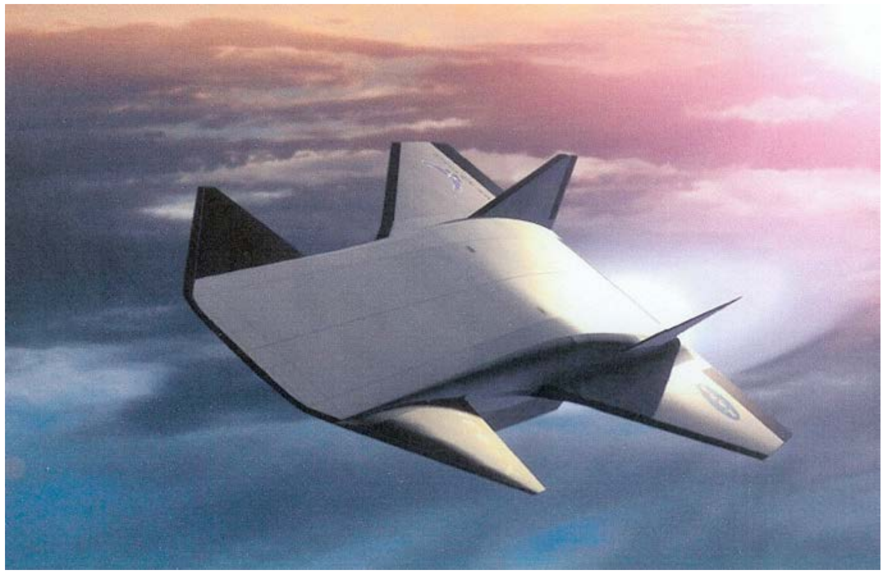


Figure 15.3-4: Artist Rendering of the Air-Breathing X-43B Hyper-X Vehicle.[10]

The purpose of NASA's research program was to develop a new Al-Mg-based alloy that has the same class 1 compatibility rating with H_2O_2, similar to the conventional 5254 alloy, but with a significant improvement in yield strength. The compositions of the alloys examined are given in **Table 15.3-2.**

Table 15.3-2: Chemical Compositions of Candidate Alloys Examined in the NASA Study.[10]

Alloy	Chemical Composition (wt. %)										
	Mg	Zn	Cr	Mn	Cu	Sc	Zr	Ti	Si	Fe	Al
5254	3.5	0.2	0.25	0.01	0.05	–	–	0.05	0.25	0.2	Balance
RX 5000	5.1	0.01	0.35	0.01	0.01	0.26	0.12	0.01	0.08	0.08	Balance
C557	4.02	0.015	–	0.62	0.003	0.24	0.096	0.023	0.062	0.095	Balance
7X0X	2.16	5.13	–	0.19	–	0.13	0.19	0.03	–	–	Balance
7X11	2.12	5.27	–	0.19	0.29	0.14	0.21	0.04	–	–	Balance

One of the alloys, C557, was commercially produced by Alcoa and is very similar to the Russian alloy 1535. The strengths of the alloys examined compared to the 5254 baseline alloy are shown in **Figure 15.3-5**. The data from the NASA study indicated that all of the alloys studied were chemically stable (inert) when exposed to 90% H2O2. With the T6 condition, the 7X11 heat-treatable alloy's yield strength was about 4.8 times higher than the conventional 5254 yield strength, while maintaining excellent H_2O_2 compatibility similar to the class 1 5254 alloy. In addition, the study showed that all of the alloys examined could be welded using the friction stir welding process.[10] Consequently, not only are the Sc-containing alloys candidates for the Hyper-X Program, but they look attractive for other aerospace programs as well.

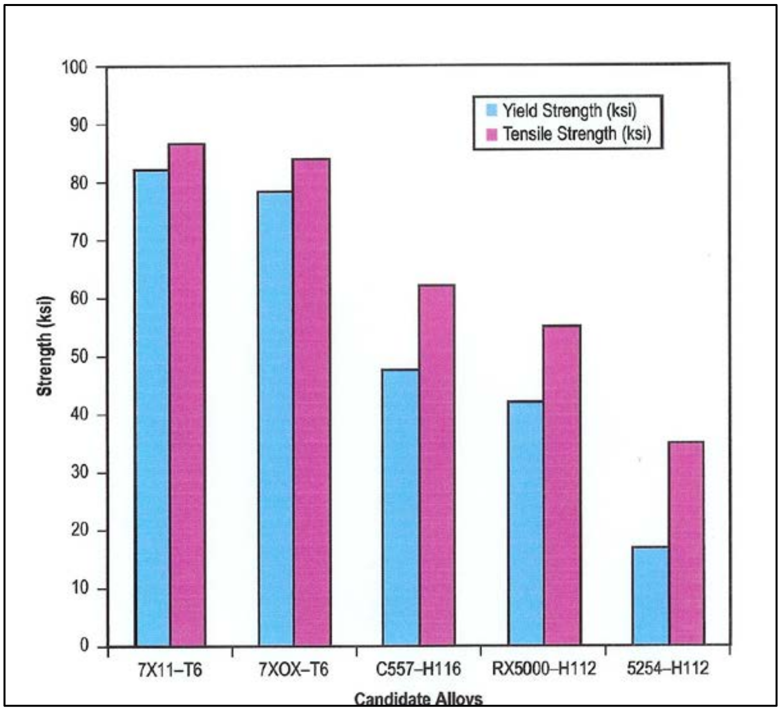


Figure 15.3-5: Strengths of NASA's Candidate Materials Compared to the 5254 Baseline Alloy.[10]

References

[1] http://www.alcoa.com/aerospace/en/info_page/suite_alloys.asp

[2] C. Giummarra and L. Yocum, Alcoa Technical Center; "New Developments in Extruded Integrally Stiffened Panels," A presentation.

[3] G. Venema, T. Morales, R. Ramage, P. Magnusen, D. Mooy, A. Wilson, C. Giummarra, J.J. Witters and R. J. Rioja, Alcoa Technical Center; "New Flat Rolled Products from Alcoa: A Progress Report on 2199," a presentation.

[4] E.A. Starke, Jr. and J.T. Staley; "Application of modern aluminium alloys to aircraft," in Fundamentals of Aluminium Metallurgy, Edited by Roger Lumley, Woodhead Publishing, Chapter 24, pp. 747-783.

[5] L.A.Willey, 1971, US Patent 3619181.

[6] R. Gradinger, R. Schneider and F. Palm; "2nd Generation of AlMgSc materials dedicated for short manufacturing chains in the aerospace industry," 1st EUCOMAS Conference, Berlin, pp. 63-76.

[7] M. Miermeister, A Büger, S. pangel, I. Kröpfl and A. Heinz; "Aleris advanced aluminium sheet and plate products for high-performance aircraft applications", Paper presented at the 1st EUCOMAS, Berlin, pp 85-100.

[8] J. Lui, J.T. Staley and W.H. Hunt, Jr.; Third ASM Int. Conf. On Synthesis, Processing and Moswllinf, Paris France, June 1997, p. 91

[9] Jostein Röyset; "Scandium in Aluminium Alloys Overview: Physical Metallurgy, Properties and Applications," Metallurgical Science and Technology,

[10] J.A. Lee and P.S. Chen; "Aluminum-Scandium Alloys: Material Characterization Friction Stir Welding, and Compatibility With Hydrogen Peroxide," NASA/TM-2004-213604, December 2004.

15.4. Nanotechnology and Nanomaterials

Nanotechnology is the investigation, application, and production of structures, molecular materials, and systems with a dimension or production tolerance of less than 100 nanometers. The minute scale of the system components alone enables the realization of new functionalities and properties for improving existing products and applications or developing new ones.[1] Nanomaterials exploit physical phenomena and mechanisms that cannot be derived by simply scaling down the associated bulk structures and bulk phenomena.[2] Using this definition, nanotechnology has been around for many years, e.g., Guinier-Preston zones in age-hardenable aluminum alloys[3] and the addition of nanosized carbon particles to rubber for improved mechanical properties (tires), the use of nanosized particles for catalysis in the petrochemical industries, and the nucleation of nanosized silver clusters during photographic film exposure.[4] The concept of nanotechnology was first discussed in 1959 by the physicist Richard Feynman in his talk "There's Plenty of Room at the Bottom," in which he described the possibility of synthesis via direct manipulation of atoms. Although not widely known, the term "nanotechnology" was first used by Nari Taniguchi in 1974, and Eric Drexler used the term in his 1986 book "Engines of Creation: The coming Era of Nanotechnology," which proposed the idea of a nanoscale "assembler."[5] Research in the field began to take off after the development of the scanning tunneling microscope in 1981 and other microscopy methods and techniques that allowed the examination and manipulation of individual atoms.

Nanotechnology entered the more public arena in 2001 when President Clinton brought worldwide attention to nanotechnology through his budget approval for the United States. The funding in this budget for the National Nanotechnology Initiative (NNI) was $422 million, which demonstrated the anticipated relevance of nanotechnology to the U.S. economic growth as well as nanotechnology's strategic importance to national security. Three years later, in December 2003, President Bush signed the 21st Century Nanotechnology Research and Development Act, which allocated a budget of $849 million to the NNI, doubling the initial budget from 2001. Governments from around the world reassessed their nanotechnology plans and budgets[6] and began to develop their own focused long-term position in nanotechnology.[2, 7, 8] By 2003 government investments into nanotechnology increased to over $3 billion worldwide.[6]

Nanomaterials are composed of structural elements whose characteristic size in at least one dimension is of the order of a few nanometers. Nanomaterials, thus, include nanometer-sized microstructures, suspensions of nanometer-sized crystallites, high-surface-area materials, carbon-based materials (such as nanotubes), materials with nanostructured surface regions, nano-meter-sized thin films, and nanosized devices.[2] Nanomaterials are created by two different approaches: (1) assembly of atoms into nanostructures (bottom-up), and (2) development and transformation of large structures, i.e., by severe deformation and/or creation of composites by dispersion of nano-sized particles in a suitable matrix (top down).[9–10] There are a number of processes that can be used for producing nanomaterials in bulk powders, coatings, thin films, laminates, and composites. Inert gas condensation can be used to produce nanostructured metals, alloys, intermetallics, ceramic oxides, and composites. The smallest particle sizes produced using this method are about 5–25 nm. Another process commonly used to produce nanostructured materials is mechanical alloying, which is an example of a “top down” approach and results in metal powders that then need to be consolidated. Of course one of the problems associated with this method is to maintain the nanostructure during consolidation. Severe plastic deformation, e.g., equal-channel-angular extrusion, can be used to fabricate a variety of nanostructured metals and intermetallics. Other methods include the so-gel process, rapid solidification, thermal spraying, electro deposition, jet vapor deposition, sputtering and chemical vapor deposition, infiltration, and condensation.[11]

One important area of nanotechnology is the use of nanomaterials for coatings for wear resistance, corrosion resistance, and thermal protection. Plasma spraying, a branch of thermal spray processing, has attracted the attention of synthesizing bulk nanostructured coating and near-net-shape components.[12] Ceramic coatings are attractive because they possess good thermal and electrical properties, and are more resistant to oxidation, corrosion, erosion, and wear than metals in high-temperature environments. Nanoparticles of diamond as well as chemical compounds used for hard coatings (SiC, ZrO2, and Al2O3) are commercially available, with typical particle sizes in the range 4–300 nm.[13] Plasma-sprayed ceramic coatings have been successfully used by the U.S. Navy for application in shipboard and submarine applications such as arm weldment, bulkhead pivot arm, bearing sled, front and aft door support, magnet arm, sockets and arm pivot pins, periscope guides, hydraulic piston, and reduction gear set.[14] Plasma-sprayed ceramics have also been frequently used as a corrosion-resistant coasting in a variety of industrial applications. It has been shown that there is a higher corrosion resistance of plasma-sprayed “nanostructured” coating as compared to its conventional counterparts.[15] Nano-sized silica has proved to be an alternative to toxic chromate conversion coating.[13]. In addition to this ceramic coating, TDA Research, Inc. had developed nanoparticle-based, organic corrosion inhibitors that are highly effective and chromate-free. These nanoparticles have organic corrosion inhibitors anchored to the surface that are triggered to release by the corrosion process. TDA claims that these materials provide excellent corrosion resistance in epoxy primers on high-strength aluminum alloys that are used on aircraft and space systems. Nanostructured materials have received significant interest for thermal barrier coatings (TBC) because of their extraordinary properties.[12] TBCs are used to provide thermal insulation to metallic/superalloy parts in aircraft engines as well as protection for space reentry vehicles. There are several studies that report that yttria-stabilized nanostructured zirconia coatings have low thermal conductivity, a high coefficient of thermal expansion, and excellent mechanical properties.[12] However, more studies need to be conducted to determine their effectiveness for aerospace systems.

NASA Langley has a long history of research and development of coatings for corrosion resistance as well as for thermal barriers. The Laboratory is well positioned to aid in the development of nanostructured coatings for advanced aerospace systems.

Recently, Steve Hales[16] and coworkers have experimented with radio frequency plasma synthesis of boron nitride nanotubes (BNNT) for structural applications. The crystal structure and physical morphology of BNNTs are analogous to carbon nanotubes (CNTs). BNNTs offer the same potential benefits as CNTs, but exhibit superior chemical and thermal stability. BNNTs are insulators and are more compatible than CNTs with metal matrix composites, i.e., no fiber-matrix galvanic interactions and much higher temperature application. However, large quantities of high-quality BNNTs need to be available to effectively explore their ultimate potential in aerospace applications. The high temperatures and chemical reactions associated with synthesis of BNNTs have severely restricted the quality and quantity of products available.

The first synthesis of BNNTs occurred in 1995 and even today the yield of multi-walled nanotubes (MWNTs) is in the grams level, and the mass production of high-quality, low-defect single-walled nanotubes (SWNTs) remains a challenge. The paper by Hales and coworkers gives an excellent review of the different approaches taken over the past decade to produce BNNTs and provides details on the current radio frequency plasma synthesis of BNNTs being pursued at Langley. The projected advantages of using the Langley Research Center (LaRC) radio frequency plasma spray (RFPS) facility for the synthesis of large quantities of high-purity BNNTs are summarized in this paper. This research is truly innovative and offers the potential to greatly advance the state-of-the-art in production of BNNTs for aerospace applications.

References

[1] The Encyclopedia of Nanoscience and Nanotechnology. H.S. Nalwa [ed.], USA, 2004.

[2] GENNESYS, White Paper, Editors H. Dosch and M.H. Van de Voorde, Max Planck Institut fur Metallforschung, Stuttgart, Germany, February 2009.

[3] E.A. Starke, Jr. and Erhard Hornbogen; Acta Metall. Mater., 41, 1, 1993.

[4] James S. Murday; “The Coming Revolution Science and Technology of Nanoscale Structures”, in AMPTIAC Quarterly. A Look Inside Nanotechnology, Volume 6, No. 1.

[5] Nanotechnology, from Wikipedia, the free encyclopedia, accessed 1/25/14.

[6] Nanotechnology; “Global Strategies, Industry Trends and Applications”, edited by Jurgen Schulte, Wiley and Sons, West Sussex, England, 2005.

[7] Nano-Initiative-Action Plan 2010, Federal Ministry of Education and Research, Germany.

[8] Business Strategy of the State Corporation; “Russian Corporations of Nanotechnologies”, Until the year 2020, RUSNANO.

[9] Joel Hemanth; “Development and Property Evaluation of Aluminum Alloy Reinforced with nano-Zr-O2 Metal Matrix Composites”, Materials Science and Engineering, Volume 507, Issues 1–2, Masy 2009, pp. 110–113.

[10] Victor N. Gulbin, Valentin Yu. Kondevich; “The Composite Materials Reinforced with Nano-Powers”, All-Russian Institute of Light Alloys, Moscow Russia.

[11] Robert Lane, Benjamin Craig and Wade Bobcock; “Materials Engineering With Nature’s Building Blocks”, in AMPTIAC Quarterly. A Look Inside Nanotechnology, Vol. 6, No. 1.

[12] Anup Kumar Keshri and Arvind Agarwal; “Plasma Processing of Nanomaterials for Functional Applications-A Review”, Nanoscience and Nanotechnology Letters, Vol. 4, 212, pp. 228-250.

[13] V.S. Saji and Joice Thomas; “Nanomaterials for corrosion control”, Current Science, Vol. 92, No. 1, 2007, pp.51–55.

[14] M. Gell, E. H. Jordan, Y. H. Sohna, D. Goberman, L. Shaw, and T. D. Xiao; Surf. Coat. Technol. Vol. 146, 2001, p. 48.

[15] W. Tian, Y. Wang, T. Zhang, and Y. Yang; Mater. Chem. Phys. Vol.118, 2009, p. 37.

[16] Hales, Stephen J.; Alexa, Joel A.; Jensen, Brian J.; Thomsen, Donald L.; “Radio Frequency Plasma Synthesis of Boron Nitride Nanotubes (BNNTs) for Structural Applications: Part I”, NASA/TP-2016-219001, 2016.

15.5. Fiber Metal Laminates

In 1966, Gil Kaufman, working at the Alcoa Laboratories in Pittsburgh, showed that the fracture toughness of adhesively laminated aluminum plies was improved in comparison to that of an equivalent monolithic plate due to the individual plies failing in a plane stress state.[1] Subsequently, Johnson and colleagues at NASA Langley showed that significant improvements in fatigue and crack growth resistance could also be realized by adhesively laminating thin aluminum plies together.[2,3] In the early 1980s, Johnson extended this work to show that adhesively laminated titanium plies improved fracture toughness by almost 40%, increased fatigue life by an order of magnitude, and slowed down through-the-thickness crack growth rates[4] by 20%.

During the 1970s and 1980s, composites were widely studied, but were very expensive. In order to reduce costs, researchers in England bonded combinations of aluminum and composites as reinforcements onto rods, tubes, and beams and determined the efficiency of these combinations in comparison to monolithic aluminum.[5] Lower costs of the combinations compared with full composites were the driving force. NASA Langley Research Center also emphasized the lower cost and treated the reinforcement as a way to reduce the weight while limiting the risk of applying a completely new material. NASA researchers were especially interested in local reinforcements bonded to aluminum structures in the space shuttle components.[5] Later, engineers from Fokker Aircraft visited NASA and saw the results of these tests. They realized that this work was close to the bonded structures that were used on built-up, laminated structure for the Fokker F-27. They then came up with the idea to add fibers to the adhesive of their laminates. This work proved the concept of fiber reinforcement was technically interesting, but the results were not spectacular and there were many problems related to durability and quality control, which they thought would lead to expensive products.[5]

Professors and students at Delft University began to examine the concept of fiber metal laminates and quickly realized that the production of the laminates required partnerships with material suppliers for strong fibers and aluminum alloy sheets. This lead to a partnership with the Dutch chemical company AKZO to supply aramid fibers suitable for the laminate and Alcoa to provide the thin aluminum alloy sheets.[5] Contacts were also established with 3M, who made good adhesives and was able to manufacture the prepregs. Two aluminum alloys were used: 7075 (and later 7475) and 2024. The patent on fiber metal laminates (FML) was filed in the United States on January 9, 1981. As inventors of the new material, it mentioned Schijve, Vogelesand, and Marissen. There were actually two patents: a general one covering a combination of metal sheet and fibers, and one on stretching the 7075 that was used to put the alloy in a state of compression after manufacturing the laminate to improve the fatigue resistance.[5] The name of the applicant was Delft University, but AKZO holds the patent rights. The material was designated as aramid-reinforced aluminum laminates (ARALL). A schematic[6] of ARALL is shown in **Figure 15.5-1**.

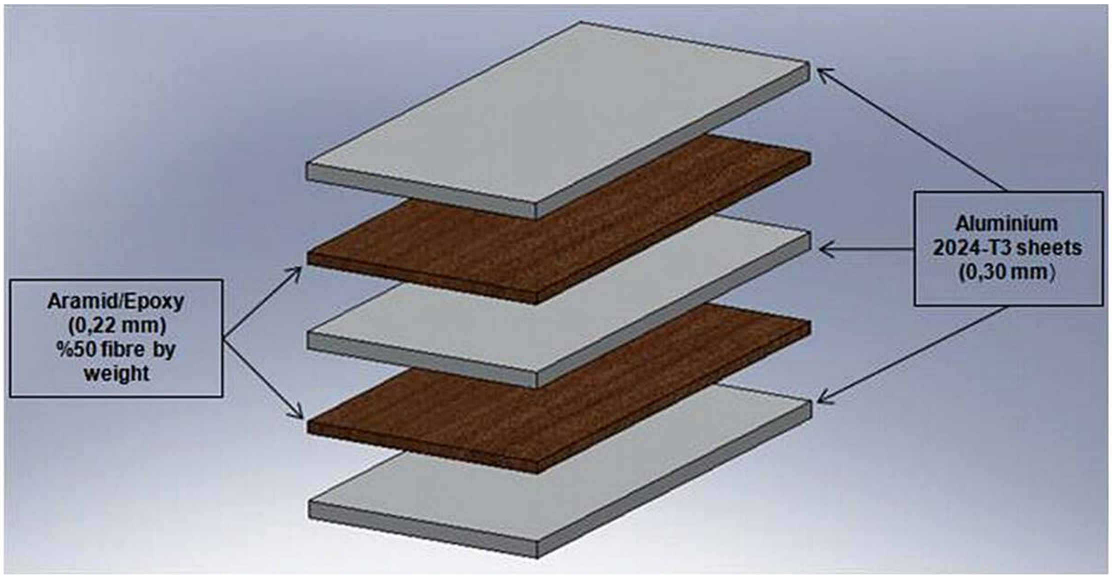


Figure 15.5-1: Schematic of a Fiber Metal Laminate (ARALL 2).[6]

The first use of ARALL in aircraft was as a number of wing hatches of an access hole of the Fokker 50 (**Figure 15.5-2**) which was given certification by the Dutch Airworthiness authorities RLD.

Figure 15.5-2: Fokker 50 Aircraft.

However, French studies for the fuselage shell of an Airbus A320 were disappointing, and only one contract for the application was won by Alcoa for the C-17 military transport aircraft in 1988. Only the cargo door with dimensions of 5.6 by 9.7 meters was successful. It was manufactured from ARALL-3 by McDonell Douglas and led to 26% weight savings. The ARALL panels that could be produced by Alcoa were too small and had to be connected together with expensive titanium straps resulting in the laminate being about 10 times as expensive as aluminum. Only about thirty C-17s were built with ARALL cargo doors.[5]

GLARE (GLAss Reinforced) laminate is currently the most successful FML, patented by Akzo Nobel in 1987 and now entering commercial application on the Airbus A380, which received a full type certificate from the FAA and European Aviation Authorities. The patent for GLARE cites as inventors Roebroeks and Vogelesang, two former professors at the Faculty of Aerospace Engineering, Delft University of Technology, where much of the R&D for GLARE was done in the 1970s and 1980s.[7] A partnership between AKZO and Alcoa started to operate in 1991 to produce and commercialize GLARE. A formal agreement to establish the Structural Laminates Company, a joint venture of AKZO (1/3 owner) and Alcoa (2/3 owner), was signed in June 1991. Research and laboratory tests showed that GLARE had both impact and fire resistance and containers made from GLARE could contain a blast similar to that which occurred in the explosion that resulted in the Lockerbie crash over Scotland.[5] Subsequently, the FAA tested and approved the use of GLARE for containers, and it was then used to manufacture the ECOS[3]® containers by Galaxy Scientific Corporation, which are in production.

It is possible to "tailor" GLARE during design and manufacture such that the number, type, and alignment of layers can suit the local stress and shapes throughout an aircraft. This allows the production of double curved sections, complex integrated panels or very large sheets. The real breakthrough for GLARE came when Airbus selected it in 2001 for the upper fuselage section of the A380 (**Figure 15.5-3**).

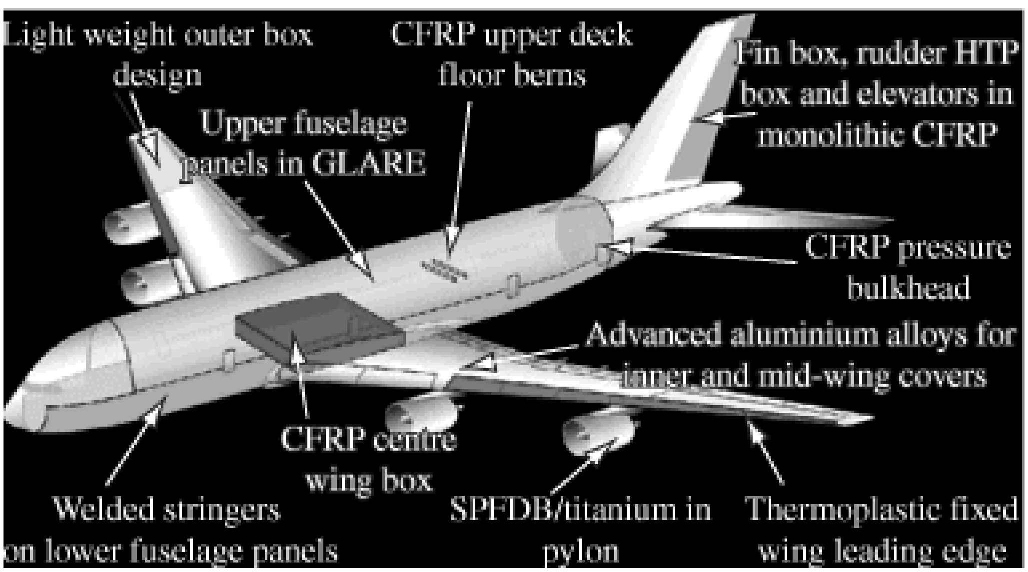


Figure 15.5-3: Metal/fiber Applications in the Airbus A380.[8,9]

While a simple manufactured sheet of GLARE is more expensive than an equivalent sheet of aluminum, considerable production savings can be made using this optimization. A structure properly designed for GLARE will be significantly lighter and less complex than an equivalent metal structure, and will require less inspection and maintenance and enjoy a much longer lifetime-till failure, making it a cheaper, lighter, and safer option overall.[7]

GLARE is expensive to produce, and dimensional restrictions apply. The NASA Langley Research Center consequently developed a material similar in design to GLARE, which is manufactured using dry fibbers and vacuum assisted resin transfer molding. The material is called VARTM FML. VARTM FML has the advantage of being cheaper in manufacturing, and produced panels are not dimensionally limited by the size of the autoclave. However, in contrast to the aluminum alloy foils in GLARE, the foils in medium sized to larger panels of VARTM FML need to be perforated in order for the resin to infiltrate. This clearly is a disadvantage since the holes (0.016 inches in diameter) in the metal foils act as crack initiators.[10,11]

The upper use temperature of materials such as ARALL and GLARE is about 200°C, which corresponds to a skin temperature of a Mach 2 aircraft. In order to achieve higher speeds, higher temperature materials are required. To meet this challenge engineers and scientists at NASA Langley Research Center developed a high-temperature metal laminate based upon titanium, carbon fibers and a thermoplastic resin.[12] This composite, known as the hybrid titanium composite laminate, or HTCL, is an extension of the ARALL and GLARE developments that took place at Delft University. The HTCL family of metal laminates took the concept of adding fibers to the adhesive bond line and applied it to the high-temperature regime of supersonic flight. The high temperatures found in supersonic flight necessitate the use of titanium rather than aluminum, and the substitution of the adhesive with an adhesive that could withstand the higher operating temperature for an extended period of time.[12] The initial material was produced using Ti-6Al-4V titanium alloy, IM7 carbon fibers, and LaRC-IA polyimide as the constituent materials in the HTCL.[13] This class of HTCL is usually referred to as TiGr. Extensive examination of TiGr has been conducted at NASA Langley[14] and elsewhere.[15] Boeing had a particular interest in TiGr during the High-Speed Civil Transport and the National Aerospace Programs and applied for a patent for titanium-polymer hybrid laminates in 1998. The patent was issued on September 5, 2000.[16]

In order to use the unique advantages of TiGr materials,[17] it is necessary to develop methodology to predict their deformation and failure in strength limiting applications, particularly for airframe joints in which bolts or rivets are used.[15] In addition, it is important to develop and optimize adhesives, fibers, titanium alloy, and manufacturing procedures to enhance both mechanical and high-temperature capability. Further work on TiGr is required at NASA Langley to determine the fundamental mechanisms and reliability of this advanced material to mature this material system for application in future aerospace systems.

References

[1] J.G. Kaufman; “Fracture Toughness of 7075-T6 and –T651 Sheet, Plate and Multilayered Adhesive-Boned Panels”, Journal of Basic Engineering, Vol. 89, 1967, pp. 503-507.

[2] W.S. Johnson and J.M. Stratton; “Effective Remote stresses and Stress Intensity Factors for an Adhesive Bonded Multi-ply Laminate”, Engineering Fracture Mechanics, Vol. 9, 1977, pp. 411-421.

[3] W.S. Johnson, W.C. Rister, and T. Spamer; “Spectrum Crack Growth in Adhesively Bonded Structure”, Journal of Engineering Materials and Technology, Vol. 100, 1978, pp. 57-63.

[4] W.S. John; “Damage Tolerance Evaluation of Adhesively Laminated Titanium”, Journal of Engineering Materials and Technology, Vol. 105, 1983, pp. 182-187.

[5] C.A.J.R. Vermeeren; "An Historic Overview of the Development of Fibre Metal Laminates", Applied Composite Materials, Vol. 10, 2003, pp. 189–205.
[6] Tamer Sinmazcelik, Egemen Avcu, Mustafa Özgür Bora and Onur Coban; "A review: Fibre metal laminates, background, bonding types and applied test methods", Materials and Design, Vol. 32, 2011, pp. 3671–3685.
[7] GLARE, from Wikipedia, the free encyclopedia, accessed January 30, 2014.
[8] Edson Cocchieri Botelho, Rogério Almeida Silva, Luiz Cláudio Pardini, Mirabel Cerqueira Rezende; "A review on the development and properties of continuous fiber/epoxy/aluminum hybrid composites for aircraft structures", Mat. Res. vol.9 no.3 São Carlos July/Sept. 2006.
[9] A. Vlot and J.W. Gunnink, Fibre Metal Laminates, Kluwer Academic Publishers, Dordrecht, The Netherlands, 2001.B. J. Jensen, R. J. Cano, S. J. Hales, J. A. Alexa, E. S. Weiser, A. C. Loos, and W. S. Johnson; "Fiber Metal Laminates Made by the VARTM Process", Advanced Materials & Processing Branch, NASA Langley Research Center, Hampton, VA 23681-0001. 2009.
[10] B. J. Jensen, R. J. Cano, S. J. Hales, J. A. Alexa, E. S. Weiser, A. C. Loos, and W. S. Johnson; "Fiber Metal Laminates Made by the VARTM Process", Advanced Materials & Processing Branch, NASA Langley Research Center, Hampton, VA 23681-0001. 2009
[11] E.K. Baumert, W.S. Johnson, R.J. Cano, B.J. Jensen and E.S. Weiser; "Mechanical Evaluation of New Fiber Metal Laminates Made by the VARTM Process", Advanced Materials & Processing Branch, NASA Langley Research Center, Hampton, VA 23681-0001.
[12] W.S. Johnson, Ted Q. Cob, Sharon Lowther and T.L. St. Clair; "Hybrid Titanium Composite Laminates: A New Aerospace Material", NASA Langley Research Center, Hampton, VA 23681-0001.
[13] J.L. Miller, D.J. Progar, W.S. Johnson, and T.L. St. Clair; "Preliminary Evaluation of Hybrid Titanium Composite Laminates", NASA Technical Memorandum 109095, April 1994.
[14] W. Steven Johnson and Edward Li; "High Temperature Hybrid Titanium Composite Laminates: An Early Analytical Assessment", Applied Composite Materials, Vol. 3, 1996, pp. 379–390.
[15] Jacob M. Hundley, Jenn-Ming yang and H. Thomas Hahn; "Bearing Strength Analysis of Hybrid Titanium Composite Laminates," AIAA Journal, Vol. 46, No. 8, August 2008, pp. 2074–2085.
[16] Willard N. Westre et al; "Titanium-Polymer Hydrid Laminates", United States Patent Number 6,114,050, September 5, 2000, Assignee: The Boeing Company, Seattle, Washington.
[17] E. Li and W.S. Johnson; "An Investigation into the Fatigue of Hybrid Titanium Composite Laminate", Journal of Composites Technology & Research, JCTRER, Vol. 20, No. 1, 1998, pp. 3–12.

15.6. Process Modeling

A major new manufacturing initiative has been announced by the White House entitled "Materials Genome Initiative:[1] A Renaissance of American Manufacturing." It can take 20 or more years to transition a material from discovery to a commercial product. Lithium ion batteries, for example, were first proposed in the mid-1970s but only achieved broad market adoption and use in the late 1990s. The major focus of this effort is to reduce the "time-to-market" from discovery to deployment for new classes of materials. New materials can enable companies to make safer, lighter vehicles, packaging that keeps food fresher and more nutritious, and solar cells as cheap as paint. However, additional work is required to find economical ways of advancing new material technology without sacrificing durability and safety of using new materials.

As part of the President's Advanced Manufacturing Partnership, the goal of the Materials Genome Initiative, is to double the speed with which new materials are discovered, developed, and manufactured into useful engineering products. The White House released a white paper describing the initiative, "Materials Genome Initiative[2] for Global Competitiveness," produced by the Cabinet-level National Science and Technology Council.

In the same way that the Human Genome Project accelerated a range of biological sciences by identifying and deciphering the basic building blocks of the human genetic code, the Materials Genome Initiative will speed our understanding of the fundamentals of material science, providing a wealth of practical information that entrepreneurs and innovators will be able to use to develop new products and processes.

The President's FY12 budget includes $100 million to launch the Materials Genome Initiative, with funding for the Department of Energy, the Department of Defense, the National Science Foundation, and the National Institute of Standards and Technology. The initiative will fund computational tools, software, new methods for material characterization, and the development of open standards and databases that will make the process of discovery and development of advanced materials faster, less expensive, and more predictable.

Realizing the goals of the Materials Genome Initiative will require an unprecedented level of collaboration among all stakeholders, including government, industry, academia, professional societies, and national labs. By working together, we can use advanced materials to help solve our most pressing national challenges and promote a renaissance of American manufacturing.

15.6.1. Process Models

Recent advancements in titanium have included development of lower-cost alloys, reduction of processing costs by methods such as powder metallurgy, welding, improvements in forming technologies, use of appliqués in corrosion applications, etc. There has also been considerable effort to develop models that are intended to enable a less costly more rapid alloy/heat treatment development. These models will take into account chemistry, texture development throughout the processing steps, and microstructure evolution through each of the thermomechanical and thermal processes involved in fabrication of mill product, forgings, etc. At least initially, these models will be premised on physical models and neural networks

The authors are optimistic about the future prospect of using modeling to predict properties, and provide guidance on the chemistries and processing requirements to achieve specific properties. This is still a ways out in the future, but progress is being made that provides optimism that modeling will provide a means of shortening the lead time and reducing the amount of testing which will be required to introduce a new product into service.

References

[1] http://www.whitehouse.gov/blog/2011/06/24/materials-genome-initiative-renaissance-american-manufacturing.

[2] http://www.whitehouse.gov/sites/default/files/microsites/ostp/materials_genome_initiative-final.pdf.

15.7. Near-Net-Shape Fabrication Technologies

Advanced near-net-shape technologies has been a focus of the Langley metallic materials group for the past several years. This has been an excellent cooperative activity with Marshall Space Flight Center and industry partners. These activities have included extrusions, roll forming, Welded Preforms, and superplastic forming and diffusion bonding (SPF/DB). In the early days, the efforts were led by Barry Lisagor and Tom Bales. More recently, the efforts have been led by John Wagner,[1,2,3] Marcia Domack,[4] and Eric Hoffman.[5] The current and potential future team members are shown in **Figure 15.7-1**.

Figure 15.7-1: Advanced Near-Net-Shape Team Members.

Figure 15.7-2 shows the large tooling required in metal near-net-shape fabrication processes. If a large number of parts are to be manufactured, then expenditures for tooling can be amortized across the total number of parts made and can be cost effective. However, if the production run is small, then cost of tolling is significant.

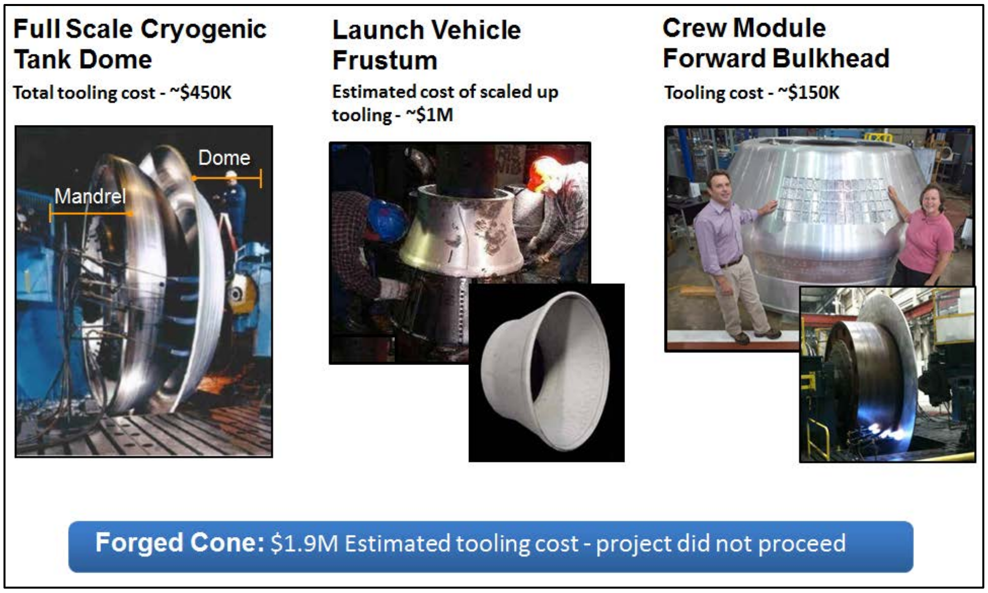


Figure 15.7-2: Typical Large Tooling Required in Metals Near-Net-Shape Fabrication Processes.

The Langley team has been working to overcome this cost issue by researching new approaches to near-net shape forming. Examples of this work are shown in **Figure 15.7-3** and **Figure 15.7-4**. The counter rolling process illustrated in **Figure 15.7 4** uses rollers on both sides of the metal to form the required shape without the need for expensive tooling. This process also has flexibility for shape changes simply by reprogramming the controls.

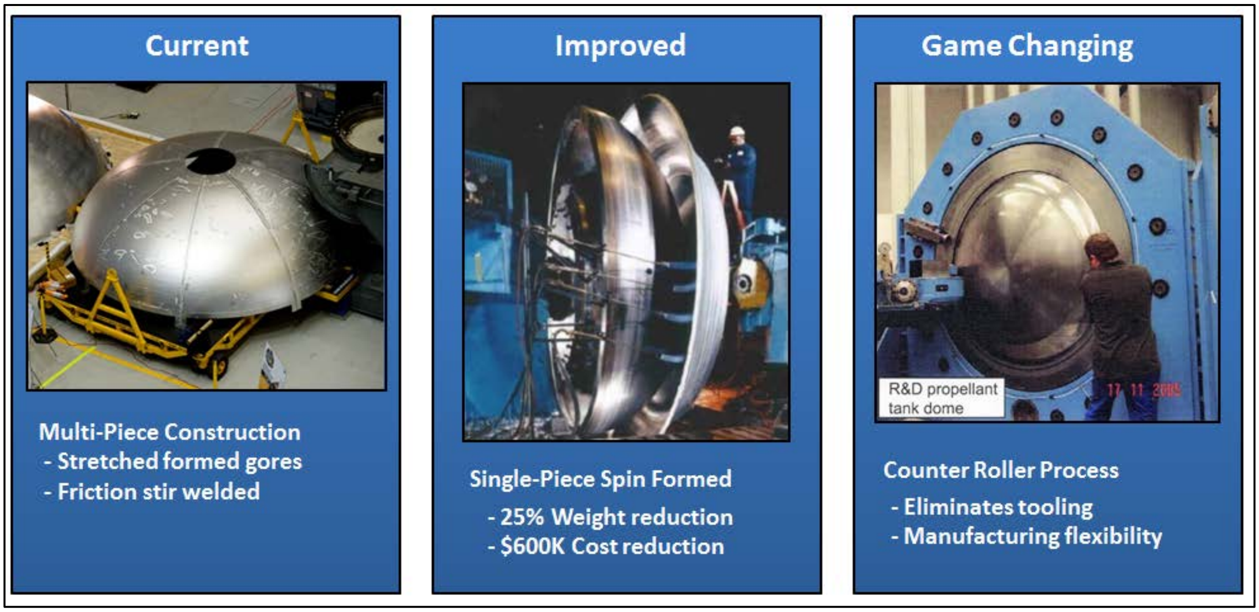


Figure 15.7-3: Large Dome Fabrication for Launch Vehicle Cryogenic Propellant Tanks.

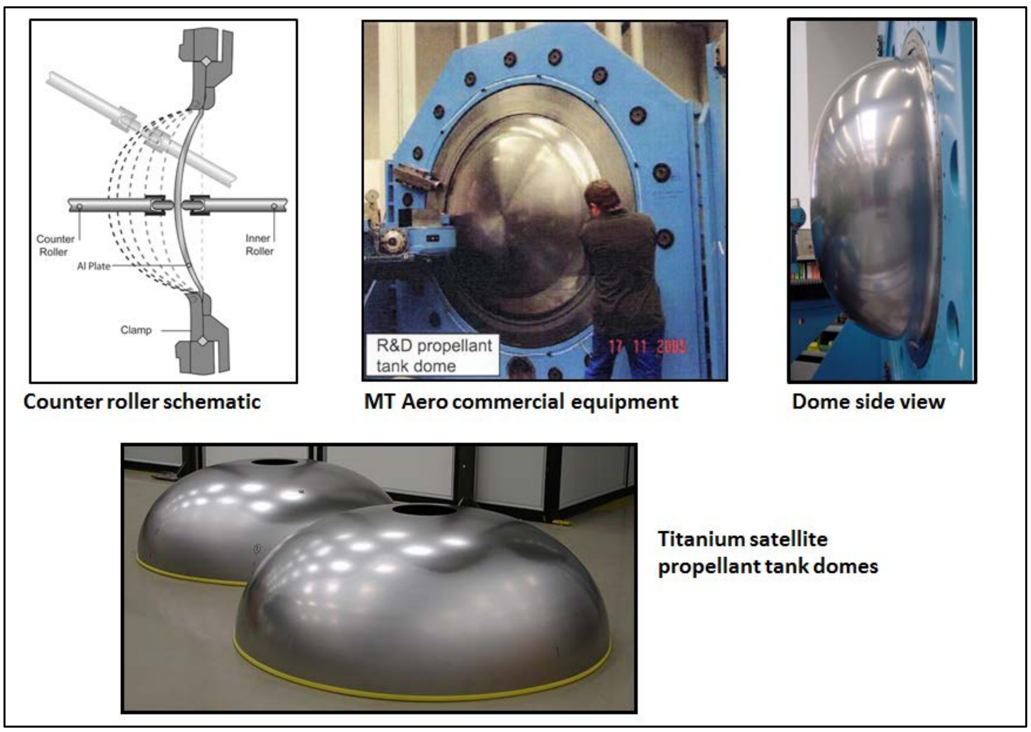


Figure 15.7-4: Counter Roller Spin Forming State-of-the-Art Titanium Satellite Propellant Tanks.

Another approach investigated by the metals group at Langley is flow forming. The basic approach is illustrated in **Figure 15.7-5**. The ultimate goal is to be able to form large integrally reinforced cylinders for aerospace launch vehicles without requiring extensive machining of the panels to remove material.

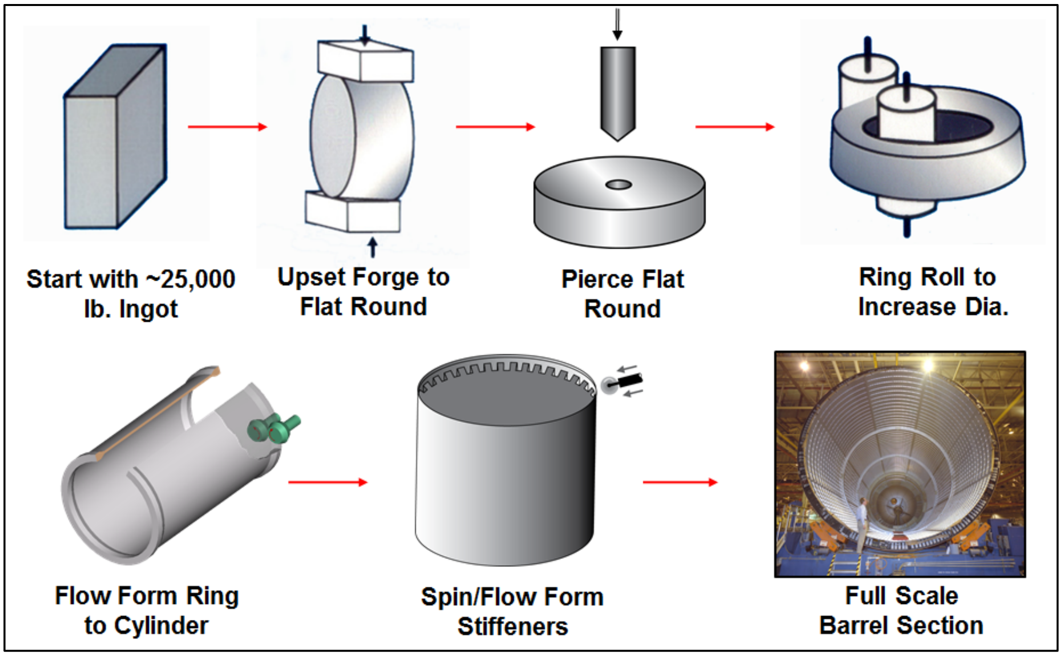


Figure 15.7-5: Scale-Up of Spin/Flow Forming of Integrally Stiffened Cryogenic Tank Structure.

Wagner and Domack[6] recently prepared a NASA Fact Sheet that highlighted a new effort to combine spin/flow forming processes that could revolutionize cryotank fabrication by producing a net shape integrally stiffened cylinder (ISC) in one forming operation. During this one step process, a rotating circular blank is formed over a cylindrical mandrel which has grooves that correspond to the stiffener shape. The metal flows into the grooves as the stiffeners and cylinder take shape. Discussion of this process can be found in section 6.2.

A NASA team[5] recently completed a critical assessment of using spin forming process for manufacture of a single-piece aft bulkhead for the Orion crew module (CM). The aft bulkhead was manufactured from Al 2219 alloy. This effort was performed for the Multi-Purpose Crew Vehicle (MPCV) Program and was led by Dr. Robert Piascik, NASA Technical Fellow for Materials at the Langley Research Center (LaRC). A picture of the Al 2219 spun-formed aft bulkhead is shown in **Figure 15.7-6**. An extensive amount of testing and characterization was done in support of this assessment to correlate spin forming process parameters with resulting microstructure and mechanical properties to accelerate deployment of a spin-formed aft bulkhead for Orion. The assessment found no issues to preclude using a spin-formed bulkhead and provided key data to the Orion Program. The assessment team made several recommendations for additional testing to better understand metallurgical features and critical issues related to stress corrosion cracking (SCC) susceptibility particularly in the short transverse direction of the spun dome. The data generated in this study will greatly contribute to test programs for future spun/flow formed structural components.

Figure 15.7-6: Aft Bulkhead Following Heat Treatment.

References

[1] Wagner, John; Domack, Marcia and Hoffman, Eric; "Recent Advances in Near-Net-Shape Fabrication of Al-Li Alloy 2195 for Launch Vehicles," National Space & Missile Materials Symposium, Keystone, CO, June 26, 2007
[2] Troeger, Lillianne P.; Domack, Marcia S.; Wagner, John A.; "Microstructural and Mechanical Property Characterization of Shear Formed Aerospace Aluminum Alloys," NASA/TM-2000-210540.
[3] Wagner, John; Domack, Marcia; "Innovative Forming of Advanced Metallics," Strategic Interchange Meeting; 27-28 Jan. 2015; Augsburg; Germany, http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160006928.pdf
[4] Ivanco, Marie L.; Domack, Marcia S.; Stoner, Mary Cecilia; Hehir, Austin R.; "Cost-Benefit Analysis for the Advanced Near Net Shape Technology (ANNST) Method for Fabricating Stiffened Cylinders", NASA/TM–2016-219192, May 2016.
[5] Hoffman, Eric K.; Domack, Marcia S.; Torres, Pablo D.; McGill, Preston B.; Tayon, Wesley A.; Bennett, Jay E.; Murphy, Joseph T.; "Spin Forming Aluminum Crew Module (CM) Metallic Aft Pressure Vessel Bulkhead (APVBH) - Phase II", NASA/TP-2015-218674, NESC-RP-13-00884, L-20517, NF1676L-20636, Jan 01, 2015.
[6] Domack, Marcia S.; Wagner, John A.; "Innovative Manufacturing of Cylinders with Integral Stiffeners," NASA Tech Brief NP-2014-11-573-LaRC, NF1676L-20572.

15.8. Additive Manufacturing

Karen Taminger,[1,2,3] Rob Hafley,[4,5] Marcia Domack,[6,7] and several other members[8] of the research team at Langley have championed additive manufacturing for the past several years. The general rationale for additive manufacturing (AM) in aeronautical systems is (1) operate under a "design-to-constraint" paradigm; make parts too complicated to fabricate otherwise; (2)

reduce weight by 20% with monolithic parts; (3) reduce waste (green manufacturing); (4) eliminate reliance on original equipment manufacturers for critical spares; (5) and extend life of in-service parts by innovative repair methods. These points are further highlighted for aircraft structures in **Figure 15.8-1**. Additional information on work being pursued at NASA Langley Research Center is shown in **Figure 15.8-2**.

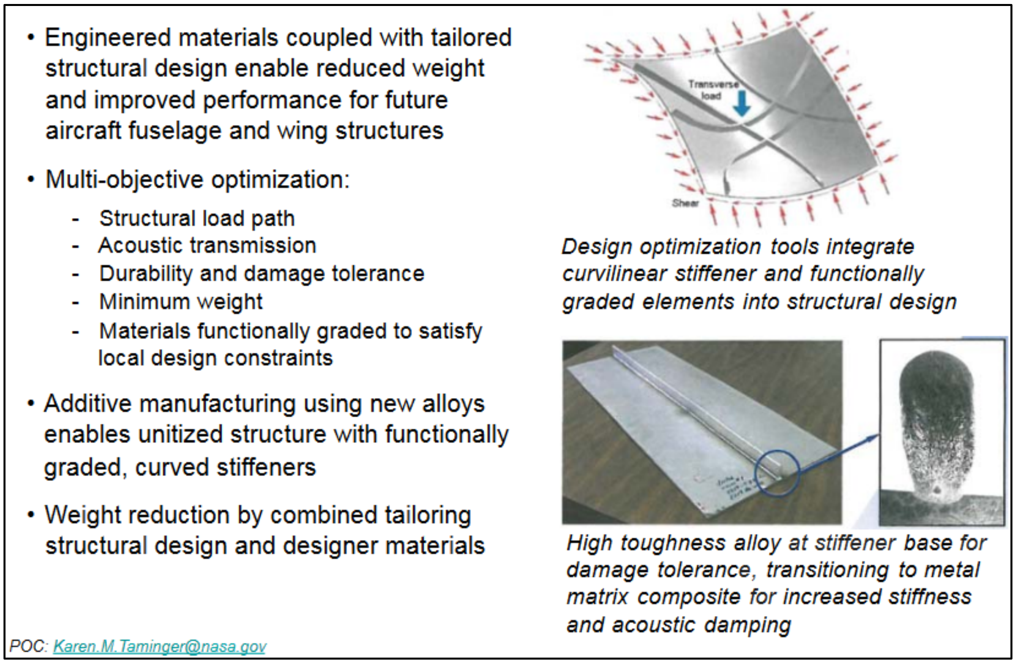


Figure 15.8-1: Additive Manufacturing Research at Langley Research Center.

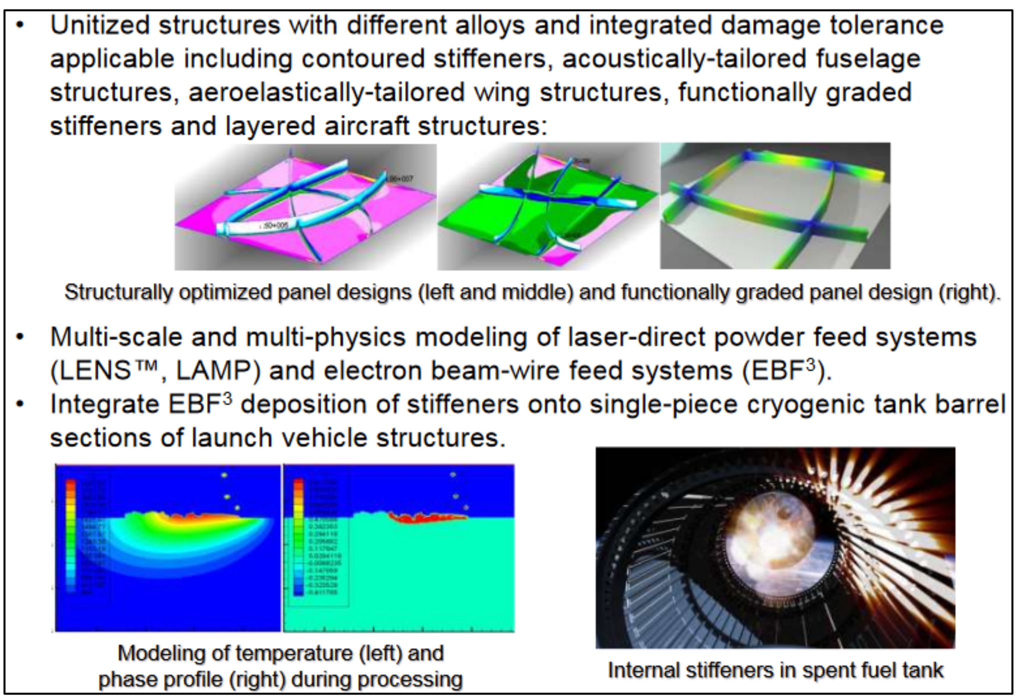


Figure 15.8-2: Research Thrusts in AM at Langley Research Center.

The basic rational for additive manufacturing in space is shown[9] in **Figure 15.8-3**.

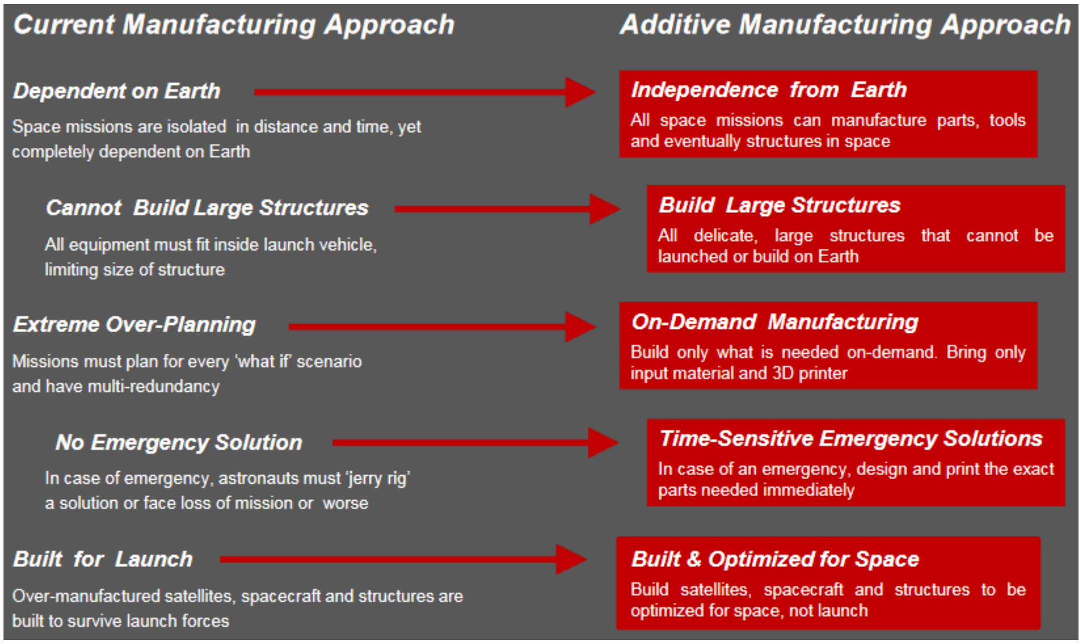


Figure 15.8-3: Rational for Additive Manufacturing in Space.

One of the best examples of the progress made in additive manufacturing for space systems is shown in **Figure 15.8-4**. The picture shows a hot-fire test at Glenn Research Center's Rocket Combustion Laboratory of an Aerojet Rocketdyne liquid-oxygen/gaseous hydrogen RL-10 rocket injector assembly built using additive manufacturing. The test was very successful.

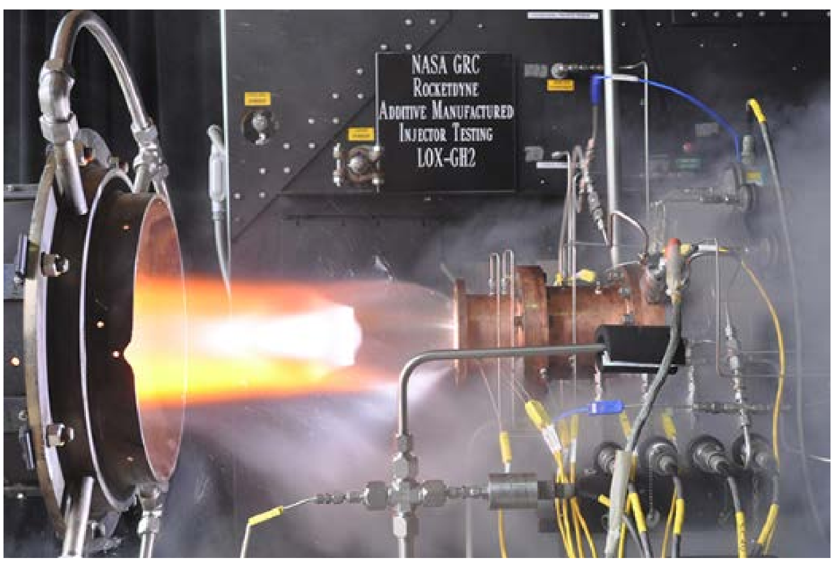


Figure 15.8-4: Hot-Fire Test at Glenn Research Center's Rocket Combustion Laboratory.

Industry is actively engaged in exploiting the potential benefits of additive manufacturing, as illustrated by the examples shown in **Figure 15.8-5**.

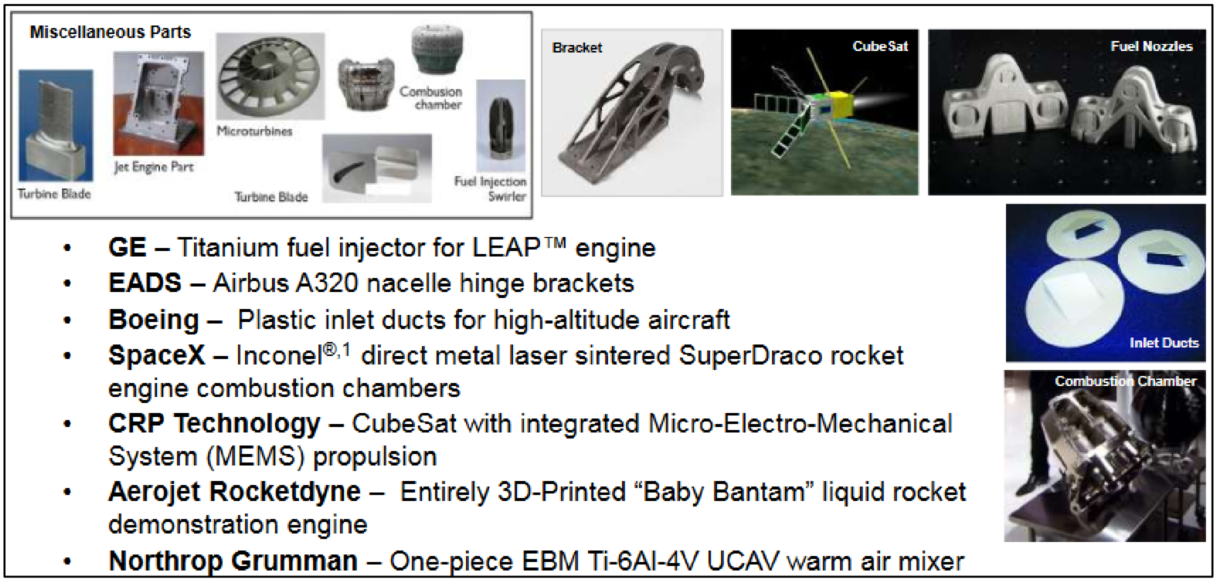


Figure 15.8-5: Examples of AM Parts Being Made by Industry.

Perhaps the biggest issue at the present time is the need to develop a technology base and procedures to certify additive manufactured parts for critical structures. A key barrier for AM processes and equipment is that existing nondestructive evaluation (NDE) methods and techniques are not optimized for AM processes, materials, or parts. Techniques are either non-existent or lacking for in-situ process NDE and post-process NDE of finished AM parts. Using conventional NDE techniques is challenging or still emerging. A key report outlining NASA efforts to address NDE issues for additive manufactured parts was recently published by Waller et al.[10] In this report, they note that there are significant gaps in the technology base required to mature additive manufacturing to enable certification for critical structural parts such as the following:

- A lack of data on fracture toughness, fatigue strength, and other key properties for AM materials
- Consistent wire feed stock materials optimized for AM processes
- NDE methods capable of interrogating features that are unique to AM parts, such as fine scale porosity, complex part geometry, and intricate or inaccessible internal features
- Closed-loop feedback systems for reliable in-situ process monitoring using sensors designed for the AM build environment
- Protocols for post processes such as hot isostatic pressing (HIP), heat treating, and shot peening and understanding the effect of these processes on final part properties and consistency
- Guidelines for how to qualify and certify both AM processes and finished AM parts qualification and certification of processes is complicated by the wide variety of machine types and the vast processing parameter space

- Qualification and certification of finished AM parts is hampered by lack of available data, poor understanding of the effect of defect, and in certain cases, inability or uncertainty in detecting the critical flaw

Qualification and certification is perhaps the most pressing need and a comprehensive approach is needed to bring all the required disciplines together to work cooperatively to mature this very promising technology.

15.8.1. Background

Few new technologies have impacted product development as much as layer manufacturing techniques (LMT). Parts produced by LMT are based on adding material instead of removing, e.g., milling. The procedure is based on a 3-D CAD model, which is sliced into thin layers by arithmetical means, which can then be made individually as a stack of cross-sections resulting in the 3-D part, e.g., the stereolithography technique. In combination with 3-D CAD, it provides the product developer with a very powerful tool to optimize its design and shortens the time needed to develop the product. New technologies such as concept modelers are able to produce prototypes with acceptable tolerances in a short time.

The highest benefit in all layer manufacturing technologies comes from the reduced time to market. It is followed by fast changes in design and flexibility in technical changes both in design and manufacturing processes. LMT limit these changes to data and not hardware modifications. Hence, improvement of quality and product maturity resulting from testing and field experience can still be introduced without high cost of changing tools or manufacturing processes. LMT enables the possibility to create physical prototypes automatically without any human intervention during the realization of the part. Expanding the number of materials and improving the material properties used in these layer manufacturing processes gave the opportunity to create better quality prototypes.

Solid freeform fabrication (SFF) refers to an additive manufacturing process that offers several advantages that include higher speed of production, less energy intensive prduction, maximum material utilization, ability to produce complex shapes, and design freedom as parts are produced directly from CAD (e.g., AutoCAD) data.[11] SFF involves five basic steps:[12] (1) generation of CAD data from the software like AutoCAD, Solid edge etc.; (2) conversion of the CAD data to Standard Triangulation Language (STL) file; (3) slicing of the STL into two dimensional cross-section profiles; (4) building of the component layer by layer; and lastly (5) removal and finishing. There are various types of SFF technologies; laser-based processes are mostly employed in fabrication of functionally graded materials (FGM). Laser-based SFF processes for FGM include laser-cladding-based method, selective laser sintering (SLS) , 3-D printing (3-DP), and selective laser melting (SLM). Laser cladding and selective laser melting are capable of producing fully dense components. SFF processes provide manufacturing flexibility amongst other advantages but parts produced are characterized by poor surface finish, making it necessary to carry out a secondary finishing operation. There are lots of research efforts in this direction to improve surface finish, dimensional accuracy, etc.

The 3-D printing technology is used for prototyping and distributed manufacturing with applications in architecture, construction, industrial design, automotive, aerospace, military, engineering, civil engineering, dental and medical industries, biotech (human tissue replacement), fashion, footwear, jewelry, eyewear, education, geographic information systems, food, and many other fields. NASA is currently investing in both electron beam deposition and selective laser sintering. SLS is an additive manufacturing technique used for the low volume production of prototype models and functional components. An additive manufacturing layer technology, SLS involves the use of a high-power laser (for example, a carbon dioxide laser) to fuse small particles of plastic, metal (direct metal laser sintering), ceramic, or glass powders into a mass that has a desired three-dimensional shape. The laser selectively fuses powdered material by scanning cross-sections generated from a 3-D digital description of the part (for example from a CAD file or scan data) on the surface of a powder bed. After each cross-section is scanned, the powder bed is lowered by one layer of thickness, a new layer of material is applied on top, and the process is repeated until the part is completed.

Because finished part density depends on peak laser power rather than laser duration, a SLS machine typically uses a pulsed laser. The SLS machine preheats the bulk powder material in the powder bed somewhat below its melting point, to make it easier for the laser to raise the temperature of the selected regions the rest of the way to the melting point.

Unlike some other additive manufacturing processes, such as stereolithography and fused deposition modeling, SLS does not require support structures due to the fact that the part being constructed is surrounded by un-sintered powder at all times, this allows for the construction of previously impossible geometries.

References

[1] Taminger, Karen M. and Hafley, Robert A.; “Electron Beam Freeform Fabrication for Cost Effective Near-Net Shape Manufacturing”, NASA/TM-2006-214284,L-19241.

[2] Taminger, K.M.B. and Hafley, R.A.; “Electron Beam Freeform Fabrication: A Rapid Metal Deposition Process”, Proceedings of the 3rd Annual Automotive Composites Conference, (2003).

[3] Taminger, K.M.B. and Hafley, R.A.; “Characterization of 2219 Aluminium Produced by Electron Beam Freeform Fabrication”, Proceedings of 13th SFF Symposium, 482-489, (2002).

[4] Gonzales, Devon; Liu, Stephen; Domack, Marcia; and Hafley, Robert; “Using Powder Cored Tubular Wire Technology to Enhance Electron Beam Freeform Fabricated Structures”, Report Number NF1676L-21966, TMS 2016 Annual Meeting and Exhibition; 145th; 14-18 Feb. 2016; Nashville, TN, Feb. 14, 2016.

[5] Zalameda, Joseph N.; Burke, Eric R.; Hafley, Robert A.; Taminger, Karen M.; Domack, Christopher S.; Brewer, Amy R.; Martin, Richard E.; “Thermal Imaging for Assessment of Electron-Beam Free Form Fabrication (EBF(sup 3)) Additive Manufacturing Welds”, Conference Paper, Report/Patent Number: NF1676L-16457, 2013.

[6] Domack, Marcia S. and Taminger, Karen M.; “Metallurgical Mechanisms Controlling Mechanical Properties of Aluminum Alloy 2219 Produced By Electron Beam Freeform Fabrication”, NASA/TM-2006-214316, Sept. 2006.

[7] Taminger, Karen M.; Hafley, Robert A.; Domack, Marcia S.; “Evolution and Control of 2219 Aluminum Microstructural Features Through Electron Beam Freeform Fabrication”, NASA/TM-2006-214297, L-19246, March 01, 2006.

[8] Watson, J.K., Taminger, K.M.B., Hafley, R.A., and Petersen, D.D.; "Development of a Prototype Electron Beam Freeform Fabrication System", Proceedings of 13th SFF Symposium, 458-465, (2002).
[9] Waller, Jess; Saulsberry, Regor; Parker, Bradford; Hodges, Kenneth; Burke, Eric; Taminger, Karen; "Summary of NDE of Additive Manufacturing Efforts in NASA", Review of Progress in Quantitative Nondestructive Evaluation, Session 5, Additive Manufacturing I Boise, ID July 21, 2014.
[10] Waller, Jess M., Parker, Bradford H., Hodges, Kenneth L., Burke, Eric R., Walker, James L.; "Nondestructive Evaluation of Additive Manufacturing, State-of-the-Discipline Report", NASA/TM-2014-218560.
[11] X. Lin and T. M. Yue; "Phase formation and microstructure evolution in laser rapid forming of graded SS316L/Rene88DT alloy", Mater Sci Engng, vol. A402, (2005), pp.294-306.
[12] M. A. Boboulos; "CAD-CAM & Rapid Prototyping Application Evaluation", PhD & Ventus publishing Aps, accessed online on 1st March 2012, available at www.bookBoom.com.

15.9. Functionally Graded Alloys and Built-up Structure

Many engineering components today have service conditions that require the properties to vary with position. Differing stresses, temperatures, and environments necessitate a range of material properties that often cannot be achieved in a component with a single composition. One solution is to replace these components with functionally graded materials, which are composite materials, engineered with different phases whose composition changes gradually with position. In FGMs, abrupt changes in composition or properties that can act as stress concentrations are eliminated, decreasing the possibility of failure. Unfortunately, graded materials are not regularly integrated into industrial components because the design and manufacturing processes include many unresolved challenges. In terms of design, optimization routines must be developed to identify the gradient in properties that provides superior component performance for a given set of service conditions. The component then needs to be manufactured correctly to produce the microstructural gradient leading to the predetermined property gradient.

Functionally graded material belongs to a class of advanced material characterized by variation in properties as the dimension varies.[1,2] Bone and teeth are examples of natural[3] functionally graded materials. The overall properties of FMG are unique and different from any of the individual material that forms it. There is a wide range of applications for FGM and it is expected to increase as the cost of material processing and fabrication processes are reduced by improving these processes.

In a recent overview article [4] on functionally graded materials, the authors state that "Functionally graded material is an excellent advanced material that will revolutionize the manufacturing world in the 21st century." There are different kinds of fabrication processes for producing functionally graded materials. Functionally graded materials can be divided into two broad groups: thin and bulk FGM. Thin FGMs are relatively thin sections or thin surface coating, while the bulk FGMs are volumes of materials that require more labor-intensive processes. Thin section or surface coating FGMs are produced by physical or chemical vapor deposition, plasma spraying, self-propagating high-temperature synthesis, etc.[5] The three most researched methods of producing bulk FGMs are the powder metallurgy technique, the centrifugal casting method, and solid freeform technology.[3] Functionally graded materials find their applications in aerospace, automobiles, medicine, sports, energy, sensors, optoelectronic, etc. As the fabrication process is improved, cost of powder is reduced and the overall process cost is reduced, hence expanding the application of FGM. Because of the importance of FGMs, there are lots of research efforts directed at improving the material processing, fabrication processing and properties of the FGM dimensional accuracy, etc. The solid freeform fabrication technique offers a great advantage over powder processing and fabrication method for producing FGM. However, more research needs to be conducted on improving the performance of SFF processes through extensive characterization of functionally graded material in order to generate a comprehensive database and to develop a predictive model for proper process control. To bring down the cost of producing FGM, improvement is needed in process control through development of more powerful feedback control for the overall FMG fabrication process improvement (i.e., full automation).

The challenges in the deposition of dissimilar materials are mainly related to the large differences in the physical and chemical properties of the deposited and substrate materials. These differences readily cause residual stresses and intermetallic phases. This has led to the development of functionally graded materials that exhibit spatial variation in composition. Laser direct metal deposition offers a wide variety of dissimilar and functionally graded materials deposition due to its flexibility. Despite considerable advances in process optimization, there is a rather limited understanding of the role of metallurgical factors in the laser deposition of dissimilar and functionally graded alloys.

A comprehensive review of processing techniques for producing functionally graded materials can be found in a review paper by Kieback, Neubrand, and Gasik.[6,7] While there is a broad spectrum of successfully implemented FGM manufacturing techniques, there remains a need in the procedures and protocols to guarantee a reliable and predictable distribution of material constituent phases and properties throughout the structure. This is a fertile area for additional R&D.

A unique characteristic of FGM is the ability to tailor a material for a specific application. For example, tailoring the metallic to optimize the critical properties for the specific loads and environments associated with different part of the structure. This has traditionally been done by selecting different alloys for different structural parts based on strength or fatigue requirements. Functionally grading can result in a structure where the behavior close to the wing box is totally different from on top of the wing. The approach has the potential to reduce both weight and cost of the structures. One of the challenges for the materials engineer is to become more integrated into the conceptual design process so that the design requirements are fully understood and can be factored into the alloy development and processing studies in an intelligent way to give a systems-level solution. The materials engineer of the future must take a systems analyses approach in planning and execution their R&D projects.

It should be noted that NASA SBIR 2012 Solicitation had a subtopic managed from NASA Goddard Space Flight Center (GSFC) entitled “Advanced Manufacturing and Material Development for Lightweight Metallic Structures.” PROPOSAL NUMBER: 12-1 H5.02-9371 entitled “Additive Friction Stir Deposition of Aluminum Alloys and Functionally Graded Structures,” was submitted by Kumar Kandasamy. Readers are encouraged to follow the SBIR subtopic to learn more about NASA-funded work in advanced manufacturing and in particular functionally graded materials.

References

[1] P. Shanmugavel, G. B. Bhaskar, M. Chandrasekaran, P. S. Mani and S. P. Srinivasan; "An overview of fracture analysis in functionally graded materials", European Journal of Scientific Research, vol.68 No.3 (2012), pp. 412–439.
[2] A. A. Atai, A. Nikranjbar, and R. Kasiri; "Buckling and post-buckling Behaviour of semicircular functionally graded material arches: a theoretical study", Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, (2012), vol. 226, pp. 607–614.
[3] R. Knoppers, J. W. Gunnink, J. Van den Hout, and W. Van Vliet; "The reality of functionally graded material products", TNO Science and Industry, The Netherlands, pp 38–43.
[4] Mahamood, R.M., Akinlabi, E.T., Shukla, M., Pityana, S.; "Functionally Graded Material: An Overview", Proceedings of the World Congress on Engineering 2012 Vol III WCE 2012, July 4–6, 2012, London, U.K.
[5] M. Ivosevic R. Knight, S. R. Kalidindi, G. R. Palmese and J. K. Sutter; "Solid particle erosion resistance of thermally sprayed functionally graded coatings for polymer matrix composites", Surface Coat Tech, 2005.
[6] B. Kieback, A. Neubrand, and H. Riedel; "Processing techniques for functionally graded materials", Materials Science and Engineering, (2003), pp. 81–105.
[7] M. M. Gasik; "Functionally graded materials: bulk processing techniques", International Journal of Materials and Product Technology, vol. 39, (1-2), (2010), pp. 20–29.

15.10.Severe Plastic Deformation

Heavy plastic deformation, now usually called severe plastic deformation (SPD), at relatively low temperatures is one of the main research topics in the material science community. It permits large scale production of materials or composites with crystallite sizes between a few nanometers and a few 100 nm. They have extraordinarily high strength, some of them have excellent ductility, and they offer tunable physical properties.

Severe plastic deformation is a generic term describing a group of metalworking techniques involving very large strains that are imposed without introducing any significant changes in the overall dimensions of the specimen or work-piece. A further defining feature of SPD techniques is that the preservation of shape is achieved due to special tool geometries that prevent the free flow of material and thereby produce a significant hydrostatic pressure. The presence of a high hydrostatic pressure, in combination with large shear strains, is essential for producing high densities of crystal lattice defects, particularly dislocations, which can result in a significant refining of the grains. As the dimensions of the work-piece practically do not change in an SPD operation, the process may be applied repeatedly to impose exceptionally high strains. Optimization of routes and regimes of SPD can eventually introduce an extremely fine microstructure into the processed material which will extend, reasonably homogeneously, throughout the bulk. A distinctive feature of these ultrafine-grained materials is that they contain a high fraction of grain boundaries having high angles of misorientation.

The potential of SPD processing for the production of bulk nanostructured materials with special mechanical and physical properties has been highlighted at several international meetings known as the NanoSPD conferences. The International NanoSPD Steering Committee organizes this conference series and has also established formal definitions for the various terms associated with SPD processing.

Severe plastic deformation processing aims to get microstructural refinement to a level not achievable with traditional processing. Some recent research applied it to titanium in order to produce medical implants for study. CP Ti is desirable mainly for its superior biocompatibility, but suffers from low strength compared to either steel or alloyed titanium. It is easy to form, however, and thus lends itself to economical SPD processing in general.

In this case, equal-channel angular pressing was used; it involves relatively low temperatures, incredible pressures and an angled extrusion die to induce high deformation with no geometry change of the input stock. This refined the grain structure of the titanium down to the nanoscale, which, according to the Hall-Petch relationship, will increase strength. The Hall-Petch relationship can reach a threshold in nanocrystalline materials, but, in this case, the strength nearly doubled and surpassed that of damage-tolerant variants of titanium 6Al-4V, the alloy responsible for the lion’s share of applications in industry. Fatigue life also nearly doubled, and, although damage tolerance suffered, the levels were still more than acceptable for medical devices.

15.11. Advanced Structural Concepts

Haden Wadley[1] and coworkers has performed interesting work in advanced structural panel concepts. These concepts have been investigated to study ways to improve blast impact resistance. In order to study the mechanisms that might be invoked to enhance the ballistic performance of sandwich structures, they experimentally investigated the effects of filling the empty space within a model stainless steel, pyramidal lattice core sandwich panel with polyurethane elastomers, aramid fiber fabrics, and alumina prisms (and combinations of the same) (**Figure 15.11-1**). The purpose of including their work here is not to review ballistic impact behavior, but rather to point out that innovative structural concepts need to be investigated along with materials development when looking for new ways to reduce weight and improve performance.

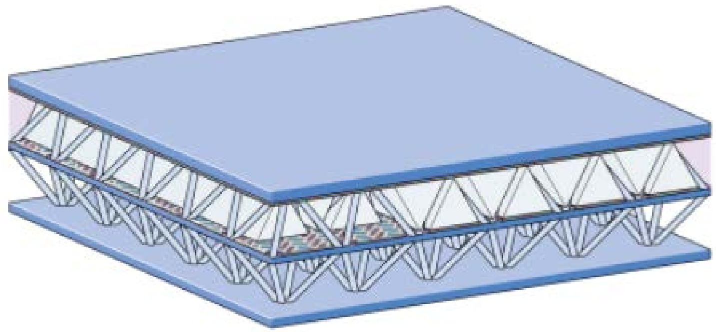


Figure 15.11-1: Sketch of a multilayer sandwich structure comprising a sandwich core with ceramic inserts as the top layer and the empty sandwich panel as the bottom layer. This structure is expected to have multifunctional capabilities in terms of both blast and ballistic performances.

The method used to manufacture the lattice core is shown in **Figure 15.11-2**. In this study, the authors[1] manufactured the core from 1.9 mm thick 304 stainless-steel sheets by first punching rhomboidal holes to obtain a perforated sheet, and then folding this sheet node row by node row to obtain regular pyramids. Again the objective here is to show that out of the box thinking can lead to a new and innovative way to create advanced structural concepts.

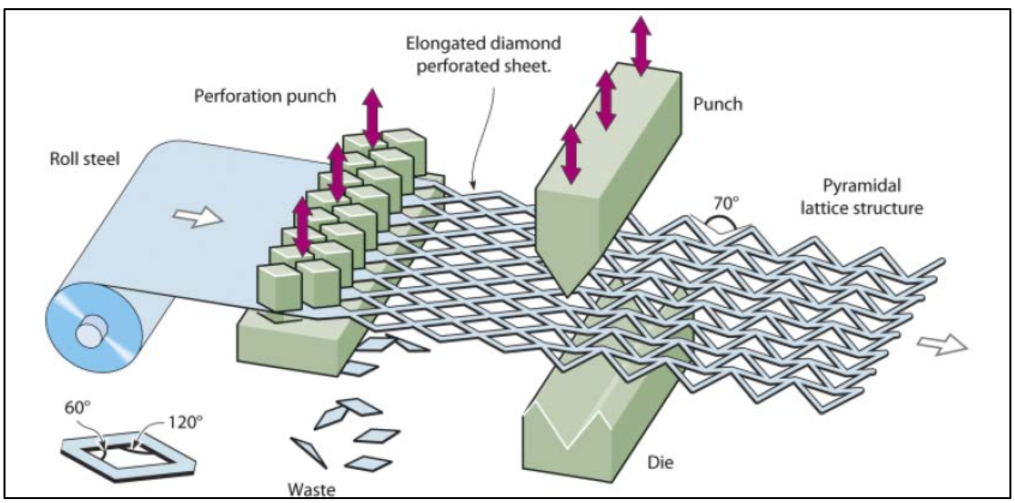


Figure 15.11-2: Sketch of the punching and folding operation to manufacture the pyramidal truss lattice core.[1]

References

[1] Christian J. Yungwirth, John O'Connor, Alan Zakraysek, Vikram S. Deshpande, and Haydn N. G. Wadley; "Explorations of Hybrid Sandwich Panel Concepts for Projectile Impact Mitigation", J. Am. Ceram. Soc., 94 [S1] S62–S75, (2011).

16. METALLIC MATERIALS R&D CHALLENGES

A materials revolution has been underway for several years. Because of the importance of lightweight materials and structures in aerospace systems there has been and continues to be a global emphasis on advancing materials and structures technologies to enhance the performance of future air vehicles, space launch vehicles, and spacecraft systems. Metallic materials, composites, and ceramic materials are being improved through multidisciplinary R&D programs focused to meet stringent system level requirements. Recent advancement in manufacturing technologies for such as additive manufacturing and near-net-shape processes are receiving a lot of attention for lowering cost. Systems trade studies have and continue to point to the need to lower final part count and cost, reduce time to produce components, automate production of complex geometries, develop inspection/quality control techniques and instrumentation for "on the fly" inspection, establish methodologies and computer codes to accurately predict failure and ensured durability, identify environmentally friendly materials and processes, mitigate any hazardous health issues during production or in service use, and develop manufacturing technologies to enable on demand production to digitally specified CAD/CAM criteria. Technologies in materials design, process modelling, and material behaviour prediction that will lead to new lightweight and multifunctional materials and structures are critical for meeting stringent requirements for future NASA missions.

In prior sections we have highlighted accomplishments from past NASA R&D on metallic materials and structures. Working with material suppliers, key universities, and the aerospace companies NASA has made excellent contributions to the advancement of metals technologies for aircraft and space applications. NASA is in a strong position to continue to make advancements in the future based on the skills of the staff and the facilities available. In this section we have highlighted promising areas of future research where NASA is in a unique position to continue to improve lightweight alloys, advanced manufacturing technologies, and life prediction methodologies to enable lighter, safer, and more robust air vehicles and space launch vehicles.

To put these proposed future research directions in context with other technology development needs for future NASA missions we will first examine recent technology roadmaps developed for NASA by the National Research Council (NRC) for space applications and the highlight of a decadal survey for NASA's aeronautical program. The balance of the chapter will then address technical challenges.

16.1. Roadmaps

Two recent studies (**Figure 16.1-1** and **Figure 16.1-2**) were performed by the NRC for NASA in which lightweight materials and structures were identified as high-priority technologies for future NASA space missions and for aeronautics.

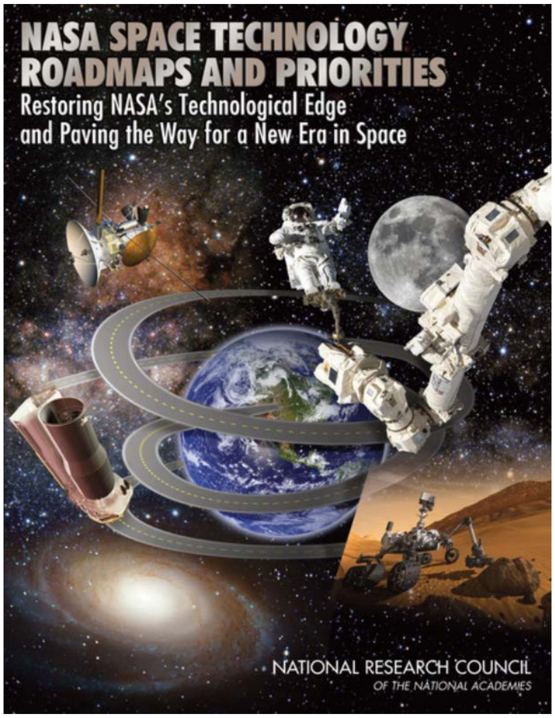


Figure 16.1-1: NASA Space Technology: Roadmaps and Priorities.

16.1.1. Space Roadmaps

The National Research Council (NRC) recently published a book entitled "NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space" which contains the results of a study performed for NASA.[1] A brief excerpt from that report states:

"Lightweight Space Structures: Develop innovative lightweight materials and structures to reduce the mass and improve the performance of space systems such as (1) launch vehicle and payload systems; (2) space and surface habitats that protect the crew, including multifunctional structures that enable lightweight radiation shielding, implement self-monitoring capability, and require minimum crew maintenance time; and (3) lightweight, deployable synthetic aperture radar antennas, including reliable mechanisms and structures for large-aperture space systems that can be stowed compactly for launch and yet achieve high-precision final shapes."

Lightweight materials and structures were identified as high priority for all three NASA technical objectives considered by NRC:

- Technology Objective A: Extend and sustain human activities beyond low-Earth orbit. Technologies to enable humans to survive long voyages throughout the solar system, get to their chosen destination, work effectively, and return safely
- Technology Objective B: Explore the evolution of the solar system and the potential for life elsewhere. Technologies that enable humans and robots to perform in-situ measurements on Earth (astrobiology) and on other planetary bodies
- Technology Objective C: Expand our understanding of Earth and the universe in which we live. Technologies for remote measurements from platforms that orbit or fly by Earth and other planetary bodies, and from other in-space and ground-based observatories.

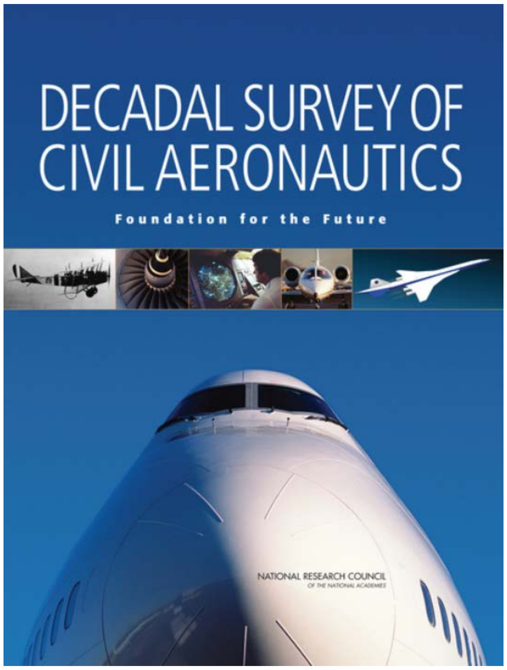


Figure 16.1-2: Decadal Survey of Civil Aeronautics.

16.1.2. Aeronautics

A number of documents and policies over the past several years have been put in place to establish the goals for NASA's Aeronautics Program. These documents include the NASA charter documents, the National Research Council's *Decadal Survey of Civil Aeronautics*,[2] the "National Aeronautics Research and Development Policy," the National Plan for Aeronautics Research and Development," and "Vision 100—Century of Aviation Reauthorization Act and the Integrated Work Plan," to name just a partial list.

The highest priority materials and structures research and technology challenges taken from the Decadal Survey are shown below in **Figure 16.1-3.**

C1 Integrated vehicle health management
C2 Adaptive materials and morphing structures
C3 Multidisciplinary analysis, design, and optimization
C4 Next-generation polymers and composites
C5 Noise prediction and suppression
C6a Innovative high-temperature metals and environmental coatings
C6b Innovative load suppression, and vibration and aeromechanical stability control
C8 Structural innovations for high-speed rotorcraft
C9 High-temperature ceramics and coatings
C10 Multifunctional materials

Figure 16.1-3: Materials and Structures Priorities Identified in Decadal Survey.

Although metallic materials and metal matrix composites are not specifically spelled out in this list, they are included in C2, C6a, and C10. It should also be noted that C13 was Advanced Airframe Alloys.

In 2012, NASA developed a DRAFT Space Technology Roadmap for the NRC recommending the overall technology investment strategy and prioritization of NASA's space technology investment.

In the following sections, we have attempted to identify high-payoff opportunities for NASA to explore that fit within their charter and for which they have the expertise and facilities to advance key aerospace materials and structures in support of current and future NASA programs.

Pathway Forward in Metallic Materials and Structures

- **Processing Modeling and Fabrication of Light Alloy Near Net Shape Structures**
- **Direct Deposition Technology for Complex Geometrical Shapes**
- **Metal laminates and Hybrid Composites**
- **Liquid Metals – Amorphous Metals**
- **Damage Science – Computational Modeling and Simulations**

Figure 16.1-4: New Opportunities in Metallic Materials.

References

[1] NRC Report: NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space (2012) http://www.nap.edu/catalog.php?record_id=13354.

[2] National Research Council, Decadal Survey of Civil Aeronautics: Foundation for the Future, The National Academies Press, Washington, D.C., 2006.

16.2. Al alloys and Al-Metal Matrix Composites (MMC)

Aluminum alloys have always been the primary material of choice for structural components of aircraft since about 1930. Although polymer matrix components are being used extensively in high-performance military aircraft and the new Boeing 787 and the Airbus A380, aluminum alloys will continue to be used for many commercial and military applications.

There have been a large number of research and development activities focused on Al-Li-X alloys in many countries, universities, and industrial and government laboratories. NASA played a significant role, both in-house at Langley and through out-sourcing to universities and industry, in the development of processing parameters, property measurement and treatments for property improvement, and welding technology of Al-Li-X alloys.

Although the early Al-Li-X alloys and the second generation of Al-Li-X alloys had undesirable performance and manufacturing characteristics, fundamental studies identified the root causes of those problems and led to the improved third generation of Al-Li-X alloys having high strength/fracture toughness, fatigue, and corrosion resistance. Finally, a number of the new alloys are currently being used:

- The F16 Fighter Aircraft (Weldalite™, 2297)
- The A380 Airbus (2196)
- The Boeing 787 Dreamliner (2099/2199)

- Being considered for the A350 Twin-engine Aircraft (Alcan Alloys 2098/2198)
- Super Lightweight Tank for the Shuttle (2195) (**Figure 16.2-1**).

Figure 16.2-1: The Super Lightweight Tank for the Space Shuttle (2095).

The properties of the third generation of Al-Li-X alloys can be tailored to meet a variety of needs of future aircraft and spacecraft for weight savings, performance enhancement, and reduced inspection and maintenance. Because aluminum alloys are used in a variety of product forms including sheet, plate, extrusions, forgings, tubes, etc., different processing procedures may be necessary. In addition, different components of aircraft and space vehicles require different sets of properties, and this may require a variety of aluminum-lithium alloys to be used on a particular aircraft or space vehicle, along with other materials, e.g., composites, titanium alloys, etc. Having already made significant contributions to the processing of these new Al-Li alloys the scientists and engineers at NASA Langley are well positioned to continue research and development for near-net-shape manufacturing for structural components in both aircraft and space vehicles.

NASA Langley has also been involved in the development of high-temperature aluminum alloys for use in structural components of high-speed aircraft. For example, in 1992 NASA initiated the High-Speed Research (HSR) Program directed towards developing materials for the possible production of a high-speed civil transport. Besides the researchers at NASA Langley, the research team also consisted of Alcoa, Allied-Signal, Boeing, McDonnell Douglas, Reynolds Metals, and the University of Virginia. Four classes of aluminum alloys were investigated: (1) ingot metallurgy (I/M) 2XXX containing Li (Reynolds) and I/M 2XXX without Li (Alcoa); (2) I/M 6XXX (Alcoa); (3) two powder metallurgy (P/M) 2XXX (Alcoa and Allied-Signal); and (4) two different aluminum-base metal matrix composites (MMC) (Alcoa and UVA). The I/M alloys were targeted for a Mach 2.0 aircraft and the P/M and MMC alloys were targeted for a Mach 2.4 aircraft.

Most of the recent work on aluminum metal matrix composites has been focused on discontinuously reinforced Al (DRA). The development of affordable and scalable process and manufacturing techniques has been responsible for the widespread commercial usage of discontinuously reinforced MMCs with the development of the Duralcan liquid metal processing route and the DRA Al composites P/M process leading to many major automotive applications and most aeronautical applications. The use of DRA in F-16 ventral fins was followed by selection for fuel access door covers, and the use of DRA cylinder liners in the Toyota Celica was followed by selection of DRA brake components in the Toyota RAV4-EV and the use of MMC cylinder liners in the engines for Honda, Toyota, Daimler, and Porsche. Also, sharing information for the F-16 applications led to the fan exit guide vanes of some Pratt & Whitney engines.

Although the HSR Program discontinued funding for the development of aluminum technology in December 1996, the alloys developed on the program had attractive properties, and research and development work continued in-house at NASA Langley and at the aluminum companies. The research on two of the alloys, C415 and C416, resulted in the development of 2040 (C415), which is currently used for forged aircraft wheels (**Figure 16.2-2)** where elevated temperature properties are important. Aluminum aircraft wheels are subjected to demanding operating conditions during service such as heat, carbon dust, runway and aircraft fluids, and high-energy braking events. Alloy 2040 possesses an enhanced combination of desired materials properties and produces wheel designs lighter in weight than those of other aluminum wheel alloys, e.g., 2014 and 7050.

The demand for lighter structures and advanced manufacturing technologies has led to the development of Al-Mg-Sc alloys, which have a density similar to the latest aluminum-lithium alloys. They offer excellent fatigue and damage tolerance properties. These alloys are amenable to laser-beam and friction stir welding and parts can be produced using additive manufacturing technology and could well fit into NASA Langley's program on advanced manufacturing technology.

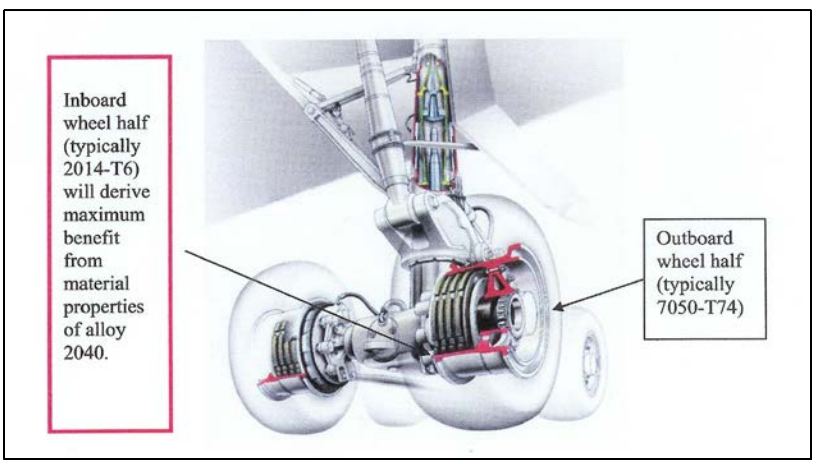


Figure 16.2-2: Alloy 2040 is targeted for use at the Inboard Wheel Half, which is subjected to High Thermal and Mechanical Loads.

16.3. Mg Alloys

Magnesium is the lightest structural metal with a density of 1.738 g/cm, considerably lower than aluminum, titanium, and iron. Due to its attractive specific properties, it has been, and will continue to be, considered for structural applications in a wide variety of aircraft and helicopters. However, magnesium has a number of problems that are of concern to the design engineer and which have limited its use. Its corrosion resistance was initially a problem but it was found that this was due to the normal presence of trace impurities of iron, nickel, and copper, and improving the purity of the base metal essentially eliminated this problem. Magnesium's position on the electromotive chart leads to extensive corrosion when in contact with other metals, so often coatings are applied to isolate magnesium from other materials.

There are a number of R&D projects at the present time in the European Union, the United States, Israel, France, and Austria directed at improving the properties of magnesium for use in the aerospace industry. In particular, the Israeli Company AMTS has been developing a complete range of solutions for applying wrought magnesium within the aerospace industry. For commercial aircraft these include cockpit instrument panel, service door inner panel and rudder pedal. In addition, Israel is using magnesium in unmanned aerial vehicles, and, of course, helicopters. Boeing has also been active in examining magnesium for aerospace applications with a focus on interior applications, e.g., seat frames. Some of the objectives of current R&D programs are

- development of new magnesium wrought products (sheets and extrusions), that provide significantly improved static and fatigue strength properties, as high as 5083 for non-structural applications and 2024 for secondary structural applications;
- simulation and validation of forming and joining technologies for the innovative material and application;
- development of environmentally friendly surface protection systems and advanced design concepts;
- development of material models and failure criteria for the prediction of forming processes, plastic deformation and failure behavior of components.

Magnesium Elektron has been working very hard on getting approval for the use of magnesium in aircraft seating. This approval has been granted according to the minutes of the June 2013 FAA Committee. The announcement stated that "With the results of the magnesium full-scale testing and the progress demonstrated in the development of the lab scale test method, the FAA will now allow magnesium in aircraft seats, providing the requirements and conditions as set out in the Special Conditions are satisfied."

It is obvious that with all of the current research and development activities around the world on magnesium alloys new opportunities will soon arise for lightweighting many aerospace structures with this lightest structural metallic material. NASA is well positioned with the facilities and expertise to make significant contributions to necessary improvements to magnesium alloys, especially in the area of developing manufacturing technologies.

16.4. Hybrid Metal Laminates and Metallic Matrix Composites

In 1966, Gil Kaufman, working at the Alcoa Laboratories in Pittsburgh, showed that the fracture toughness of adhesively laminated aluminum plies was improved in comparison to that of an equivalent monolithic plate due to the individual plies failing in a plane stress state. Subsequently, Johnson and colleagues at NASA Langley showed that significant improvements in fatigue and crack-growth resistance could also be realized by adhesively laminating thin aluminum plies together. In the early 1980s, Johnson extended this work to show that adhesively laminated titanium plies improved fracture toughness by almost 40%, increased fatigue life by an order of magnitude, and slowed down through-the-thickness crack growth rates by 20%.

During the 1970s and 1980s professors and students at Delft University began to examine the concept of fiber metal laminates and quickly realized that the production of the laminates required partnerships with material suppliers for strong fibers and aluminum alloy sheets. This led to a partnership with the Dutch chemical company AKZO to supply aramid fibers suitable for laminates and Alcoa to provide the thin aluminum alloy sheets. This cooperative research resulted in the development of aramid-reinforced aluminum laminates (ARALL) (See **Figure 15.5-1**) and later Glass Reinforced (GLARE).

The first use of ARALL in aircraft was as a number of wing hatches of an access hole of the Fokker 50, which was given certification by the Dutch Airworthiness authorities RLD. However, French studies for the fuselage shell of an Airbus A320 were disappointing and only one contract for the application was won by Alcoa for the C-17 military transport aircraft in 1988. Only the cargo door with dimensions of 5.6 by 9.7 meters was successful. It was manufactured from ARALL-3 by McDonell Douglas and led to 26% weight savings. The ARALL panels that could be produced by Alcoa were too small and had to be connected together with expensive titanium straps resulting in the laminate being about 10 times as expensive as aluminum. Only about thirty C-17 aircraft were built with ARALL cargo doors.[1]

GLARE is currently the most successful fiber metal laminates, patented by Akzo Nobel in 1987 and now entering commercial application on the Airbus A380, which received a full type certificate from the FAA and European Aviation Authorities. A partnership between AKZO and Alcoa started to operate in 1991 to produce and commercialize GLARE. A formal agreement to establish the Structural Laminates Company, a joint venture of AKZO (1/3 owner) and Alcoa (2/3 owner), was signed in June 1991. Research and laboratory tests showed that GLARE had both impact and fire resistance, and containers made from GLARE could contain a blast similar to that which occurred in the explosion that resulted in the Lockerbie crash over Scotland. Subsequently, the FAA tested and approved the use of GLARE for containers, and it was subsequently used to manufacture the ECOS containers by Galaxy Scientific Corporation, which are in production.

It is possible to “tailor” GLARE during design and manufacture such that the number, type, and alignment of layers can suit the local stress and shapes throughout an aircraft. This allows the production of double curved sections, complex integrated panels or very large sheets. The real breakthrough for GLARE came when Airbus selected it in 2001 for the upper fuselage section of the A380. While a simple manufactured sheet of GLARE is more expensive than an equivalent sheet of aluminum, considerable production savings can be made using this optimization. A structure properly designed for GLARE will be significantly lighter and less complex than an equivalent metal structure, and will require less inspection and maintenance and enjoy a much longer lifetime-till failure, making it a cheaper, lighter, and safer option overall.

References

[1] Elke Hombergsmeier; "Development of Advanced Laminates for Aircraft Structures", ICAS 2006, 25th International Congress of the Aeronautical Sciences, 2006.

16.5. Metallic Cellular Structures and Foams

Metallic foams create a relatively new class of structural materials possessing enormous application potential in lightweight construction. The development of metallic foams and cellular structures were driven by the desire for greater performance. Features in metallic foams and cellular structures consist of metallic areas and open spaces, i.e., holes. The properties, and therefore potential applications, of cellular metals and foams are usually a sensitive function of relative density, cell type (open/closed), and cell size distribution. Applications for acoustic damping, catalyst support and perhaps impact energy absorption are well served by stochastic materials. Applications where load support or thermal management dominates are optimized by a periodic truss structure. However, as Wadley has pointed out, it is not yet clear if the increased cost of the periodic cellular manufacturing process under development today can be compensated for by the reduction in weight. Also, ongoing improvements in foaming processes may, overtime, reduce the discrepancies in performance and further lessen the impact of the periodic materials. **Figure 16.5-1** shows schematic representations of several lattice topologies: (a) tetrahedral, (b) pyramidal, (c) 3-D Kagome, (d) diamond weave, (e) hollow truss, and (f) egg box (figure provided by Haydn Wadley).

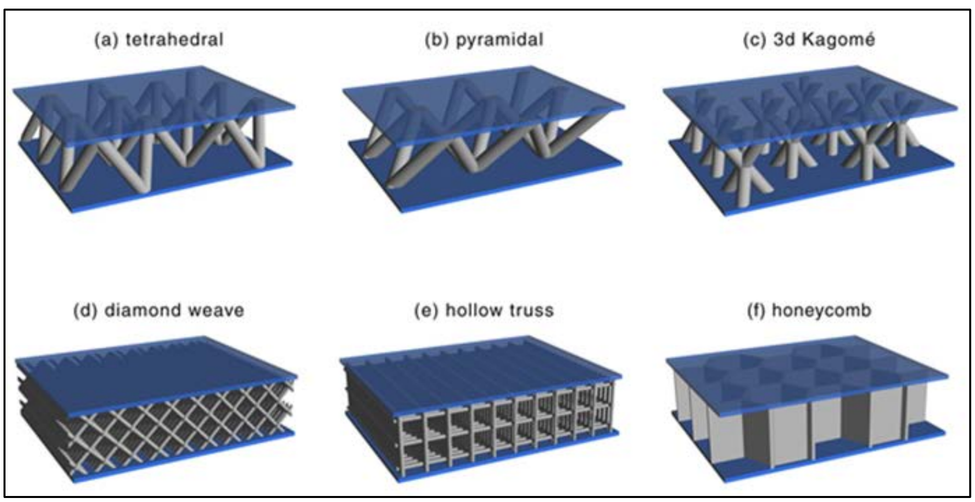


Figure 16.5-1: Example Metallic Cellular Structures and Foams.

Metallic foams are a promising alternative to honeycomb structures as they offer comparable structural and thermal performance without the presence of micrometeoroids and orbital debris shielding-detrimental channeling cells. In a recent paper by Ryan, Hedman, and Christiansen[1], hypervelocity impact tests on the double-layer honeycomb and double-layer foam configurations showed that for comparable mechanical and thermal performance, the foam modifications provided a 15% improvement in critical projectile diameter at low velocities (i.e., 3 km/s) and a 3% increase at high velocities (i.e., 7 km/s) for normal impact. With increasing obliquity, the performance enhancement was predicted to increase, up to a 29% improvement at 60º (low velocity). Ballistic limit equations have been developed for the new configuration, and consider the mass of each individual shield component to maintain validity in the event of minor configuration modifications. Previously identified weaknesses of open-cell foams for hypervelocity impact shielding such as large projectile diameters, low velocities, and high-degrees-of-impact obliquity have all been investigated and found to be negligible for the double-layer configuration.

Revolutionary materials and structures are high-payoff research areas for NASA to continue funding. A unified approach of basic research and synthesis of new metallic material product forms, (e.g., porous and direct deposited metals), should be pursued in order to establish processing-structure-property correlations, develop design methodology using physical models that link structural function with material characteristics, and to conduct environmental durability studies under extreme environment conditions expected during vehicle service life.

References

[1] Shannon Ryan, Troy Hedman, Eric L. Christiansen, “Honeycomb vs. Foam: Evaluating a Potential Upgrade to ISS Module Shielding for Micrometeoroids and Orbital Debris”, NASA/TM-2009-214793, Sept. 2009.

16.6. Nanotechnology and Nanomaterials

One important area of nanotechnology is the use of nanomaterials for coatings for wear resistance, corrosion resistance, and thermal protection. Plasma spraying, a branch of thermal spray processing has attracted the attention of synthesizing bulk nanostructured coating and near-net-shape components. Ceramic coatings are attractive because they possess good thermal and electrical properties and are more resistant to oxidation, corrosion, erosion and wear than metals in high-temperature environments. Nanoparticles of diamond as well as chemical compounds used for hard coatings (SiC, ZrO_2, and Al_2O_3) are commercially available, with typical particle sizes in the range 4–300 nm. Plasma-sprayed ceramic coatings have been successfully used by the U.S. Navy for application in shipboard and submarine applications such as arm weldment, bulkhead pivot arm, bearing sled, front and aft door support, magnet arm, sockets and arm pivot pins, periscope guides, hydraulic piston, and reduction gear set. Plasma-sprayed ceramics have also been frequently used as a corrosion resistant coasting in a variety of industrial applications. It has been shown that there is a higher corrosion resistance of plasma-sprayed “nanostructured” coatings as compared to conventional counterparts. Nano-sized silica has proved to be an alternative to toxic chromate conversion coating.

NASA Langley has a long history of research and development of coatings for corrosion resistance as well as for thermal barriers. The Laboratory is well positioned to aid in the development of nanostructured coatings for advanced aerospace systems.

16.7. Near-Net-Shape Fabrication Technology

Near-net-shape (NNS) manufacturing is initial production of a part that is very close to the final net shape, reducing the amount of subsequent machining, etc., in order to reduce the final cost of the part, both in labor and materials. NNS methods include extrusion, spin forming, and roll forging. NASA Langley investigated NNS manufacturing during the Integral Airframe Structures (IAS) Program for manufacture of airframe primary structure. Airframes of commercial aircraft are primarily of riveted aluminum skin and stringer construction where complete parts are built up from individually fabricated detail components. IAS is an alternate approach in which the part is "integrally stiffened" where the skin and stringers are integrated into a single piece of structure. Integral structures can be less expensive to manufacture than built-up structures in both labor cost and materials and result in an overall lighter component. The IAS Program investigated and gained significant experience toward validating the feasibility of using "integrally stiffened" construction for commercial transport aircraft fuselage structure. The objectives of the program were to build and test a structure that was less expensive than current "built-up" structure, yet equal in structural performance and weight. The IAS Program has shown significant results toward the advancement and application of integrally stiffened fuselage structure. Testing performed as part of this program provided valuable data and experience for designing integral fuselage structure.

It is possible to extrude wide panels with integral stiffeners, and this technology has been applied to transport aircraft in the former Soviet Union where the facilities to produce extrusions exist.[2] NASA Langley, along with Boeing, have been considering extruded integral-stiffened panels as opposed to riveted aluminum skin and stringer construction or integral machined thick plate. An example of an integrally-stiffened extruded panel is shown in the **Figure 16.7-1**.

Figure 16.7-1: Extruded 2090 Integrally Stiffened Panel.

In order to take full advantage of this technology, the properties, including strength, fatigue resistance, corrosion resistance, thermal management, etc., must meet or exceed that of conventionally processed material. The effect of crystallographic texture and grain shape on the mechanical and corrosion properties of near-net-shape extrusions must be understood if these products are to find application in launch vehicles or aircraft structures. NASA Langley had an extensive program to characterize the texture, microstructure, and properties of near-net-shape extrusions, both sheet and plate. Some of this research and development was conducted in cooperation with Russian researchers from the All-Russia Institute of Aviation Materials (VIAM).

Shear forming, also known as flow forming, is a near-net-shape manufacturing technique in which seamless cylindrical structures are produced by reducing the wall thickness and extending the length of ring-shaped preforms. Shear forming was originally developed for steel and successfully used for fabrication of D6AC steel cylinders for space shuttle solid rocket boosters; the shear forming of aluminum is in the early stages of development. There are two methods of shear forming: the counter-roller method and the mandrel method. NASA Langley worked with engineers at Ladish Co. of Cudahy, Wisconsin to develop the technology of shear-formed large cylinders of aluminum alloys for space applications. An example of one of these cylinders that was formed using the counter-roller method is shown in **Figure 16.7-2**. By eliminating welds from a multi-piece construction of large cylinders, the shear forming process is both safer and cheaper. To be useful as structural components, these cylinders must be stiffened and methods such as bonding, welding, and additive manufacturing have been considered. Langley researchers have also demonstrated that thick-walled, flow-formed cylinders can be fabricated and then machined to produce the required stiffeners, but this is a material-inefficient and costly approach.

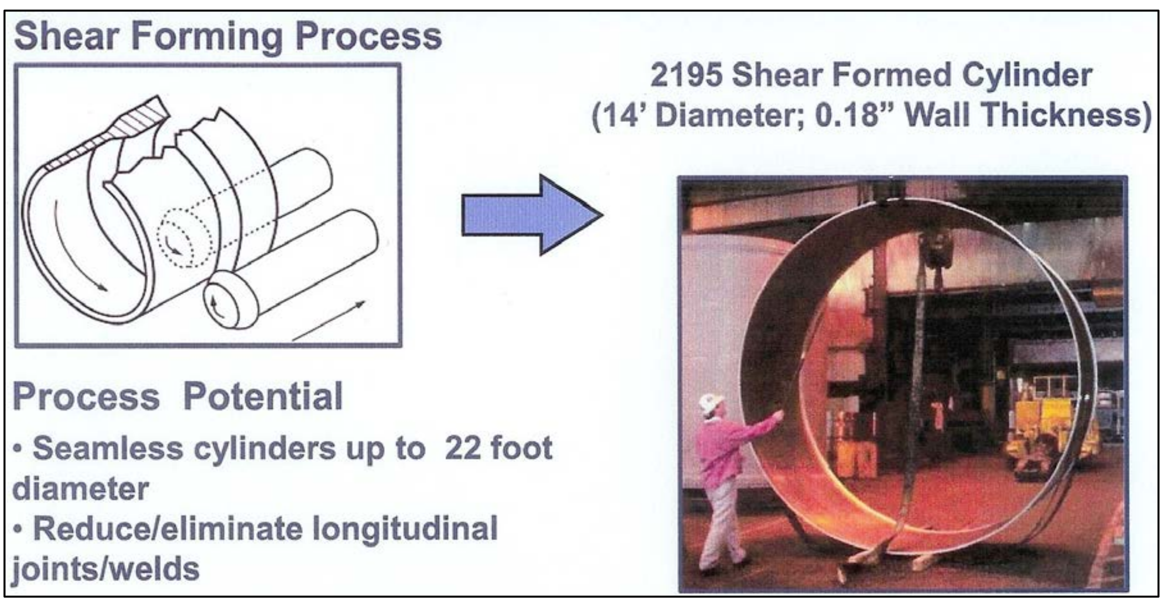


Figure 16.7-2: Example of the Shear Forming Process and a Shear Formed Cylinder Made From 2195.

The team at NASA Langley and the German companies MT Aerospace and Leifeld Metal Spinning are currently developing an innovative manufacturing process for single-piece net-shape integrally-stiffened cylinders for launch vehicle cryotanks. The combined spin-/flow-forming process that is under development could revolutionize cryotank fabrication by producing a single-piece net-shape integrally-stiffened cylinder in one forming operation. Leifeld has been using this technology for the manufacture of small steel automotive parts, such as the commercially produced steel clutch housing, but the Langley program is the first to use this technology for aluminum, in particular, the Al-Li alloy 2195. During this one-step process, a rotating circular blank is formed over a cylindrical mandrel, which has grooves that correspond to the stiffener shape. Metal flows into the grooves as the stiffeners and the cylinder take shape. NASA is working to optimize and scale up the ISC process to fabricate large, aerospace-quality Al-Li alloy cryotanks. The goal is to form net-shape cryotank walls and stiffeners in one forming operation. This will eliminate the need for machining and longitudinal welding of the cryotank barrel section and can reduce barrel fabrication cost by 50%. For an ET-size cryotank, raw-material-scrap rate would be reduced from 90% to 5%, translating into an $8 million savings per tank. Eliminating welds, weld defects, and thick weld lands will also increase safety and lower overall cryotank weight.

A major advancement in near-net-shape spin forming technology is counter roller spin forming, a low-cost, adaptable tooling process developed by MT Aerospace, shown in

Figure 16.7-3. This technology eliminates the large forming mandrel needed in conventional spin forming, providing significant manufacturing flexibility. Counter-roller spin forming can accelerate schedules by eliminating tool manufacturing lead-time and can enable designers to fabricate out-of-the-box concepts. The adaptable tooling concept employs two opposing rollers, inner and counter rollers, to form the metal. The rollers move outward together to shape a spinning circular metal blank to a contour defined and controlled by a computer program. The adaptable and flexible fabrication method will also enable designers to conduct fabrication trials on innovative high-risk, high-payoff structural concepts that were prohibited in the past, in part, by the cost of tooling. NASA Langley researchers are working closely with the German developers with the long-term objective of producing a highly flexible fabrication method that can be used to manufacture multiple components of varied geometry on a single machine.

A common challenge for all of these developmental near-net-shape manufacturing technologies is to demonstrate significant-enough benefit, either in improved performance or reduced costs and mass, to warrant replacement of established manufacturing methods.

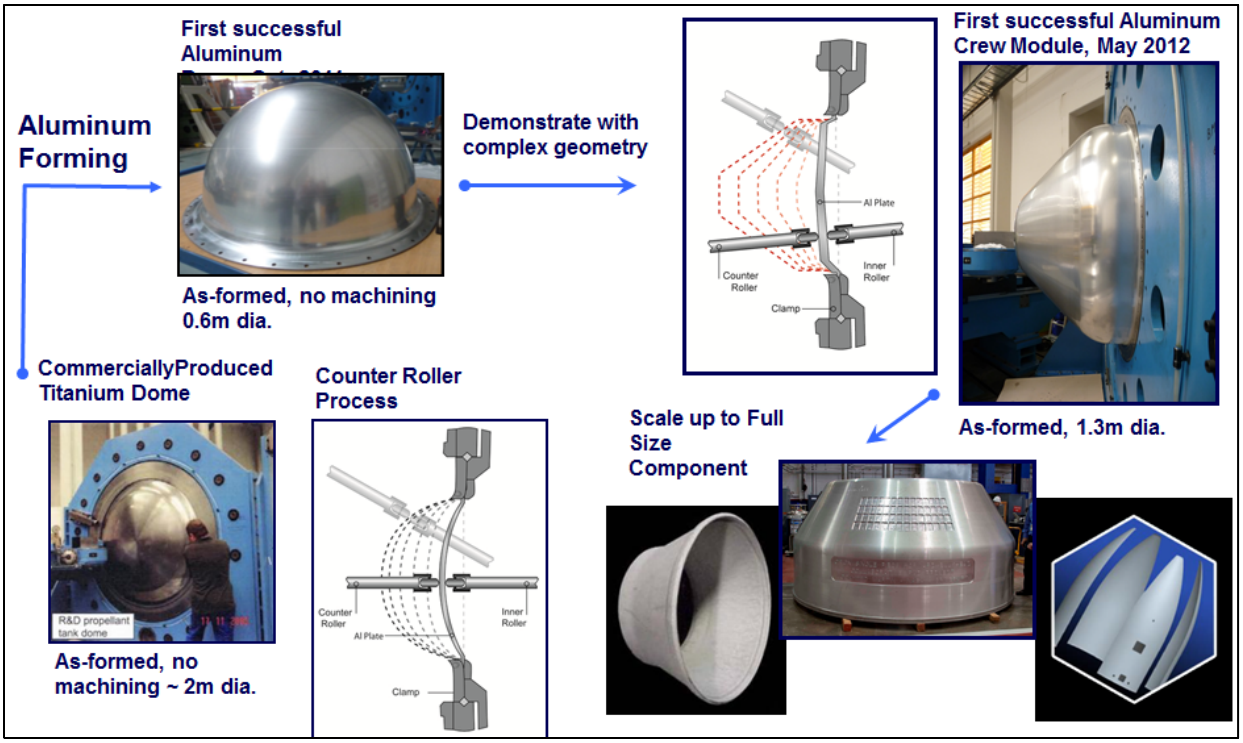


Figure 16.7-3: Counter Roller Spin/Flow Forming.

16.8. Additive Manufacturing Technology

Additive manufacturing technology is an area that Langley, through the dedicated work of Karen Taminger, Robert Hafley, and others has played a key national leadership role and has conducted cutting edge work especially on electron beam freeform fabrication (EBF^3). Langley under the leadership of Karen Taminger should continue to champion this technology for aerospace applications. Also, additional staff should be added in this area to replace key people retiring like Robert Hafley. Hafley was a member of the ASTM Committee F42 on Additive Manufacturing Technologies and significantly contributed to drafting a new standard for directed energy deposition.

Additive manufacturing (AM) is the biggest possible game changer in manufacturing of aerospace parts to come along in quite some time. Additive manufacturing is a novel near-net-shape fabrication technique used to produce solid components by consolidating partial, or fully melted, layers of powder, or wires, or ribbons. The materials to be deposited are melted by a focused heat source, such as an electron beam, laser, or plasma as in arc welding. Each layer is a section of a final 3-D CAD final component model; i.e., the 3-D geometry of the final component is formed by building up a stack of 2-D profiles layer-by-layer.

Current approaches for fabricating functional metal hardware for aerospace components include forging, casting, and extruding. Material properties and part complexity generally dictate which process is selected. However, these often result in starting with a block of material and machining down to the final part. This results in significant lead-time in ordering large billets of material, long spindle times in machining, and significant material waste in the production of machining chips. Layer-additive technologies can be considered “green manufacturing” in that the amount of energy and material used to develop a final part is considerably less with additive manufacturing as compared to conventional approaches. Layer additive technologies also offer significant reduction in lead-time, cost, and waste (in the form of few machining chips and less "toxic waste" from the cutting fluids).

In a recent article[1] published in The Wall Street Journal June 8, 2016 by Daniel Michaels entitled "What 3-D Printing Can Do for Metals," discussed the growth of 3-D printing with metals. In this article he cites comments from Dr. Emmelmann, (Prof. Dr. Ing. Claus Emmelmann, CEO, Laser Zentrum Nord GmbH, Hamburg), who states that sales of 3-D printing systems, which can cost up to $1 million, have increased by eightfold over the past decade. This article shows the data (

Figure 16.8-1) on both sales of 3-D printers by year and annual global sales of products fabricated by 3-D metal printers by year.

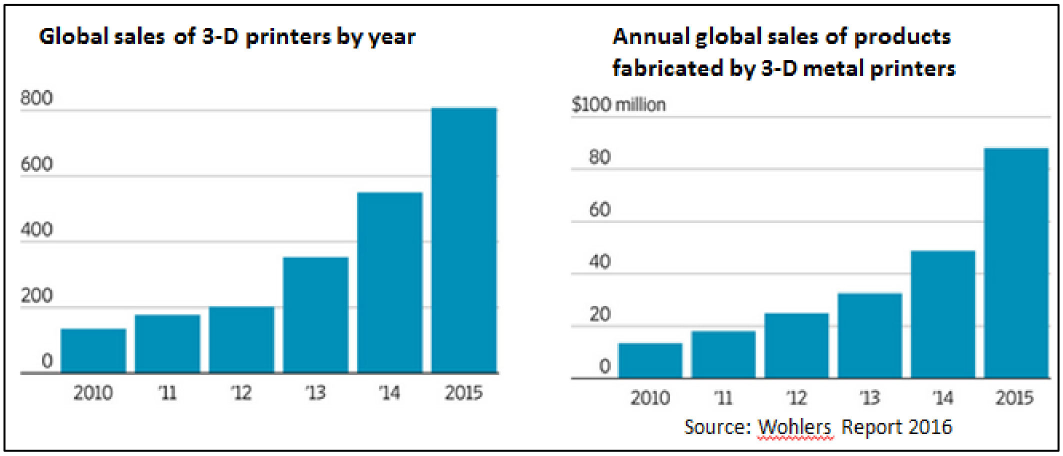


Figure 16.8-1: Global Growth of 3-D Metal Printing (Source: Wall Street Journal Article, "What 3-d Printing can do for Metals," 6/7/16 by Daniel Michaels).

Current efforts are not about using additive manufacturing to make the same parts as in the past but rather they are about fundamentally rethinking how to use this technology to make complex parts in a way to both reduce cost and improve performance. Airbus and other aerospace companies are aggressively pursuing application of this technology to make aerospace quality parts at lower cost. General Electric is now printing fuel nozzles for jet engines, and Boeing has been making 3-D metal structural components for more than a decade. Alcoa is also working to develop new alloys for new designs that can also result in new properties for specialty applications. Additive manufacturing is opening new design approaches for manufacturing complex parts from alloys with chemical compositions specifically tailored to meet critical service requirements. However, there is a continuing need for metallurgical studies to fully characterize structural parts and fully understand how these parts will perform in aerospace service environments.

16.8.1. Electron Beam Freeform Fabrication

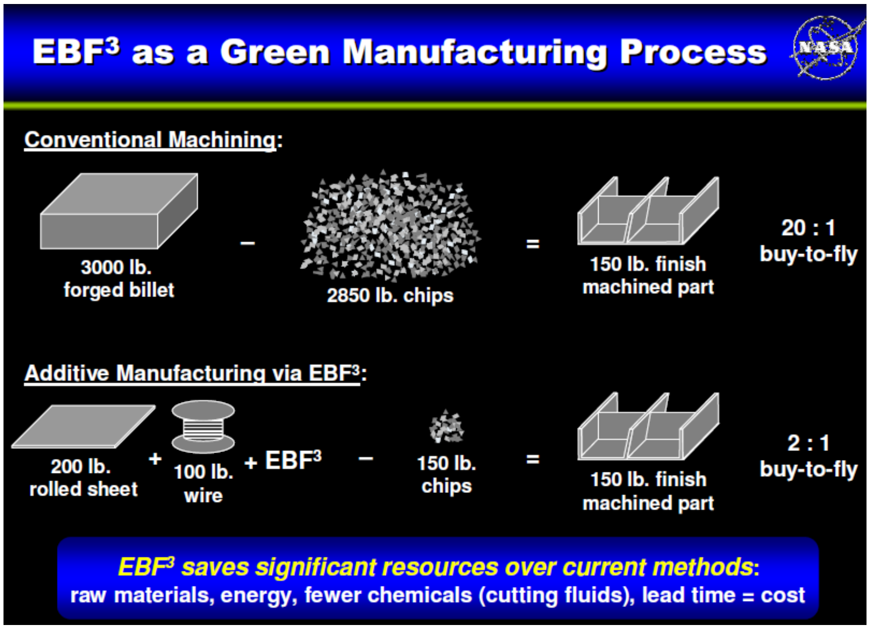


Figure 16.8-2: Advantages of Freeform Additive Manufacturing.

Researchers at NASA Langley Research Center are developing a new solid freeform fabrication process, electron beam freeform fabrication (EBF^3) as a rapid metal deposition process that works efficiently with a variety of weldable alloys. EBF^3 deposits of 2219 aluminum and Ti-6Al-4V have exhibited a range of grain morphologies depending upon the deposition parameters. These materials have exhibited tensile properties comparable to typical handbook data for wrought plate product after post-processing heat treatments. The EBF^3 process is capable of bulk metal deposition at rates in excess of 2500 cm^3/hr. or finer detail at lower deposition rates, depending upon the desired application. This process offers the potential for rapidly adding structural details to simpler cast or forged structures rather than the conventional approach of machining large volumes of chips to produce a monolithic metallic structure. Selective addition of metal onto simpler blanks of material can have a significant effect on lead-time reduction and lower material and machining costs. Examples of parts manufactured by this process at NASA Langley are shown in **Figure 16.8-3**.

Figure 16.8-3: Electron Beam Freeform Fabrication (EBF^3); As-deposited and Machined.

Additive manufacturing is opening new opportunities for designing, tailoring, and producing lightweight aerospace components. The high degree of geometrical freedom of design enables more effective lightweight construction solutions compared to conventional approaches. For complex aircraft components made with multiple assembled parts, 3-D metal printing can result in a considerable weight reduction, which in turn translates into lower fuel consumption and the potential to increase the load capacity of aircraft. Another benefit of additive manufacturing is that the high cost of tooling and other pre-production expenses can be eliminated. Functional samples of components that are very close to being ready for use can be built in the early stages of a new project. This means that sources of error can be identified in the early stages of the design process, which allows for optimization of processes within the project as a whole. Also, because components can be directly printed from the 3-D design system, the throughput time can be reduced by up to 75%, with considerably lower one-off expenses.

Although great progress has been made in additive manufacturing, there are still new horizons to be explored. There is a need for research to fully exploit this new technology by expanding the design space in search of lower cost, and higher performance components for aerospace applications for aircraft, future launch systems and spacecraft. NASA can play a key role in exploring new design approaches and in characterizing the service life performance of 3-D metal parts.

16.8.2. Functionally Graded Alloys and Built-up Structure

In the future, designs will eventually progress to solid-freeform-fabrication-enabled concepts. New alloys will have to be developed that are specifically designed for additive manufacturing processes. New structures will also be designed that take advantage of the ability to locally tailor complex shapes, microstructures, and chemistries through functional gradients. Additive manufacturing also enables embedded multifunctionality and larger-scale component fabrication (unitized structures). The driving force for these developments will go beyond being environmentally friendly, rapid, and lower cost and be driven more by performance enhancements and reduction in weight.

References

[1] Michaels, Daniel; “What 3-D Printing can do for Metals”, Wall street Journal Article, 6/8/16, http://www.wsj.com/articles/what-3-d-printing-can-do-for-metals-1465351381?tesla=y.

16.9. Process Modeling

16.9.1. Digital Manufacturing Technology

The digital revolution is now changing nearly all manufacturing sectors as it continues to disrupt media, finance, consumer products, healthcare, and other sectors. The explosion in data and new computing capabilities—along with advances in other areas such as artificial intelligence, automation and robotics, additive technology, and human-machine interaction—are unleashing innovations that will change the nature of manufacturing itself. Digital manufacturing technologies are transforming every link in the manufacturing value chain, from research and development, supply chain, and factory operations to marketing, sales, and service. Digital connectivity among researchers, designers, managers, workers, consumers, and physical industrial assets is and will continue to change the manufacturing landscape forever. Data generated at all levels of new product development plus data available in the open literature need to be harnessed to drive innovations in manufacturing.

The National Network for Manufacturing Innovation is organizing six major research institutes to speed new manufacturing technologies to market. Although, these institutes have a digital component, one is focused specifically on digital manufacturing. Advances in virtual and augmented reality, next-level interfaces, advanced robotics, and additive manufacturing are leading to digital disruption. And in the next decade a seamless flow of data across the value chain will likely link every phase of the product life cycle, from design, sourcing, testing, and production to distribution, point of sale, and use.

NASA Langley can increase their value to the National Manufacturing efforts for aerospace hardware by becoming more involved in the digital manufacturing movement. Consider having someone become familiar with the thrusts of the National Networks for Manufacturing and even attend meetings, if possible. Strengthen the link between materials processing and sensor development and process modeling based on real-time monitoring of key processing parameters. All-virtual design is becoming a reality and digital manufacturing is a key part of that process.

16.9.2. Materials Genome Initiative

The Materials Genome Initiative is a multi-agency initiative designed to create a new era of policy, resources, and infrastructure that support U.S. institutions in the effort to discover, manufacture, and deploy advanced materials twice as fast, at a fraction of the cost. Since the launch of Materials Genome Initiative (MGI) in 2011, the Federal Government has invested over $250 million in new R&D and innovation infrastructure to anchor the use of advanced materials in existing and emerging industrial sectors in the United States.

NASA’s (MGI) element is a multi-center effort within the Advanced Manufacturing Technology project, which is funded by the Game Changing Technology Program, managed by NASA Langley Research Center.

NASA's MGI element is consistent with the national Materials Genome Initiative and is currently focused on developing computational materials tools to reduce the cost and time to develop and certify components manufactured using novel additive manufacturing processes for aerospace vehicles. Additive manufacturing allows for near-net-shape processing reducing material waste, time and cost of traditional, subtractive manufacturing. NASA is developing physics-based computational models to predict the melt pool, where powder or wire precursors are heated by a laser to form a solid component, the microstructural evolution, and material behavior. These tools will be used to develop basic understanding to optimize the manufacturing process and to guide the certification process.

16.10. Residual Life Prediction Methodology

16.10.1. Multi-scale modeling

Multi-scale modeling of failure in hybrid material systems—dealing with interfaces, composition gradient zones, and stiffness gradients—will continue to be an important area for aerospace systems. Development of new hybrid materials for tailored digital designs is expected as designers explore more innovative approaches to reducing weight and increasing performance of space-related hardware.

This area of research needs to be a key thrust of Langley's materials and structures program and will become even more important as digital manufacturing transforms the landscape of new product development.

16.10.2. Integrally Stiffened Structures: Damage Tolerance

NASA Langley has been a key player in this area of research for many years. However, with the continued efforts to reduce weight and cost and tailoring of metallic structures to meet ever more stringent design requirements this area of research needs to be a primary thrust of net-shape R&D efforts. Fracture toughness and damage tolerance are critical factors in improved safety and durability of aerospace systems. Digital manufacturing technology combined with additive manufacturing increases the need to better understand the metallic microstructure and resulting material properties particularly in zones where the composition or microstructure has been tailored to achieve stringent design requirements.

16.11. Environmental Interaction

The long-term performance of materials in operational service environments is a critical area of research. As new hybrid and composition tailored metallic components are manufactured by digital manufacturing processes, such as additive manufacturing environmental interaction studies, are needed to verify long term durability. Environmental interaction models are needed for digital manufacturing algorithms to guide product design and development to prevent an unexpected "Achilles heel." Safety has and will continue to be of upmost importance in man-rated aerospace vehicles. Also the high cost of space missions dictates that all hardware be robust and highly reliable in hostile space environmental environments.

16.12. Advanced Inspection Technologies (NDE)

16.12.1. Sensory Materials for Structural Health Management

New and improved sensors are needed to monitor and guide real-time manufacturing processes and for structural health monitoring of critical hardware components in service. As space-flight materials become stronger, lighter weight, and applied with lower margins of potential failure, the problem of determining their state of health in real time is not only more important, but more difficult. Materials for sensors used for real-time structural damage monitoring are needed to provide a digital map of time dependent changes in performance which could indicate the need for closer inspection of repair of parts before failure or unacceptable degradation in performance. Most of the recent research on structural health management of aerospace systems has been focused on polymer matrix composites.[1] However, as more metallic materials come on the market either as bulk metallic glasses, amorphous metals, metal matrix composites, or additively manufactured metal hybrids, new approaches to structural health management will be needed.

16.12.2. Intelligent Materials

The challenge is to incorporate intelligence into the material so that the intelligent "system" is no longer a system but is embodied in the smallest part of the matter. The materials of the future will be an integrated material where intelligence, multi-functionality, and autonomy are designed at the smallest level.

References

[1] Reveley, Mary S.; Kurtoglu, Tolga; Leone, Karen M.; Briggs, Jeffrey L.; Withrow, Colleen A.; "Assessment of the State of the Art of Integrated Vehicle Health Management Technologies as Applicable to Damage Conditions", NASA/TM-2010-216911, 2010.

17. Epilogue: Material Needs and R&D Strategy for Future Programs

The speed of change in today's global economy demands a collaborative approach to innovation. Today's world is faster, more complex, and better networked than ever before. By collaborating with external partners that share strategic areas of interest in R&D, NASA can deliver the aerospace materials and structures solutions needed to get new ideas in structural concepts and flight hardware into service faster and more efficiently. NASA's partnerships with world-renown universities, national labs, and industry leaders can multiply NASA's knowledge pool and continues to position NASA on the cutting-edge of innovations within the aerospace markets. In the past NASA has had strong collaborative research with universities, other federal laboratories and industry partners. However, the emergence of social and technical networks combined with a global explosion of technology places renewed importance on maintaining existing partnerships and crafting new partnerships tailored to the changing environment in which NASA must function.

NASA Langley should seek to establish an aerospace materials and structures Innovation Center of Excellence with leading universities and industry partners to work on research and development projects focused on innovative development of new lightweight materials, processes, and fabrication technology to enable new structural concepts with reduced weight and cost and enhanced structural efficiency while achieving a robust durability.

By collaborating with the best and brightest around the nation and perhaps world, in some non-competitive technologies, that have expertise in the sciences at the foundational level, NASA Langley can create a powerful leveraging engine.

Looking to the future, NASA must maintain and strengthen a competence that goes well beyond materials to an understanding of how materials can work together with structural and design innovations to provide optimal solutions when launch vehicles and aircraft are built, flown, maintained, and ultimately recycled after completing their operational lifetimes.

17.1. R&D Research Environment Challenges and Strategies

In 2011, Rifkin published a book[1] entitled "The Third Industrial Revolution" about how lateral power is transforming energy, the economy, and the world. The book was a New York Times best-seller and has been translated into 19 languages. Rifkin describes how the current Industrial Revolution is drawing to a close and why and how we should work to shape the next one. In the First Industrial Revolution in the 19th century printing technology with cheap steam power created a print-literate workforce with communication skills. In the Second Industrial Revolution in the 20th century, convergence of communication (telephone, radio, television) and centralized electricity and oil gave rise to a more dispersed society organized around the internal combustion engine, suburban construction, and a mass consumer society. In the Third Industrial Revolution in the 21st century, collaborative power unleashed by the coming together of internet technology and distributed renewable energies, fundamentally restructures human relationships, from top to bottom and side to side, with profound implications for the future of society. The entire system is interactive, integrated, and seamless. This interconnectedness creates whole new opportunities for cross-industry relationships. (Additional content about Rifkin's "Third Industrial Revolution" is included in Appendix A: Rifkin's Views on Third Industrial Revolution.)

The ideas and principles espoused by Rifkin have inspired the authors of this monograph to contemplate the future challenges and opportunities for NASA Langley in materials and structures as NASA enters its own Third-Generation Period.

17.1.1. A Third-Generation NASA

The first generation of NASA was the NACA period from 1918 to 1958. The second generation of NASA spans the time frame from 1958 when NASA was formed from NACA until the end of the Shuttle Program in 2011. This period was characterized by human spaceflight starting with Project Mercury, the Apollo Program, the Space Shuttle Program, and the International Space Station. The shuttle *Atlantis*, mission STS-135, flew in July 2011, retiring the final shuttle in the fleet. The Space Shuttle Program formally ended on August 31, 2011. If the post-shuttle era of NASA can be characterized as the beginning of a third generation of NASA, a logical question to ask is what does that mean for the future of materials research at Langley?

What does a third-generation NASA look like? Although the third generation of NASA is yet to be written, some of the characteristics of the future are beginning to emerge. One might ask if there are parallels between a Third Industrial Revolution and a Third-Generation NASA, and if there are, what are the implications for NASA? The authors' views on this are outlined in **Figure 17.1-1**. The reader may choose to draw different parallels, or no parallels, but all are challenged to develop their own vision of the future and continually update their vision as changes unfold in their environment. One thing we all know is that nothing stays the same, change is inevitable, and the future belongs to those who embrace change as an opportunity and proactively plan.

Third Industrial Revolution – Third Generation NASA

Energy Economic Model	Techno-Economic Model
• Pillar 1: a goal of 20 percent renewable energy by 2020.	• Pillar 1: goal of 40 percent green R&D (collective learning) by 2020.
• Pillar 2: buildings – green power plants	• Pillar 2: Every Researcher is a Knowledge Generator
• Pillar 3: store distributed renewable energy	• Pillar 3: Subject Matter Experts and Networks – one NASA
• Pillar 4:energy Internet – share and receive	• Pillar 4:Technical Internet – share and receive
• Pillar 5: Transport - plug in electric and hydrogen fuel cell vehicles to the buildings	• Pillar 5: Mobility – Virtual R&D Teams and Distributed Funding

Figure 17.1-1: A Third-Generation NASA—What is it?

Some of the issues and challenges facing NASA as a government agency are listed in **Figure 17.1-2**. This list is certainly not exhaustive, and other issues facing NASA could be added. However, an examination of some of the issues would logically suggest that NASA must continue to reinvent itself if NASA is to remain a world-class organization that is valued by the American public. A sustainable post-shuttle era NASA requires a new game plan for public relevance and support. Human spaceflight to Mars and beyond requires a solution to the health hazard posed by radiation damage to the humans. This difficult issue will certainly add stimulus to robotic missions wherever improving sensor technology is enabling new and exciting data to be collected at far destinations in our universe. Development of new probes and sensors for remotely collecting all types of scientific data is a rich area for advanced work in materials. To capitalize on this trend, NASA should invest additional resources in research on new materials R&D for robotic missions and foster faster implementation of these materials into space hardware.

Emerging Issues and Challenges

1. **NASA is an "Aging Agency"**
2. **Air Travel is viewed as Routine and a Commodity**
3. **Man Space Flight is no longer viewed by all as the New Frontier**
4. **Space Launch viewed by some as better done by Private Enterprise**
5. **The debt crisis has tipped the odds dangerously in favor of an endgame for Agencies in the Discretionary Part of the Federal Budget**
6. **Roles of Federal Laboratories in a global multinational industrial society**
7. **Conducting Cutting Edge Research in a Global Technology Explosion Environment**
8. **Securing Project Pull in a Shifting Mirage of Potential Future Projects and Missions (short half-life roadmaps).**

Figure 17.1-2: National and Global Issues and Challenges for NASA.

17.1.2. Langley in a Third-Generation NASA

A sustainable post-shuttle era for NASA requires a new game plan for public relevance, and support activities within NASA should encourage curiosity and foster a new research and technology development and training culture, capable of innovation in new materials and able to enhance the integration between research on materials and hardware applications. There is a need to develop a "challenge-oriented inter-discipline" environment. Suggestions for keeping Langley as a vibrant federally funded research laboratory are outlined in **Figure 17.1-3**. Having researchers at the cutting edge of their discipline with a proven track record for delivering on promised milestones is essential to winning new work. A key part of this is a proactive personnel policy that is responsive to changing technologies and seeks to continue to train existing staff in new areas and also hires new graduates from universities working emerging new technology areas. Mentoring is also critical for new employees. In a global technology development environment with multinational companies, it is critical that NASA Langley seek out partners to work collaboratively on technology development and to facilitate insertion into engineering products. Because technology advancements are happening globally in every discipline, area researchers must actively scan the relevant literature to keep abreast of advancements made both within the States and globally. The United States no longer has a significant advantage in new technology development. Stakeholders and end users of our technology must be brought into our circle of communication.

Langley in a Third Generation NASA

- Maintain Role of Excellence in R&D
- Sustain and Strengthen Development of Current and Future Generation of Subject Matter Experts
- Proactive Role in Formation and Participation in Collaborative R&D Networks and Partnerships
- Develop Strategy to Capitalize on Global Technology Development
- Provide Technology Solutions to Partners and Clients at a Higher Level than Individual Technologies
- Foster Increased Interaction with End Users

Figure 17.1-3: Langley in a Third-Generation NASA.

The views expressed here are based on the background and experience of the authors and do not represent an official NASA position. The roles defined for Langley are predicated on the belief that aeronautics and space missions will remain important national priorities. Suggestions on possible future roles for Langley are listed in **Figure 17.1-4**. Air travel continues to grow, and issues such as air traffic management, community noise issues, aircraft emissions, and cost of air travel will require NASA's help to solve and should remain research-focused areas at Langley. More efficient aircraft are required to reduce fuel burn, reduce emissions, reduce cost of air travel, and enhance international competitiveness. The emergence of uninhabited aircraft flying in the same airspace as passenger air vehicles poses challenges that will require new technology solutions to insure safety of air travel.

Future Scenario - Langley

1. Continued Leadership Role in Aeronautics R&D
2. Problem Solver for Commercial Launch Industry
3. New Technology Solutions Partner of Choice for Other NASA Space Flight Centers and Space Science Projects
4. Integrated Solutions for National Economic Growth (Partnerships with other Government Agencies and Departments)

Figure 17.1-4: Creating a Sustainable Future for Langley Research Center.

The commercial launch industry is in the early stage of development, and NASA Langley can provide expert help to solve technical issues and help to insure safety much the same way that new technology solutions were developed for both past launch systems. Langley should also be a proactive partner with the other NASA centers and strive to be a preferred provider of new technology solutions for their missions. In addition, Langley needs to strengthen collaborative R&D with other government agencies to support national priorities in areas that promote economic growth for the country.

17.1.3. Materials and Structures in a Third-Generation Langley

Lightweight robust structures and materials are expected to remain a key need for future aeronautics and space missions. Langley has a rich history of making significant contributions to past NASA missions and to the development of the aircraft industry. Four key actions that are judged to be essential for Langley's structures and materials program to thrive in a third-generation NASA are shown in **Figure 17.1-5**.

Structures and Materials in a Third Generation NASA

1. **Develop and Sustain Core Team of Subject Matter Experts in both Metals and Composite Structures**
2. **World Class Laboratories and Testing Facilities for New Concepts and Analyses Validation**
3. **Fabrication and Manufacturing Science and Technology must be an Integral Part of R&D**
4. **Form Technical Partnerships and Consortiums with Universities, Industry, Material Suppliers, and Aerospace Industry**

Figure 17.1-5: Structures and Materials in a Third-Generation NASA.

In looking to the future, it is essential that one not lose sight of the principles that were involved in past successful projects. Some of these have been captured in **Figure 17.1-6**. These factors are derived from analyzing past highly successful Langley materials and structures projects to uncover reoccurring elements judged to be critical to their success.

Success Factors

1. **Opportunity Identified**
2. **Technical Excellence Established in Past R&D**
3. **Critical Skills and Facilities Available – In-House (Best)**
4. **Champion Motivated to Lead**
5. **Team Building**
6. **Sufficient Pre-work to Validate Proposed Solution to Problem**
7. **Opportunity to Directly Interface With Person(s) Who Own the Problem**
8. **Interface With Designers who Need a Solution**
9. **Technical Expert Makes the Presentation of Proposed Work**
10. **Program Plan Developed to the Point of Scoping the Level of Effort Required**
11. **Keep Line Management Informed (No Lone Ranger)**

Figure 17.1-6: Common Success Factors for Securing New Work.

Another important factor in having a successful project is picking the right problem to tackle. Some of the attributes that are common to identifying a “good opportunity” are listed in **Figure 17.1-7.** Avoid any project that requires a “monumental effort for an incremental gain.”

What Makes a Good Opportunity?

- First, does it solve a WIDESPREAD problem?
- Second, do the people with the problem have enough money to pay for solving that problem?
- Third, is it easy to reach the people with the problem?
- Fourth, is the solution a really good one?

Figure 17.1-7: What Makes a Good Opportunity.

Additional factors that should be considered in planning new work are listed in **Figure 17.1-8**.

Keys to Securing New Work

1. Examine Current and Future Role and Missions for Potential Future Problem Areas
2. Identify Key Decision Makers and Seek Opportunities to Interface With them on Their Problems
3. Interface with Other Disciplines – What can you do in your Discipline to help them Solve their Problems?
4. Perform Preliminary Analyses and Simple Validation Experiments to Identify Possible Solutions – Pre-work
5. Build Partnerships with Key Players
6. Be Strategic in Your Thinking – Luck is Preparation

Figure 17.1-8: Keys to Securing New Materials and Structures Work.

Becoming knowledgeable about future NASA missions and the work of advisory groups such as the National Research Council (NRC), which often has been chartered by NASA to develop roadmaps of critical technology needs, is essential to planning new work. Communication with other disciplines is fertile ground because new breakthroughs are often found at the intersection of two or more disciplines. Partnerships can strengthen advocacy for new proposals and can be a rewarding experience for stimulating cross-discipline thinking leading to new insights.

17.1.4. Pathway Forward for Materials and Structures

We now shift to outlining a short list of recommendations (**Figure 17.1-9**) for planning a pathway forward to establishing the aerospace materials and structures innovation Center of Excellence.

Pathway to a Sustainable Future

1. **Asking the Big Questions about Future Viability**
2. **Recognizing Limitations and "Puffed up" Sense of Importance**
3. **Launching a Transformation to a Sustainable Techno-Economic Era**
4. **Setting Targets and Benchmarks**
5. **Resetting Research and Development Priorities**
6. **Develop/Sustain Cutting Edge Technical Capabilities and "Economic World Class" Research Staff**

Figure 17.1-9: Pathway to a Sustainable Future.

A sustainable future for a vibrant and healthy structures and materials future will require a unified effort on the part of senior researchers and line management and project managers. The accomplishments of the past do not guarantee that Langley's structures and materials efforts will be successful in the future. Careful study and searching for relevant roles in future NASA projects is essential for continued funding. Proactive efforts to identify areas where structures and materials can make solid contributions to the success of focused programs are a must.

The continued development of subject matter experts is a key issue for any R&D organizations, and NASA Langley is no exception. **Figure 17.1-10** addresses some of the concerns about the development and sustainment of subject matter experts. In a global technology world where the pace of change in technology is ever increasing, engineering obsolescence is a very real threat to any high-tech organization. Staying on the cutting edge of all aspects of any technology area is difficult at best and nearly impossible in some cases. High tech is a priority for not only the developed nations, but also to the developing nations. Companies have emerged that have made a profitable business of scouring technical journals, conference proceedings, and other forms of searches to draft and sell "intelligence" reports on the status of emerging new technologies. Although this is being driven primarily by the venture capital market, it points to the issue of staying abreast of emerging new technologies and the issues associated with intellectual capital. Therefore, a new approach is required.

The focus needs to be on developing the skills required to "quickly spin-up" in emerging new technology areas that offer high potential impact to developing systems. "Google Engineering" is not sufficient. This is not to minimize the importance of Google searches for new technology information, but more is required. Collaborative relationships must be developed that are not only national, but, in selected cases, must reach to international partners. This can be particularly profitable in areas that are not competition sensitive. NASA should also expand attendance at international conferences and encourage participation in working groups of technical societies.

Growth and Sustenance of SME's

1. In the Past SME's were Grown using Base Level Funding and were Essential to the Development and Execution of Focused Projects

2. Creativity and Innovation in Game Changing Technologies were Incubated and Grown with Base Funding and Matured in Focused Projects

3. Distributed Knowledge Base World Mandates a New Approach to the Development of SME's
   - Collaboration, Partnerships, Sharing Data and Knowledge, Joint Projects, etc.
   - Formulate and Advocate an Agency Level SME Development Plan and Funding

Figure 17.1-10: Growth and Sustainment of Subject Matter Experts.

One of the challenges associated with developing and sustaining technical expertise is associated with the nature of NASA programs. Being at the cutting edge of a new emerging technology requires investment that is not generally supported by focused projects. NASA is a project agency and the very nature of projects is that they have a beginning and an ending with key deliverables and scheduled milestones along the way. There is little room to explore alternative technologies that are at a low technology readiness level (TRL). Cutting edge research requires doing research usually at the fundamental level. For many years NASA had a base program that supported research at a low TRL level and was conducive to developing a highly skilled staff in critical technology areas.

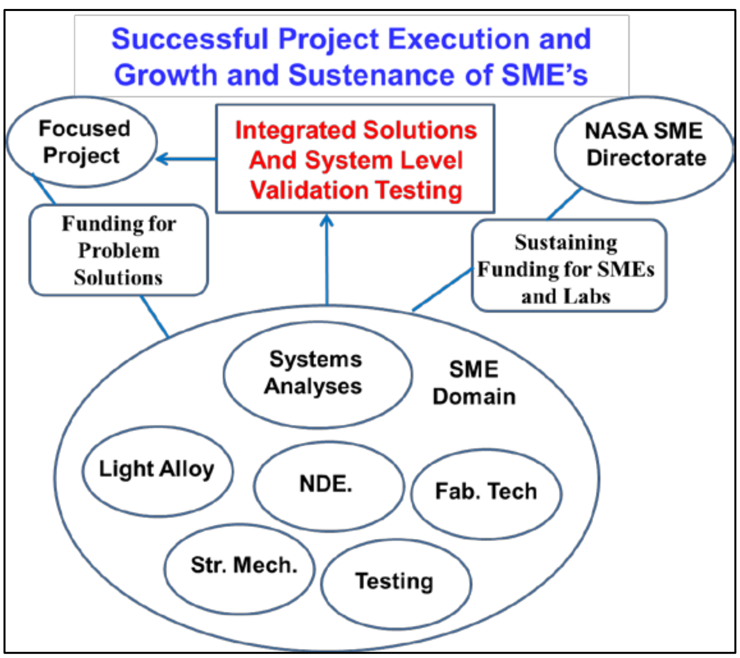


Figure 17.1-11: Successful Project Execution and Growth of Technical Capabilities.

Figure 17.1-11 shows a schematic of a model that combines cooperation of focused projects and foundational research and development. This model is not new or unique, but rather is taken from the past where NASA executed both types of programs under one organizational unit in headquarters. When tough problems were encountered in a focused project the project looked for an engineering solution around the problem so as not to slip the project schedule. Many times the longer term solution was worked out in the base program and increased the foundation technology base for future projects.

References

[1] Rifkin, Jeremy; "The Third IndustrialRevolution", http://www.thethirdindustrialrevolution.com.

17.2. Systems Engineering

There are many new trends in system engineering that must be acknowledged and embraced in all future aerospace research and development programs. It is imperative that materials and structures engineers become familiar with and embrace the systems engineering approach to planning and executing new R&D programs.

The role of systems engineering continues to expand in all phases of research and development programs from fundamental research to building hardware systems. System-level studies are valuable to identify those technical areas that offer the greatest benefit to meet mission requirements. Although the assessment of potential benefits from specific base research projects is far from an exact science, the results from system-level studies does provide valuable guidance for investment decisions. Research portfolios, even in government laboratories, are relying more and more on technology assessments to select focus areas that offer the biggest potential payoffs. Savvy R&D managers are encouraging multidisciplinary teams to work together to maximize the benefits of collaboration and of everyone having a clear vision of the end system level goals. Quantifying the potential payoff of a new technology is critical to securing funding for the project.

Systems engineering has proven to be invaluable for analyzing and understanding complex systems. As manufacturing and material production become more integrated, as is the case for additive manufacturing systems, analyses can add valuable insight into the synergy between processes, alloy chemistry, stress levels, loading conditions, and environmental/durability requirements. These studies can help to reduce complexity.

17.2.1. Design

In a paper entitled "Evolution of U.S. Military Aircraft Structures Technology" by Paul and coauthors,[1] they note that although aircraft structural design has been, for the most part, evolutionary, not revolutionary, it does not mean that there have not been specific technologies that have had major impact in the past and others that are presently in an early stage of development that will have profound impact in the future (**Figure 17.2-1**). Of the technologies currently under development, there are three areas that offer the potential for revolutionary change to aerospace structures: (1) multifunctional structures, (2) simulation-based prototyping, and (3) advanced new materials. These technologies have the potential to produce step increases in airframe efficiency and functionality. A brief discussion of these areas follows.

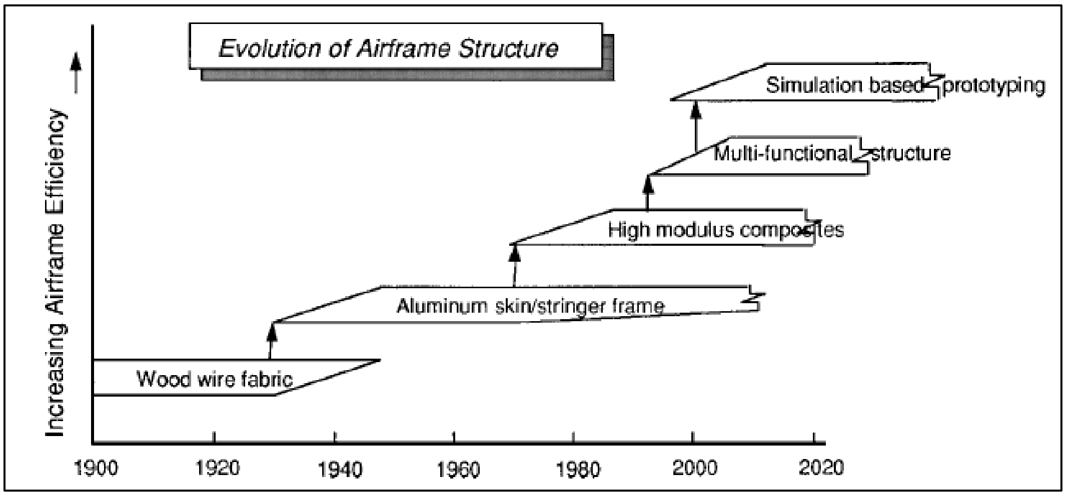


Figure 17.2-1: Step Functions in Airframe Efficiency.

17.2.1.1. Multifunctional Structures

Multifunctional structures include concepts that extend airframe functionality to perform tasks beyond load reaction to increase survivability, lethality, and aero and thermal efficiency and to reduce manufacturing costs while maintaining or improving reliability, supportability, and reparability. Multifunctional structures may contain actuators and sensors that will allow them to alter their mechanical state (position or velocity) and or mechanical characteristics (stiffness or damping). Benefits of such structures include aeroelastic control, load alleviation, and elimination of detrimental dynamic oscillations at reduced structural weight while simultaneously achieving a structural integrity equivalent to present safety requirements. The DARPA/AFRL/NASA Smart Wing[2] Project performed by a team led by Northrop Grumman Corporation (NGC), addressed the development and demonstration of smart materials-based concepts to improve the aerodynamic and aeroelastic performance of military aircraft. Under Phase I (January 1995 to February 1999), the NGC-led team developed adaptive wing structures with integrated actuation mechanisms to replace standard hinged control surfaces and provide variable, optimal aerodynamic shapes for a variety of flight regimes. Under Phase 2, a 30% scale full span wind tunnel model of an NGC Uninhabited Combat Air Vehicle design was developed. Wind tunnel tests were conducted at NASA Langley Research Center in the 16-Foot Transonic Dynamics Tunnel (TDT) in 2000 and again in 2001. The work performed under the Smart Wing Program demonstrated the feasibility of developing smart control surface designs to provide optimal aerodynamic performance at a wide range of flight conditions using multifunctional structures. An excellent review of NASA's research in smart technologies can be found in a review paper entitled "Research Activities within NASA's Morphing Program," by Anna-Maria McGowan[3] and coauthors.

Multifunctional structures are in an early stage of development, but already benefits can be foreseen in reduced life-cycle cost and reduced direct operating cost through improvements in both performance and maintainability. Active/adaptive structures, structure health monitoring, and structure/avionics integration are three areas presently being pursued.

There is a potential to reduce inspections on both new and repaired airframes, thereby reducing maintenance costs. Eventually, multifunctional structures are expected to develop to the point where they can facilitate on-demand and in-situ monitoring of damage. Once they become reliable enough, costly airframe teardown inspections need only be performed when there is a fault indication.

All three elements, sensing, processing, and actuation, need to be supported and matured simultaneously before stepwise improvement in airframe efficiency can be realized. A multifunctional airframe that integrates antenna functions and electronic countermeasures is a future step increase in technology with significant benefits for both air and space structures.

The concept of a structure with the capability of sensing and automatically responding to its environment is one that offers the potential of extremely attractive advantages in the operation of structures in any environment.

17.2.1.2. Simulation-Based Prototyping

Solid modeling coupled with feature-based design software and advanced visualization technology is already enabling the designer to change design variables and to evaluate the effect of these changes on the response characteristics of the structure in real time. It has become commonplace to display stress contours, deformations, and vibration mode shapes in computerized color graphical depictions for highlighting critical areas. In the future, there will be a system of design tools that will facilitate virtual prototyping and enable simulation of advanced technologies and configurations before physical flight. Simulation-based modeling can be a great asset to the materials and structures community because it can be used to optimize structural concepts and define loads, section thicknesses and required materials properties. By combining computational materials and process modeling, potential problems making the required product forms can be minimized.

Alternative configurations can be explored relative to their ease of manufacture and ease of assembly. With the capability to immerse the designer, the user, and/or maintainer in the design, customer familiarity with the product can begin before it is produced. In the concurrent engineering arena, CAD/CAM software will do more than facilitate communication, it will be applied to both design of subsections and assemblies. Design-to-build team members will be able to electronically interact to modify the same digital model. Virtual collaboration engineering already exists for true integrated product and process development and real-time visualization and evaluation of design concepts and manufacturing processes in a seamless simulation environment. Many more alternative structural layouts will be able to be explored in the conceptual design phase. Shared databases will enable the design data to pass directly to numerical controlled programming. New powerful microprocessors will enable logistics personnel with laptops to conduct structural health monitoring and, supported by knowledge-based expert systems and neural networks, to evaluate the significance of damage on the life of the system.

The structures and materials community needs to become more familiar with the design process to better understand how their discipline can be used and transformed into useful engineering products.[4] More engineers with system integration skills are essential to the development of large scale systems. NASA needs to cultivate these skills to promote and facilitate the development of new concepts and programs. NASA also needs to do more collaborative R&D with industry to ensure that expertise in the design process is brought into their R&D projects.

17.2.1.3. Materials Development and Multidisciplinary Design Optimization (MDO)

Early materials development, prior to the 1990s, was performed with only limited interaction with the other engineering disciplines. Following the receipt of materials requirements from the design engineering department, the materials department, in concert with suppliers, iteratively developed and characterized the materials and processes (M&P) and ultimately delivered specifications, drawing notes, and materials property design data curves to its engineering customer. During development, interactions among engineers across disciplines were limited, and confined to periodic reviews, except when serious problems arose. In this climate, ineffective communication between disciplines and the absence of standard development processes too often caused a misunderstanding of materials requirements, misjudgment of insertion risks, and non-uniform development approaches, methods, and decision-making processes. In the early days, aerospace manufacturers developed and produced many capable air vehicles, usually under the direction of highly experienced managers whose careers started in engineering and spanned the entire history of the evolving modern aircraft or space launch vehicle.

The successful development of useful engineering materials for aerospace applications must be done in a multidisciplinary environment where property requirements, product forms, fabrication technologies, shapes required, and service environments are defined by related disciplines. Multidisciplinary interaction is critical for the efficient development of safe, reliable, and affordable flight vehicles. Multidisciplinary design optimization (MDO), which has evolved remarkably since its inception 25 years ago, offers alternatives to complement and enhance the systems engineering approach to help address the challenges inherent in the design of complex engineered systems

MDO was a critical enabling technology in the NASA Morphing Project.[5] In the NASA studies,[6] (**Figure 17.2-2**) it was noted that MDO was fundamental to the design and operation of future morphing vehicles for several reasons: (1) during conceptual design, MDO balances trade-offs between different disciplines and is crucial to achieving the full potential in areas such as active flow control, adaptive structures, and biologically inspired flight; (2) during preliminary design, optimal placement of numerous distributed actuators and sensors in the vehicle ensures efficiency in vehicle design and effectiveness during operation; and (3) during detailed design and operation, MDO enhances flight control algorithms by determining the best set of actuators and sensors for varying vehicle functions.

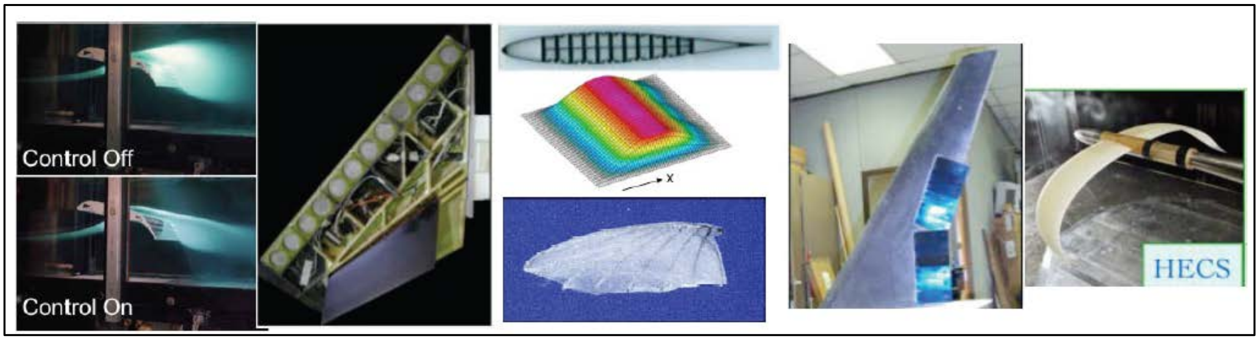


Figure 17.2-2: Examples of NASA's Morphing Research.[6]

MDO was critical to the morphing project and is critical to the successful development of materials for future vehicle systems. Materials and structures engineers need to partner with the NASA MDO experts to optimize properties and processes to meet application hardware requirements.

References

[1] D. Paul, L. Kelly, V. Venkayya, and Thomas Hess; "Evolution of U.S. Military Aircraft Structures Technology," JOURNAL OF AIRCRAFT, Vol. 39, No. 1, January–February 2002.

[2] Kudva, J.N, Martin, C.A., Scherer, L.B., Jardine, A.P., McGowan, A.R., Lake, R.C., Sendeckyj, G.P., and Sanders, B.P.; "Overview of the DARPA/AFRL/NASA Smart Wing Program," SPIE's 6th Annual Symposium on Smart Structures and Materials, Industrial and Commercial Applications Conference, Newport Beach, CA Paper number 3674-26, March 1999.

[3] McGowan, Anna-Maria R., Horta, Lucas G., Harrison, Joycelyn S., and Raney, David L.; "Research Activities within NASA's Morphing Program," RTO AVT Specialists' Meeting on "Structural Aspects of Flexible Aircraft Control," held in Ottawa, Canada, 18-20 October 1999, and published in RTO MP-36.

[4] McMasters, John; "Contributions to Aircraft Design Education," presented at the 47th AIAA Aerospace Sciences Meeting Including The New Horizons Forum and Aerospace Exposition AIAA 2009-870 5 - 8 January 2009, Orlando, Florida

[5] McGowan, Anna-Maria R.; Washburn, Anthony E.; Horta, Lucas G.; Bryant, Robert G.; Cox, David E.; Siochi, Emilie J.; Padula, Sharon L.; Holloway, Nancy M.,;"Recent Results from NASA's Morphing Project," SPIE's 9th Annual International Symposium on Smart Structures and Materials; San Diego, CA; 17-21 Mar. 2002; United States

[6] McGowan, Anna-Maria R., Vicroy, Dan D., Busan, Ronald C., Hahn, Andrew S.; "Perspectives on Highly Adaptive or Morphing Aircraft," NATO RTO AVT-168 Symposium; Lisbon; 20-24 Apr. 2009; Portugal.

17.3. Collaborative R&D

Collaborative NASA R&D has been, and will continue to be, essential for getting new technologies integrated into future hardware systems (**Figure 17.3-1**).

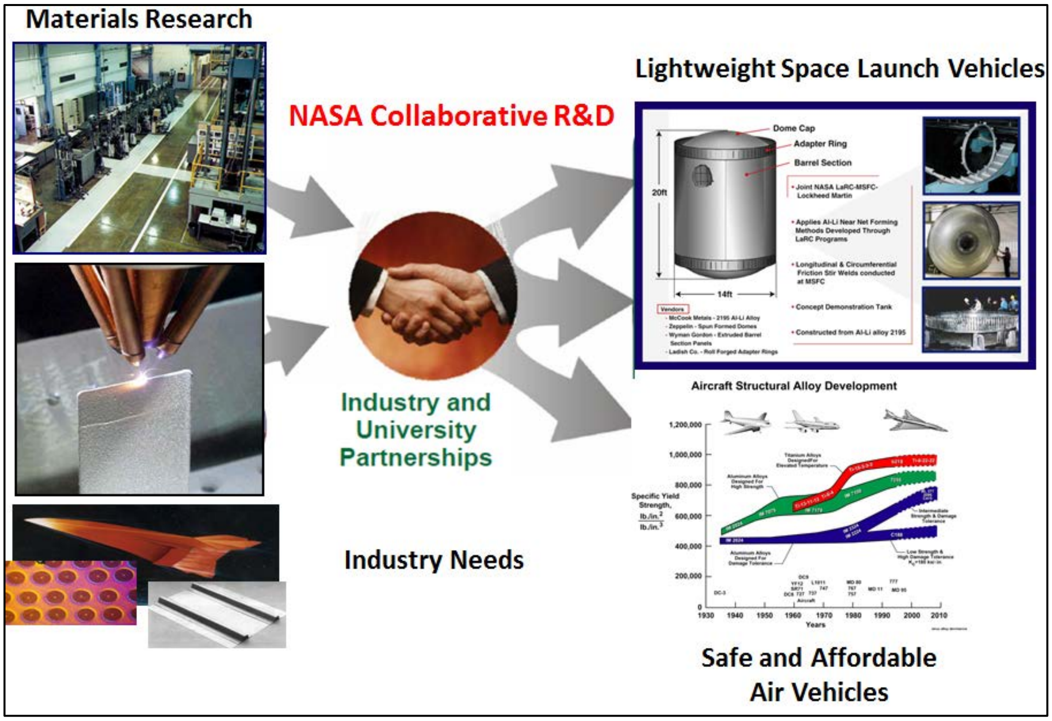


Figure 17.3-1: Collaborative R&D: A Pathway Forward.

17.3.1. The World Really is Flat

We now live in the Google internet world where information is broadly available to anyone with access to the internet. We are seeing a rapid expansion of not only social networks, but also technology networks where innovation and creativity are flourishing. Partnerships and collaborative R&D are being used extensively by global companies to get the best and brightest researchers working on their product lines. Likewise, NASA has a strong heritage of successful partnerships and collaboration with universities, other government laboratories, and industry. However, due in part to budget pressure over the past several years, there is more pressure to find ways to streamline R&D programs to accomplish more with less. There are some proactive steps that NASA can consider to strengthen collaborative research:

1. Seed money to join Cooperative Research and Development Agreements established by other government agencies in metallic materials development and manufacturing technology
2. Provide funding for university research in new technology areas. Craft these efforts as cooperative agreements and have a NASA subject matter expert be an active participant in the research
3. Join industry-initiated cooperative programs where mutual agreement can be established to handle intellectual property rights

4. Foster an environment that rewards researchers for championing technology solutions and for finding mechanisms to maximize return on investment
5. Create an environment where innovation and creativity are fostered and where multiyear stability is provided to enable maturity of new concepts

17.4. Elements of an Effective Research and Development Strategy

Some specific recommendations to shorten the time and cost to develop new materials and processes and get them into aerospace applications that support national priorities are presented below.

The following 10 elements are listed in an approximate order of importance; clearly, the importance of different elements can change with specific circumstances:

1. Annual reviews of the NASA materials and structures R&D projects patterned after the "Old NASA Advisory Council (NAC), Aeronautics Advisory Committee, Subcommittee on Materials and Structures," reviews with a critical look at requirements, objectives, and execution plans to adjust for budget changes and the external environment
2. Take a systems-level approach to integrating materials and structures R&D into existing and proposed future NASA projects that match with the charter of Langley Research Center. Better integration of materials plans requires more involvement of personnel from academia, other government laboratories, and industry in the development of the plans
3. The development of a stable, long-term materials development program that covers basic research through manufacturing and has provision for component level testing
4. The development of a sufficiently robust and, most important, a stable funding stream
5. The continued development of integrated computational materials engineering approaches that promise to shorten the materials development time
6. The implementation of a systems engineering approach to vehicle materials development that includes a risk management plan aimed at inserting materials considerations early in any vehicle development program
7. The use of existing air vehicles and demonstrators to expedite materials insertion and technology maturation
8. The inclusion of academia in transition research and development (R&D) both to take advantage of talent and facilities that exist at selected universities around the country and to ensure the development of the required workforce
9. The increased use of government-industry-academia partnerships to conduct pre-competitive R&D
10. The integration of foreign technology development and research with U.S. efforts. Opportunities for collaborative fundamental research should be pursued.

The bottom line is that the current approach to developing new materials at low levels of maturity is inadequate for today's environment with reduced infrastructure, fewer transition opportunities, increased risk aversion, and limited advocacy and funding.

17.5. Pathway Forward

The development and application of new structural materials have historically either opportunistically exploited novel and independent discoveries or have had programs established in order to use evolutionary developments in composition, microstructure, properties, and processing routes. Whether through opportunistic or concerted efforts, new materials were developed to solve known problems, to expand a material's operational envelope, or even to enable new engine design concepts. Although all new M&P technology introduces some technical, budgetary, and scheduling risk to a vehicle development program, those developments that represented revolutionary departures (i.e., the first application of a materials system or manufacturing process) have created the highest level of uncertainty. For these revolutionary materials, the materials developer too often struggles to anticipate reliably the potential for new-process-induced flaws, inherent materials defects, failure mechanisms, property balances, and manufacturing yield. To overcome some of these shortcomings a NASA strategy plan and vision needs to be developed to plan a pathway forward.

In a recent presentation[1] entitled "So Now, What? Collaborative Pathways Forward," presented by P.F. Tortorelli at a Ferritic Oxide-Dispersion-Strengthened (ODS) Alloys Workshop, Oak Ridge Nation Laboratory, Dr. Peter F. Tortorelli, Deputy Director, Materials Science & Technology Division, Oak Ridge National Laboratory proposed a more collaborative approach to the way design of experiment (DOE) advances ODS alloy for DOE applications. Dr. Tortorelli's view of the DOE's material development approach is discussed in Appendix B: DOE's Science and Energy Pathway.

Based on a review of the DOE materials development philosophy, and the background and experience of the authors the following suggestions are offered for streamlining the pathway forward for NASA's materials R&D programs:

1. NASA needs to develop a strategy to maintain and, in some cases, rebuild a world-class aerospace materials and structures R&D program. The strategy should include the regular review and updating of the materials and structures plans, with an emphasis on maintaining a highly skilled staff with cutting edge skills, the changing external environment, and maintaining a balance for the near-, mid-, and far-term activities in response to the focused long-term challenges and funding commitment.
2. Striving for more and more integrated R&D thrusts. Systems-level trade studies are essential to quantify potential payoff for new technologies to maximize investment and ensure that the most significant technologies get priority for funding.
3. Collaboration is essential. The strategy for developing future aerospace materials should define a materials development program with stable and long-term funding. The program should cover basic research TRL 1–3 through TRL 4–7 development and include manufacturing and insertion strategies. It should involve industry, academia, and other government entities, and it should selectively consider global partners for pre-competitive collaboration. Essential elements of the strategy include a steering committee, feedback metrics, and a risk reduction plan based on systems engineering practices.
4. Bilateral and multi-lateral working agreements are needed to clearly define responsibilities and expectations of all parties involved.

5. R&D programs need to focus on scalability, processing, fabrication technologies, establishment of a supplier base and acceptance by aerospace manufactures.
6. The Research Directorate at Langley should increase their communication and collaboration with the NASA System Program Offices, industry, and academia relative to materials and structures needs, advances, technology readiness, and the potential systems payoffs of technology insertion.
7. To maintain or regain the U.S. competitive advantage in the areas of air vehicle and to keep the United States on the leading edge of space technology, there is a need for advocacy within the NASA Program Directorates to increase activities in new materials development and competitive component and demonstrator programs. Component and subcomponent “build something” projects are needed to drive out critical issues related to manufacturing, inspection, and failure prediction capability.
8.

References

[1] Tortorelli, P.F.; “So Now, What? Collaborative Pathways Forward,” Ferritic ODS Alloys workshop, Oak Ridge National Laboratory, Nov. 18, 2010. http://structures.ucsd.edu/ODS2010/presentations/Peter_Tortorelli.pdf.

Appendix A: Rifkin's Views on Third Industrial Revolution

Rifkin further outlined his view of the attributes of the economic development plan for the Third Industrial Revolution as follows:

- Distributed post-carbon era
- Fossil fuel era is dying: chart a course into a green future
- Economic system that served us well in the past is on life support
- What are we good at: our uncanny ability to envision the future with such vividness and clarity that people feel as if they've arrived even before they've left the station
- The Third Industrial Revolution will lay the foundational infrastructure for an emerging collaborative age
- A two-hundred-year commercial saga characterized by industrious thinking, entrepreneurial markets, and mass labor workforces is ending
- A new era marked by collaborative behavior, social networks, and boutique professional and technical workforces is emerging
- The traditional, hierarchical organization of economic and political power will give way to lateral power organized nodally across society
- The collaborative power unleashed by the coming together of internet technology and renewable energies, fundamentally restructures human relationships, from top to bottom to side to side, with profound implications for the future of society
- In the 20th century, centralized electricity and communication scaled vertically. Internet, by contrast, is a distributed and collaborative communication medium it scales laterally
- Distributed energies, by contrast, are found in some frequency or proportion in every inch of the world: the sun, the wind, the geothermal heat under the ground, biomass—garbage, agricultural and forest waste—small hydro, ocean tides and waves

His thoughts on adapting to change include the following:

- In the business community
    - Older: tend to think more in terms of organizing economic activity in a centralized, top-down fashion.
    - Younger: gravitate toward an organizational style that is more distributed, collaborative and lateral.

- It's analogous to what happened to the music companies: the old guard just didn't understand the far-reaching significance of millions of young people file-sharing music. Then they shrunk or went out of business.
- The newspapers weren't ready for the distributed and collaborative nature of the blogosphere. Now newspapers are either going out of business or creating their own blogs.
- When IBM's cash cow, its retail computer, began to become less profitable because of the global competition among computer manufacturers, IBM needed to rethink its mission. IBM asked a simple question: What do we do as a company that is unique and that the world needs? It's not making computers, it's managing information, so now every company in the world has a chief information officer and IBM, Cisco, HP, and other companies manage their client's information flows.

- Future Role of Utilities; in the future, power and utility companies will set up partnerships with thousands of businesses to help manage their energy flows in their production processes, supply chains, and logistics networks.
- There's far more money to be made by the power and utility company managing energy, reducing the amount of energy their clients use, and then sharing the savings.

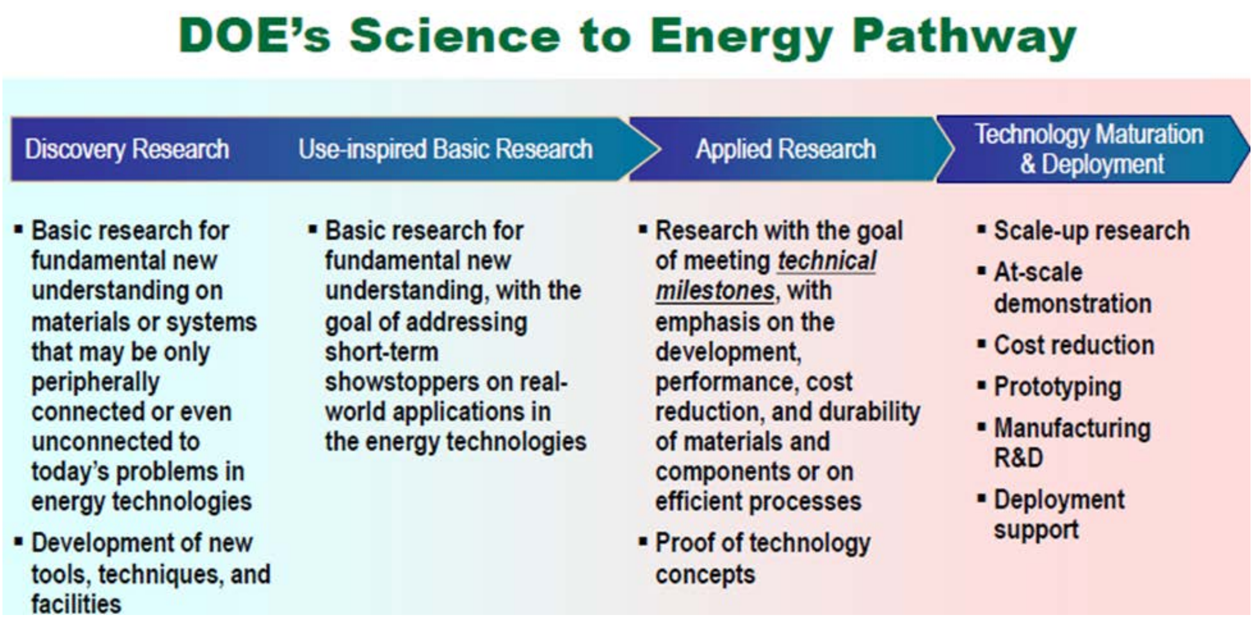
Rifkin notes on his web site [1] that "The intelligent Third Industrial Revolution (TIR) infrastructure—the Internet of Things—will connect everyone and everything in a seamless network. People, machines, natural resources, production lines, logistics networks, consumption habits, recycling flows, and virtually every other aspect of economic and social life will be connected via sensors and software to the TIR platform, continually feeding Big Data to every node—businesses, homes, vehicles, etc.—moment to moment in real time. The Big Data, in turn, will be analyzed with advanced analytics, transformed into predictive algorithms, and programmed into automated systems, to improve thermodynamic efficiencies, dramatically increase productivity, and reduce the marginal cost of producing and delivering a full range of goods and services to near zero across the entire economy."

References

[1] http://www.thethirdindustrialrevolution.com.

Appendix B: DOE's Science and Energy Pathway

In a recent presentation entitled "So Now, What? Collaborative Pathways Forward," presented by P.F. Tortorelli at a Ferritic Oxide-Dispersion-Strengthened (ODS) Alloys Workshop, Oak Ridge Nation Laboratory, Dr. Peter F. Tortorelli, Deputy Director, Materials Science & Technology Division, Oak Ridge National Laboratory proposed a more collaborative approach to the way design of experiment (DOE) advances ODS alloy for DOE applications. Dr. Tortorelli's view of the DOE's material development approach is shown below. It should be noted that the scope of the DOE materials development ranges from basic research (TRL 1–3) to scale-up and prototyping for hardware applications(TRL 6–9). NASA has a similar materials development approach and, as such, the successful strategies used by DOE and NASA share many common features.



Appendix C: Acronyms and Abbreviations

ABMA	Army Ballistic Missile Agency
AE	acoustic emission
AFRL	Air Force Research Laboratories
AGG	abnormal grain growth
AHF	aircraft hydro forming
AIAA	American Institute for Aeronautics and Astronautics
Alcoa	Aluminum Company of America
ALDF	Aircraft Landing Dynamics Facility
ALS	Advanced Launch System
ALTA	Aluminum–Lithium Test Article
AM	additive manufacturing
AMNPO	Advanced Manufacturing National Program Office
AOMC	Army Ordnance Missile Command
ARALL	aramid-reinforced aluminum laminates
ARMOR	adaptable, robust, metallic, operable, reusable
AS&M	analytical services & materials
ASIP	Aircraft Structural Integrity Program
ASTM	American Society for Testing and Materials
BA	British Airways
BMG	bulk metallic glasses
BNNT	boron nitride nanotube
CFRC	carbon-fiber-reinforced composites
CFRP	carbon-fiber- reinforced polymer
CM	crew module
CNT	carbon nanotube
COE	Center of Excellence
COLTS	Combined Loads Test System
CPB	Cryogenic Pressure Box
CST	Commercial Supersonic Technology
CTE	coefficient of thermal expansion
CTOA	crack-tip-opening-angle
DAMVIBS	Design Analysis Methods for VIBrationS
DARPA	Defense Advanced Research Projects Agency
DB	diffusion bonding
DDTRB	Damage Tolerance and Reliability Branch
DICC	debris-induced crack closure
DoD	Department of Defense
DOE	design of experiment

DRA	discontinuous reinforced aluminum
DU	depleted uranium
EASA	European Aviation Safety Agency
EBF^3	electron beam freeform fabrication
ECT	extended compact tension
EDAX	energy dispersive X-ray analysis
EDM	Electro deposition machining
ESEM	Environmental scanning electron microscope
ET	external tank
FAA	Federal Aviation Administration
FGM	functionally graded materials
FML	fiber metal laminates
FPVBH	forward pressure vessel bulkhead
FSW	friction stir welding
GA	general aviation
GASL	General Applied Sciences Laboratory
GLARE	glass reinforced laminate
GSFC	Goddard Space Flight Center
HEDM	high-energy diffraction microscopy
HIP	hot isostatic pressing
HSCT	high-speed civil transport
HSR	high-speed research
HTCL	hybrid titanium composite laminate
HTT	High-Temperature Tunnel
HYMETS	Hypersonic Materials Environmental Test System
I/M	Ingot Metallurgy
IAS	integral airframe structures
IAT	intermediate annealing treatments
ICAF	International Committee on Aeronautical Fatigue
IDEA	Integrated Design & Engineering Analysis
IDRF	Impact Dynamics Research Facility
IGA	intergranular attack
IGC	intergranular cracking
IGY	international geophysical year
IHM	integrated health management
IMI	Institutes for Manufacturing Innovation
IRAD	Independent Research and Development
ISC	integrally stiffened cylinder
ISP	integrally stiffened panels
ISS	International Space Station
IVHM	integrated vehicle health management
JSC	Johnson Space Center
KEP	kinetic energy penetrator
LA^2ST	Light Aerospace Alloy and Structures Technology
LaRC	Langley Research Center
LEO	low-Earth orbit

LH2	liquid hydrogen
LID	liquid interface diffusion
LMT	layer manufacturing techniques
LO2	liquid oxygen
LWT	lightweight tank
M&P	materials and processes
MAE	magnetoacoustic emission
MDAO	Multidisciplinary Design, Analysis and Optimization
MDO	Multidisciplinary design optimization
MGI	Materials Genome Initiative
MGVT	Mated Ground Vibration Test
MISS	Man-in-Space-Soonest Project
MLG	main landing gear
MMC	metal matrix composites
MMOD	micrometeoroids and orbital debris
MPCV	multi-purpose crew vehicle
MSC	MacNeal-Schwendler Corporation
MSD	multi-site damage
MSFC	Marshall Space Flight Center
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
NASIP	NASA Structural Integrity Program
NASP	National Aero-Space Plane
NDE	nondestructive evaluation
NDI	nondestructive inspection
NESB	Nondestructive Evaluation Sciences Branch
NESC	NASA Engineering and Safety Center
NGC	Northrop Grumman Corporation
NIST	National Institute of Standards and Technology
NLS	National Launch System
NNI	National Nanotechnology Initiative
NNMI	National Network for Manufacturing Innovation
NNMII	National Additive Manufacturing Innovation Institute
NNS	near-net-shape
NRC	National Research Council
NSMO	NASTRAN Systems Management Office
NTF	National Transonic Facility
NTRS	NASA Technical Report Server
NTSB	National Transportation Safety Board
OAST	Office of Aeronautics and Space Technology
ODS	oxide dispersion strengthened
P/M	powder metallurgy
PICC	plasticity-induced crack closure
PM	powder metallurgy
PMC	polymer matrix composite
POD	probability of detection

QPF	quick Plastic Forming
QUEST	Quantitative Experimental Stress Tomography
R&D	research and development
R&T	research and technology
RCS	Reaction Control System
RICC	roughness-induced crack closure
RLV	reusable launch vehicles
RSI	reusable surface insulation
SBKF	Shell Buckling Knockdown Factor Project
SCAR	Supersonic Cruise Aircraft Research
SCAT	Supersonic Commercial Air Transport
SCC	stress-corrosion cracking
SDI	Strategic Defense Initiative
SEM	scanning electron microscope
SFF	solid freeform fabrication
SHM	structural health monitoring
SHT	solution heat treatment
SLM	selective laser manufacturing
SLS	space launch system
SLWT	super lightweight tank
SMA	shape memory alloy
SMASH	shape memory alloy self-healing
S-N	stress (S) against the number of cycles to failure (N)
SPD	severe plastic deformation
SPF	superplastic forming
SSME	space shuttle main engine
SST	supersonic transport
SSTO	single-stage-to-orbit
STAGS	Structural Analysis of General Shells
STL	Standard Triangulation Language
STME	space transportation main engine
STP	Special Technical Publications
STS	Space Transportation System
TBC	thermal barrier coatings
TDB	Tupolev Design Bureau
TDT	Transonic Dynamic Tunnel
TMC	titanium matrix composites
TPS	thermal protection system
TRL	technology readiness level
VHP	Vacuum Hot Press
VIAM	All-Russia Institute of Aviation Materials
VILS	All-Russia Institute of Light Alloys
WFD	widespread fatigue damage

ABOUT THE AUTHORS

Dr. Darrel R. Tenney, Program Manager and Senior Scientist, AS&M

Former Chief of the Materials Division and former Director of the Airframe Systems Program (Retired), NASA Langley Research Center.

Dr. Tenney has extensive experience and expertise in research and development of advanced composites and metallic materials, application of advanced materials to aerospace structures for both aircraft and spacecraft, environmental effects on materials in both aircraft and space applications, technology assessments, identification and solutions to critical barriers, identification of key challenges for developing new R&D efforts, and experience in formulating and advocating new programs. He has conducted numerous technology assessments including assessments of the European Framework V and VI R&D Programs, and the European efforts to build composite primary structures for the Airbus Family of Aircraft. He also recently completed a consulting task for NASA related to the European Union suit before the World Trade Organization relative to NASA's past contributions to development of large aircraft. The majority of this task was related to composite applications on large aircraft (technical responses were drafted on numerous composite technologies ranging from co-curing, non-autoclave curing, damage tolerance, life-prediction methodologies, stitching, textile pre-forms, automated fiber placement, automated tow placement, and many other composite technology areas). He was also the lead on the "Evaluation of Advanced Composite Structures Technologies for Application to NASA's Vision for Space Exploration" study conducted by AS&M for NASA Langley.

Dr. Tenney was also the AS&M lead for the NASA LASER task entitled "Role of NASA Programs on Development of Composite Materials for Transport Aircraft and Space Vehicles." The results of this effort produced a publication entitled "Structural Framework for Flight" which was published in book format and distributed throughout NASA and with key industry partners. The requests for the book far exceeded the numbers of copies available.

Dr. Edgar A Starke, Jr., Technical Consultant to AS&M

Edgar A. Starke, Jr. University Professor and Oglesby Professor of Materials Science and Engineering, Emeritus, University of Virginia

Dr. Starke retired from the University of Virginia in 2008. He is a member of the National Academy of Engineering, a Fellow of ASM International, a Fellow of the Materials Society of AIME (limited to 100 living members), and an Honorary Fellow of the Japanese Institute of Metals. He was a member of the Center for Advanced Studies at the University of Virginia, 1983–1984, and Dean of the School of Engineering and Applied Science 1984–1994, Dr. Starke was Director of the Light Metals Center, University Professor and Oglesby Professor of Materials Science and Engineering from 1994 until his retirement in 2008. He has received a number of honors and awards, including the West German Alexander von Humbolt Award, the Metal Award of the Nonferrous Division of the Wire Association, NASA's Public Service Medal, Innovations in Real Materials Award from the International Union of Materials Research Societies, and the Distinguished Materials Scientist/Engineer, Structural materials of the Materials Society of AIME. Dr. Starke was a member of the National Materials Advisory Board and served as its Chair for three years. He was a U.S. Member of the Structures and Materials Panel, Advisory Group for Aerospace Research and Development (AGARD), NATO 1992–2000. Dr. Starke has served on a number of study panels for NASA, NATO, and the Department of Defense. He has published over 250 scientific papers and edited a number of books on his expertise of mechanical behavior of materials, alloy development, and the relationships between primary processing, microstructure development and mechanical properties. He holds three patents. Dr. Starke received his B.S. in Metallurgical Engineering, Virginia Polytechnic Institute in 1960, his M.S. in Metallurgical Engineering, University of Illinois, 1961, and his Ph.D. in Metallurgical Engineering, University of Florida, 1964. From 1961–1962 he was a research metallurgist at the Savannah River Laboratory. Prior to joining the University of Virginia he was Professor of Metallurgy, Director of the Fracture and Fatigue Research Laboratory at the Georgia Institute of Technology, 1964–1983.

Mr. Thomas T. Bales, Technical Consultant to AS&M

Former Chief Engineer of the Materials Division at NASA Langley Research Center and Senior Metallurgist for the Metallic Materials Branch

Mr. Bales has conducted research on the development of structural materials and the associated fabrication technology to incorporate these materials into efficient structural concepts for application on aerospace vehicles and launch systems for over 35 years. Mr. Bales' technical areas of specialization have included diffusion bonding of nickel base and light alloys, brazing of titanium and metal matrix composites, superplastic forming of titanium and aluminum alloys, and environmental effects on structural materials for a broad range of aerospace vehicles. His areas of responsibility have included program management, serving as a technical consultant on NASA and DoD programs, technical leadership of multidiscipline research, and planning and conducting individual research.

As Chief Engineer of the Materials Division, Mr. Bales served as the division focal point for the integration and implementation of all major focused material programs. He served as the directorate technical focus for airframe materials and structures for HSR and leader of the Structures, Materials and Manufacturing Area for the NASA/Air Force ALS/NLS Programs. He was nationally recognized for successfully advocating continuing research on aluminum-lithium alloys for cryogenic propellant tanks on the ALS/NLS Program, which fostered early development of alloy 2195. He also served as a technical consultant to the Division Chief and the Director for Structures to review technical presentations, and assisted in developing research program format. He was also designated as the Agency lead and was responsible for developing three program elements involving materials and structures for the Space Transportation Augmentation Program. As a nationally renowned metallurgical specialist in the forming and joining of metals, he frequently was asked to chair sessions and national symposiums on the topic and serve on steering and advisory committees of national organizations. He frequently consulted within NASA, the DoD, and industry on materials selection and performance.

Prior to his Chief Engineer role, Mr. Bales was a senior research engineer responsible for development of advanced forming and joining methods for metals and metal-matrix composites for high-speed civil transport technology including technical direction of branch engineers and support personnel. He successfully led a team that demonstrated the use of superplastic forming of titanium and aluminum alloys to improve the structural efficiency of compression panels. As a recognized expert in materials and structures for high-speed aircraft he was selected to serve on the Air Force Scientific Advisory Board for the Advanced Tactical Fighter (F-22) and the Materials Assessment Team for the National AeroSpace Plane (NASP) Program. He also led a team that developed an Enhanced Diffusion Bonding (EDB) process for fabricating titanium aluminide and TiAl metal matrix composite honeycomb-core sandwich panels for the NASP Program. He also led a team on the superplastic forming of aluminum to suppress cavitations using back pressure and post-forming pressure.

During his career at NASA, Mr. Bales also served as Assistant Head of the Materials Processing and Applications Branch of the Materials Division. He shared the responsibility with the Branch Head in the supervision of approximately 15 engineers and management of the overall operations of the materials processing laboratories. He provided guidance and leadership in several key areas including processing and joining and led major projects toward the application of advanced materials in aerospace structures.

He also served as Research Project Engineer in the Manufacturing Technology Section, Materials Applications Branch and Materials Division responsible for the development of processing and joining techniques for titanium and metal matrix composite materials for the Supersonic Cruise Aircraft (SCAR) Program. He developed a diffusion barrier concept for metal-matrix composite materials to prevent degradation of material properties due to interaction of the braze alloy and the fibers in the composite during brazing. This concept was adopted by major aerospace companies for fabricating metal matrix composite structures. He developed a joining process entitled “weld brazing” which was successfully used for the fabrication of complex titanium structures such as the Boeing 737 spoiler fabricated on the SST DOT technology follow-on-program for evaluation of the aluminum brazing process for fabricating titanium honeycomb core sandwich structure. He was Technical Leader of the NASA YF-12 Wing Panel Program. This program involved the development of seven different panel concepts designed to offer improved structural efficiency for future supersonic aircraft. Five of the concepts were certified for flight service on the YF-12 aircraft and were flown at air speeds up to Mach 3. He was selected to serve as NASA’s representative on the DOT technology follow-on program after cancellation of the National SST Program.

During the early part of this career at NASA, Mr. Bales was a Research Engineer in the Structural Materials Branch, Structures Research Division. Responsible for development of advanced joining processes for aerospace alloys. Procedures were developed for the diffusion bonding of TD-NiCr and Ti-6Al-4V alloys. Research was also conducted to eliminate stress corrosion cracking of titanium propellant tanks for the Apollo Program. Early test results demonstrated that glass-bead peening could induce a compression stress on the exposed surface sufficient to eliminate the tensile stress required for cracking. Equipment was designed at the Langley Research center for the controlled glass bead peening of propellant tanks and the first three ship sets of the reaction control propellant tanks for the Lunar Excursion Module and the Saturn SIV B tanks were successfully treated for flight service. The equipment was transferred to industry and Mr. Bales led a team to install and train industry personnel on its use to treat the remaining Saturn SIV B tanks.

Dr. James C. Newman, Jr., Technical Consultant

Former Senior Scientific and Technical (ST Position) Researcher in Mechanics and Durability Branch (Retired), NASA Langley Research Center

Dr. Newman received his Ph.D. in Engineering Mechanics from the Virginia Polytechnic Institute and State University in 1974 and worked for the NASA Langley Research Center for 37 years. He joined the Aerospace Engineering faculty in the fall of 2001.

Dr. Newman's research is centered on experimental and computational aspects of crack growth and fracture behavior of metallic materials to develop material databases, models, and theories for fatigue life, durability and damage-tolerance analyses of aging commercial aircraft, and future aerospace materials and structures.

He began his career at the National Aeronautics and Space Administration (NASA) Langley Research Center in Hampton, Virginia, in the area of fatigue and fracture of metallic materials. He is a member and past officer in the American Society for Testing and Materials (ASTM) Committee E-08 on Fatigue and Fracture. He has been the chairman or co-chairman of 12 national or international symposia on fatigue and fracture, organized eight workshops, and has edited or co-edited eleven books (ASTM Special Technical Publications). He has over 160 publications in journals and NASA reports. From 1980 to 1999, he worked on several teams to investigate problems in the Space Shuttle Transportation System (thermal protection system, solid rocket motor, external tank, and the space shuttle). During the 1990s, he was the technical manager of the fatigue and fracture research in the NASA Airframe Structural Integrity Program. He presented the Jerry L. Swedlow Memorial Lecture in 1996 at the ASTM Twenty-Eighth Fatigue and Fracture Mechanics Symposium. In 1999, he presented the Seventeenth Fredrik J. Plantema Memorial Lecture at the International Congress on Aeronautical Fatigue (ICAF). He was chairman of the Fifth Joint NASA/FAA/DoD Conference on Aging Aircraft (2001). He also received the John W. Lincoln Medal from the U.S. Air Force in 2001. He has received awards from NASA, ASTM, Federal Aviation Administration, U.S. Air Force and Boeing. He is continuing his fatigue and fracture research on metallic materials at Mississippi State University where he is a Giles Professor in the Department of Aerospace Engineering, Richard "Dick" Johnson Chair, and where he has developed a Fatigue and Fracture Laboratory.

Dr. Joseph Heyman, Technical Consultant

Chief of Innovation for Applied Research Associates; Chief Scientific Officer, Luna Innovations Inc. (retired);
Former Chief Technologist and former Branch Head of the Nondestructive Measurements Science Branch (Retired), NASA Langley Research Center

Dr. Heyman worked at the National Aeronautics and Space Administration (NASA) for 37 years and managed major NASA programs in NDE, technology commercialization, and creativity. He is a leader in nondestructive evaluation research and applications including ultrasonics, nonlinear acoustics, acoustic emission, acoustic microscopy, laser ultrasonics, thermography, radiography, tomography, shearography, fiber optics, and eddy current techniques. Dr. Heyman has conducted groundbreaking research and development in many areas of diagnostic measurement science, including spacecraft thermal protection systems, rocket motors, composite aircraft structures, metal stress and fatigue, aging aircraft fuselages, damage assessment, and acoustic resonator sensor devices. He has received over 30 NASA awards including Agency Invention of the Year and the Agency’s Highest Award for Technology Transfer. He is a past recipient of the Arthur Flemming Award as one of the 10 Top Federal Scientists in Government Service and received three of NASA’s highest awards with Medals for Exceptional Leadership, Exceptional Achievement, and Exceptional Service. In addition, NASA astronauts presented him the Silver Snoopy Award for outstanding achievements related to human flight safety and mission success for the safe shuttle return-to-flight after the *Challenger* accident. Dr. Heyman holds 34 patents and has published/presented over a hundred papers.

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14. ABSTRACT

This document is intended to serve several purposes. First, as a source of collated information on Metals Research conducted at Langley from 1917 to 1958 as a National Advisory Committee for Aeronautics (NACA) field Research Center and from 1958 to today (2014) as a National Aeronautics and Space Administration (NASA) Research Center. Although several excellent books have been written to document the historical work and outstanding contribution NACA/NASA made to aerodynamics, flight systems, and other key flight vehicle disciplines the pioneering work and contributions made in structures and materials has only been partially recorded in achievable documents. The first such document entitled "Structural Framework for Flight I: NASA'S Role in Development of Advanced Composite Materials for Aircraft and Space Structures" was published in 2010. This monograph is a companion document to the Composites Monograph and serves as a key reference for readers wishing to grasp the underlying principles and challenges associated with developing and applying advanced metallic materials and structures to new aerospace vehicle concepts. Second, it identifies the major obstacles encountered in developing and applying light alloys on advanced flight vehicles, as well as lessons learned in overcoming these obstacles. Third, it points out current barriers and challenges to "light-weighting" future vehicles. This is extremely valuable for steering research in the future when breakthroughs in new materials or processing science may eliminate/minimize some of the critical barriers that have traditionally been impediments to further reduction in the structural weight of flight vehicles. Finally, a review of past work and identification of future challenges will hopefully inspire new research opportunities and development of revolutionary materials and structural concepts for future flight vehicles.

15. SUBJECT TERMS

Aerospace vehicle concepts; Automated fabrication; Composite research; Environmental effects

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