

2019

Chapter 1

Introduction: Aims and Requirements of Future Aerospace Vehicles.

Pedro I. Rodríguez and Stanley S. Smeltzer, III
National Aeronautics and Space Administration, MSFC, Huntsville, Alabama USA

Key words: Aerospace Vehicles, Reliability, Optimization, Requirements.

Abstract: The goals and system-level requirements for the next generation aerospace vehicles emphasize safety, reliability, low-cost, and robustness rather than performance. Technologies, including new materials, design and analysis approaches, manufacturing and testing methods, operations and maintenance, and multidisciplinary systems-level vehicle development are key to increasing the safety and reducing the cost of aerospace launch systems. This chapter identifies the goals and needs of the next generation of advanced aerospace vehicle systems.

1. BACKGROUND

Throughout the late 1970's and early 1980's a number of studies [1-5] were made with emphasis on identifying the challenges of structures and materials technologies to meet the needs of both civil and defense aerospace missions. Increased safety, reliability, mission life, manufacturability, operability and repairability were critical issue areas that needed significant improvements. A large section of the technical community, however, concentrated on solving these issues by improving existing material development technologies and structural analysis methods. Development areas of emphasis were: composite and high-temperature materials, airframe structures and Thermal Protection Systems (TPS), hypersonic airbreathing propulsion structures, structural heat transfer analysis, aerothermal loads, and high temperature test techniques for TPS and airbreathing hypersonic

propulsion structures [6]. Although the development of these performance-related technologies was an important component of an improved aerospace system, it was by no means the only nor the dominating issue in developing a safer, lower-cost, and highly operable system.

The Space Shuttle is a prime example of an aerospace launch system in which high-cost life-cycle problems develop when emphasis is placed on a performance-driven rather than a reliability-driven design. Some critical high-cost issues that cannot be addressed by improvements in structures and materials technologies alone are: 1) the extensive touch-labor and staff (several thousand employees) required to assemble and process the vehicle, 2) the launch constraints such as wind loads and dynamic pressure which repeatedly result in costly launch holds, 3) the required tailoring of each launch with specific flight mechanics and loads analyses necessary, and 4) the incompatibility between design and safety requirements which resulted in development of systems like the Space Shuttle Main Engine (SSME) and the heat protection tiles which require significant maintenance and hardware replacement to meet safety requirements [7].

In today's globally competitive aerospace market, designing aerospace systems and structures for high performance is no longer the critical systems development requirement that it was thirty years ago. A workshop on "Structural Optimization of Aerospace Vehicles with Emphasis on High-Reliability" conducted at the 39th Structures, Structural Dynamics, and Materials Conference on April 20-23, 1998 identified a number of requirements in the form of needed technologies for high-reliability aircraft, launch vehicles, and spacecraft. Five major topic areas were addressed:

1. Aerospace Vehicle Systems/Subsystems Reliability
2. Systems/Subsystems Reliability for "other than" Aerospace Vehicles
3. Quantifying the Specific Components of Reliability
4. Reliability Models for Multidisciplinary Optimization
5. Multidisciplinary Optimization Tools Applicable to Design for Reliability

The prioritized list of issues and needs that resulted from the discussions ranged in content from Vehicle Systems Reliability Verification to the Development of a Database of Detailed Failure Records for Applicability to Aerospace Systems.

A high concern for the participants of the workshop was the need for efficient and accurate limit state function approximations and sensitivity analyses with respect to reliability parameters wherein large variations in the values of random variables were considered. It was clear that the discipline of Structural Optimization (SO) had matured significantly over the last 30

years, but it was also obvious that the incorporation of Reliability functions and their approximations had to become an integral part of the overall Multidiscipline Optimization (MDO) process. Additionally, the group recognized the immediate need for the development and application of advanced probabilistic structural models to perform design trade-off studies and sensitivity analyses.

Since the use of high performance computing was considered essential to the development of these technologies, improvements in the way SO was performed were also identified as important developments needed. For a truly systems-level MDO structural development a method for incorporating the reliability-based functions into the MDO infrastructure was needed. Additionally, a generic interface tool was needed wherein all optimization algorithms resided. This tool would then be used as a universal interface to accept and understand all engineering and reliability analysis results during each iteration of the optimization process.

In reliability analysis the use of Response Surfaces (RSF) is a valuable tool when the gradients of the limit state are not available. However, when the number of random variables is large it is significantly difficult to build the RSF. This limitation in turn reduces the effectiveness of the MDO analysis if indeed one is to include reliability functions. The workshop participants also identified the need for new ways of "thinking" to develop advanced methods of building RSF.

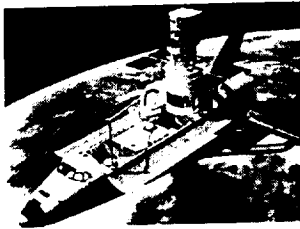
Reliability-Based MDO tools that worked seamlessly with commercial Computer Aided Design (CAD) tools or Computer Aided Engineering pre-processors were identified as needed. These tools would be essential in the design of new generation vehicles where reliability-based safety and cost constraints were of greater importance than high performance [8].

The National Aeronautics and Space Administration (NASA) is currently evaluating the next generation launch vehicle systems and the technologies that are needed to meet highly ambitious safety and cost goals. It is very interesting to see that safety, cost and reliability have superseded high performance as the primary criteria in the development of such systems.

2. NEXT GENERATION LAUNCH VEHICLES

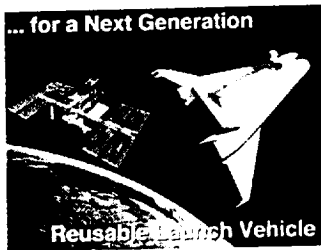
Twenty years ago the world wide commercial launch market was practically non-existent. Today it is over \$2 billion annually, and private industry participation has caused a shift in the traditional relationships between government and industry. Private aerospace companies are now

accepting and welcoming the traditional government role of development, ownership and operations of launch systems [9]. With the need for aerospace businesses to remain profitable, competitive and reliable, their dependence on new technologies is obvious and indeed essential. The global aerospace market demands a clear requirement for lower costs and increased reliability for both human space flight and expendable launch vehicles. Therefore it is imperative that investments in breakthrough technologies be made now with emphasis on two essential criteria: Safety and Cost. NASA has recently announced the new Space Launch Initiative (SLI) wherein \$4.5 billion dollars will fund, over the next five years, the development of such technologies.



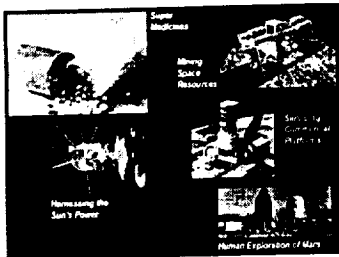
Today: Space Shuttle 1st Generation RLV

- Orbital Scientific Platform
- Satellite Retrieval and Repair
- Satellite Deployment



2010: 2nd Generation RLV

- Space Transportation
- Rendezvous, Docking, Crew Transfer
- Other on-orbit operations
- ISS Orbital Scientific Platform
- 10x Cheaper
- 100x Safer



2025: 3rd Generation RLV

- New Markets Enabled
- Multiple Platforms / Destinations
- 100x Cheaper
- 10,000x Safer

Figure 1.

Under the SLI NASA has developed an Integrated Space Transportation Plan that identifies new requirements and guidelines that will produce a step-by-step program wherein three generations of launch vehicle technologies will provide the fundamental building blocks for Safety, High Reliability, and Low Cost Aerospace Vehicles. The three generations of Reusable Launch Vehicles (RLV) are summarized in Figure 1.

The derived requirements for the space transportation systems of the future can be summarized and compared by identifying the critical technical and economic features that will prove the system viable. Figure 2. identifies these requirements for the 1st Generation Reusable Launch Vehicle (Space Shuttle).



- Cost: \$10,000 per pound to orbit
- Safety: Catastrophic Problem every 200 missions
- Crossrange: 1,100 nautical miles (blunt body)
- Payload: 50,000 pounds to Lower Earth Orbit
- Life: 100 missions
- Depot Maintenance: Every 10 missions (100 mission overhaul and recertify)
- Total Fleet Missions: 5 – 10 per year (with recertification)
- Turnaround time: 5 months
- Launch Support Personnel: 1,000 (170 at launch site)
- Vehicle IQ: Limited – requires extensive human interrogation of systems on ground
- Range Control: Unique for each flight/48 hours required for reconfiguration.

Figure 2.

For the 2nd Generation Reusable Launch Vehicles, a significant and challenging increase in safety and reduction in cost has been established as the overarching goal. Because the timeframe for development of the

required technologies to meet this goal is about 5 years, major efforts in expanding the knowledge of existing technologies must begin promptly. It will not be sufficient to perform basic research and conceptual development of new materials, design and analysis techniques, manufacturing processes, and operational methods. Innovation in vehicle configurations, improvements in current maintenance approaches, resourcefulness in manpower utilization, and improvements in management approaches are also essential for the success of the 2nd Generation development efforts. Figure 3. identifies these requirements for the 2nd Generation Reusable Launch Vehicle.



- Cost: \$1,000 per pound to orbit
- Safety: Catastrophic Problem every 10,000 missions with crew escape
- Crossrange: 700 - 1,100 nautical miles (blunt body)
- Payload: 50,000 pounds to Lower Earth Orbit
- Life: 500 - 1000 missions
- Depot Maintenance: Every 100 missions
- Total Fleet Missions: 100 per year
- Turnaround time: 1 week
- Launch Support Personnel: 100
- Vehicle IQ: Sends vehicle status to ground prior to landing
- Range Control: Mission class specific

Figure 3.

The 3rd Generation Reusable Launch Vehicle technology and launch vehicle development must indeed be filled with creativity, vision, and extreme unconventional thinking. This vehicle or class of vehicles must have unprecedented safety and reliability features. The methods for analysis and multidisciplinary design must be such that changes in the vehicle status

during any phase of its life can be directly and immediately translated into impacts to the success of the mission and safety of the crew. The materials, inspection methods, vehicle health determination and structural configurations must be such that their condition can be obtained with any change in the vehicle ground, launch, ascent, orbital, and landing environments. The operations, maintenance and refurbishment must be simple, modular wherever possible, low cost, and so highly reliable that availability and effective utilization is guaranteed every time. Figure 4. identifies these requirements for the 3rd Generation Reusable Launch Vehicle.



- Cost: \$100 per pound to orbit
- Safety: Catastrophic Problem every 1,000,000 missions with crew escape
- Crossrange: 2,700 nautical miles (sharp body)
- Payload: 20 - 40,000 pounds to Lower Earth Orbit
- Life: 2,000 - 5,000 missions
- Depot Maintenance: Every 500 missions
- Total Fleet Missions: 2,000 per year
- Turnaround time: 1 day
- Launch Support Personnel: 10
- Vehicle IQ: On-board management systems adapt to changing environments
- Range Control: Autonomous, Passive System

Figure 4.

3. MISSION REQUIREMENTS

In order to identify critical technology requirements it is necessary to understand the kind of missions that are needed to meet government and

industry goals. There can be several models identifying missions that may be accomplished through utilization of a combination of space transportation assets. These assets may be a combination of launch vehicles and other in-space transportation elements. If one keeps safety and reliability in mind it is then not necessary for any mission to be accomplished with a single vehicle. For example, if one desires to travel from New York, USA to Paris, France, one could travel safely and reliably in the Concorde Jet. However, it would be foolish to use a Concorde to fly from Atlanta, Georgia to Washington, DC. It would not be efficient, cost effective, and most importantly safe. Indeed vehicle system robustness may well be accomplished by a family of vehicles, a consortium of simpler synergistic elements, that together provide the necessary resources to achieve these goals. These architectures must, however, be integrated and complete and the solutions must address the total set of missions requirements.

If a mission is needed to deliver a spacecraft or deploy a satellite to a standard orbit of 110 nautical miles, a possible delivery system would be an *uncrewed* launch and deployment system, a mission duration of 2-3 days, and a capability of 40K-60K lbs. The frequency of launch would be determined by industry assessments of the commercial market.

If, in addition to delivery and deployment, it is desired to activate or return the payload a *crew* is more than likely required with today's technology due to tasks like activation, checkout, trouble shooting, release for operation or return to Earth if necessary. The mission duration could be 2-5 days at 110 nm and 28-57 deg inclination with 40K-65K lbs. The frequency of such a mission would be less than 3 times a year.

A mission requiring retrieval, servicing and/or return of a satellite or spacecraft would, once again, require a *crew* due to operations such as capture, retrieval, repair, servicing, or return to Earth. The operations may also include refueling capabilities. This kind of mission may require 5-7 crewmembers, 7 days, Extra Vehicular Activity (EVA) capabilities, 28-57 deg inclination, 320 nm, and 40K-65K capability. Such a mission would not occur more than once a year.

For a mission requiring a science or technology payload, an on-orbit crew would be needed to operate and tend the payload or experiment. This activity would all be conducted in a short sleeve environment whether the payload is in the cabin or in the payload bay. It would require 3-7 crewmembers, 9-16 days, 28-57 deg inclination, 150 nm, and 40K lbs capability. This mission would occur twice a year.

A mission to the International Space Station or to exchange crews from the ISS can encompass all the previously mentioned missions. The frequency of such a mission is 5 times per year with the Space Shuttle or equivalent to 5 Shuttle flights. This mission scenario must include 1 contingency flight and one additional flight every third year to change out

the Crew Return Vehicle (CRV).

A mission requiring a complex space platform assembly and servicing is a mission of 5-16 days, requiring up to 8 crewmembers. This mission is based on an on-orbit delivery, assembly and checkout, and servicing of a large complex platform. Its frequency can be 2-4 times a year. Some typical scenarios for this type of mission are:

1. Large complex space observatories
2. In-space transportation vehicles such as Orbital Maneuvering Vehicle (OMV) and Crew/Cargo Transfer Vehicle (CCTV).
3. Human exploration spacecraft and/or transportation nodes; payload masses up to 65K lbs, 220 nm and 28-57 deg inclination. Capability would be needed to transport up to 6 crewmembers to an exploration spacecraft.

In addition to these missions there are requirements for *crew rescue* wherein the launch and space system must have the capability to launch and carry out the rescue within two days of the incident. For example if a CCTV is stationed at the ISS or other space platform, it should be able to locate and rendezvous with an untethered and stranded crew person. The stranded crew member should be safely grappled, secured, and transported back to the ISS or other platform. Based on this the CCTV should have a certain feasible level of autonomy of operation. There are also Polar Orbit missions required for *crewed* scientific platform missions and *crewed* spacecraft and satellite on-orbit delivery.

To deliver the payloads needed to complete these missions successfully it is necessary to assess the potential for 2nd Generation Launch Vehicles Earth-to-Orbit (ETO) system elements that can be utilized in various applications. Some examples are:

- Launcher element commercial application for inexpensive small satellite orbit insertion.
- Launcher element incorporation into future heavy-lift capability, i.e., pathway to future space missions.
- Dual use of orbital maneuvering capability for both 2nd Generation Launch Vehicle and maneuverable CTV.

4. CRYOGENIC TANK TECHNOLOGY REQUIREMENTS

The development costs of a new reusable launch vehicle can be broken down into subsystem costs. The four major subsystems are:

Reusable Launch Vehicle Subsystem	Percent of Total Development Cost
Structures	32%
Propulsion	28%
Thermal Protection System	12%
Avionics	12%
All Other Subsystems	16%

Additionally the Structures Subsystem can be broken down into warm and cold structures. The warm structures comprise about 35% of the total dry weight of the launch vehicle while the cold structures comprise about 55%, with the remaining 10% for secondary structures. The cold structures are the fuel and oxidizer tanks and are the largest structural components in the entire launch vehicle. It is of crucial importance that advanced development be performed on these large elements in order to decrease the uncertainty in the technologies utilized and the design configurations and approaches developed. Advanced technology will reduce the entire subsystem uncertainty and mitigate cost increases from schedule slips or weight increases driven by an immature subsystem or subsystem integration issues. It will reduce the system-level development cost and schedule by concentrating on integration and operations (including reusability), increasing the experience of the development teams, and increasing the maturity of the design configurations and technical knowledge.

A recent Technology Prioritization Workshop for Critical Reusable Launch Vehicle Advanced Technology Development was conducted at NASA's Langley Research Center. The technical community (government, industry and academia) identified four major areas where significant improvement in technologies were needed to reduce the cost of launching payloads and improve vehicle reliability. These areas were, in order of importance:

- Cryogenic Tank Joining Technologies
- Integrated Cryotank Systems
- Advanced Manufacturing and Materials Technologies
- Verification and Operations Technologies

A number of specific technologies were identified and specific tasks were identified as part of the advanced development activities. To assure applicability to the 2nd Generation goals, reliability, reusability, low-cost operations and quick turn-around technologies had to be developed. The resulting list of requirements was identified:

Cryogenic Tank Joining Technologies

1. Advanced Cryotank Joint Repair Technologies
 - Eliminate Permeability through Joint
 - Reduce Manufacturing Risk
 - Standardize Joint Repair Methods
 - Design for Predictable Strength
 - Develop Validated Inspection Methods
 - Design for Low Joint Maintenance Costs
2. Composite Cryotank Bolted Joints
 - Eliminate Leakage through Conformal Seal Areas
 - Demonstrate Low-Cost Manufacturing Methods for Robust Reusable Doors and Access Panels
 - Demonstrate Reusability and Low-Cost Maintenance
 - Reduce Turn-Around Operations and Logistics Costs
3. Advanced Cryotank Joints
 - Develop Belly-Band, Splice, Complex Single-Lap, Advanced Mechanical Attachment Methods
 - Eliminate Permeability through Joint
 - Reduce Inspection and Maintenance Requirements
 - Develop Verified Advanced Analytical and Optimization Methods
 - Predict Interface Reliability
 - Reduce Part Count and Simplify Manufacturing

Integrated Cryotank Systems

For Integrated Cryogenic Tank Systems, a combined set of requirements that addresses the critical technology issues of the integrated system is needed. To address this significant structural/design problem and derive generic technologies applicable to 2nd Generation Reusable Launch Vehicles, a set of desirable attributes must be defined to attain the major goals for the tank systems. A credible set is:

1. High Strength-to-Weight ratio
2. Wide use Temperature Range
3. Dimensional Stability with Temperature Change
4. Low Thermal Conductance
5. Manufacturable in Large Sections and Conformal Shapes, with Lightweight Attachment
6. Selection of Durable Material Systems. Optimized for Life-Cycle Costs

Based on these attributes a set of Integrated System requirements can be identified:

Material Compatibility	Structural Design	Thermal Design	Repair, Manufacturing, Inspection	Optimization
<ul style="list-style-type: none"> - O2 Compatible - H2 Compatible - Hydrocarbon Compatible (if needed) - Hydrogen Peroxide Compatible (if needed) - Environmental Acceptability 	<ul style="list-style-type: none"> - Load carrying pressure shell - Elastic Design - Life > 400 functional cycles - Fracture Tough - Dimensionally stable over wide temperature range - Impermeable - Modular Design - Accommodate baffles, diffusers, and anti-vortex devices - Accommodate propulsion system instrumentation - Accommodate IVHM - Allow internal access - Integrate with combined Airframe and Engine System 	<ul style="list-style-type: none"> - Operating Temp., -420 F to TBD F - Low thermal conductivity - Non-catalytic - High exterior surface emissivity - Opaque to thermal radiation - Eliminate cryopumping - No atmospheric air liquefaction - Minimize ice, frost, condensate - Minimize propellant stratification - Minimize cryogenic heat leaks through penetrations - Accommodate requirements for propellant loading and propellant mass 	<ul style="list-style-type: none"> - Can be manufactured in large sections - Can be joined with light weight attachments - Conformal to aeroshell - Integral subsystems and penetrations - Repairable - Inspectable - Accommodates instrumentation and IVHM - Operable - Durable - Quick turn around 	<ul style="list-style-type: none"> - Low system weight (especially for SSTO) - Minimum life-cycle cost - Maximum Reusability - Maximum Reliability - Minimum Risk - Minimum inspections between regular maintenance

Advanced Manufacturing and Materials Technologies

1. Composite Materials Technologies
 - Develop advanced e-beam curable epoxies with enhanced fiber-resin interfacial adhesion.
 - Develop tough, thermoplastic matrix composites processed using non-autoclave methods.
 - Produce large composite parts by non-autoclave methods and at low temperatures to minimize residual thermal stresses.
 - Develop low cost non-autoclave manufacturing of large composite structures compatible with LO2.

2. Near-Net Manufacturing and Friction Welding of Metallic Tanks
 - Develop forming processes producing consistent high quality metallic domes with minimum joints.
 - Reduce metallic material welding costs and inspections
 - Increase structural efficiency and as-manufactured material properties.
 - Increase weld joint efficiency
 - Develop robust metallic joining techniques

3. Leakage Control Technologies and Improved Permeability Resistance
 - Develop technologies to eliminate cryotank leakage
 - Materials
 - Experimental techniques
 - Analytical methods
 - Characterize microcracking
 - Understand manufacturing defects
 - Eliminate poor fit-up
 - Eliminate material incompatibility
 - Develop advanced liner materials
 - Develop standardized permeability criteria
 - Reduce inspection intervals
 - Produce minimum gage structure
 - Validate lifetime reliability of materials

4. Advanced Cryogenic Insulation Development
 - Reduce weight and increase robustness of reusable cryoinsulation
 - Develop processing, application and repair techniques

- Develop internal-to-tank cryoinsulation configurations
 - Develop integrated cryoinsulation/Thermal protection system approaches for extreme reentry-to-cryogenic temperature regimes.
 - Improve durability and damage tolerance of cryogenic insulations.
5. Rapid fabrication of Cryogenic Propellant Tanks
- Develop advanced metal deposition processes to accommodate complex geometries and integrated insulation injection system.
 - Develop advanced mechanical and physical properties characterization methods.
 - Develop advanced processing techniques for fabrication of metallic cryogenic tanks with integrated sandwich insulation materials.
 - Eliminate joint leakage by fabricating completely continuous structural surfaces.
6. Environmental Compatibility of Candidate Cryotank Metallic Materials
- Develop material property and compatibility data for service-specific environments especially for typical materials used. i.e., Aluminum and Titanium alloys.
 - Develop improved structural efficiency of metallic tanks through material/configuration/environment tailored design.
 - Maximize material performance and reliability through accurate definition of environmental conditions and simulation of service conditions

Verification and Operations Technologies

1. Lifecycle Testing of Cryotank Components
- Develop testing methods and facilities to verify the reliability of integrated structural systems and thermal performance under combined environments.
 - Develop testing processes to characterize design processes and reduce development costs.
 - Characterize lifecycle degradation phenomena and develop verification test-based maintenance criteria

2. Structural Loads and Data Acquisition
 - Provide real-time engineering test data for cryogenic tanks with quick turn around in deliverables
 - Develop the ability to support multiple large and small scale tests
 - Provide low cost maintenance of system and real-time monitoring and data gathering
3. Real Time Control and Analysis System
 - Develop a system for integrated testing and analysis.
 - Provide real-time cryogenic tank analytical model anchoring with test data.
 - Provide real-time graphical presentation and analytical correlation with test data.
 - Develop system that provides the ability to perform fewer tests and minimize turn around time.
 - Develop a system that allows maximum test article visibility during testing through advanced facility design configuration.
4. Modal and Control Dynamics Testing
 - Develop the capability to conduct dynamic tests on a variety of structures, perform subsequent data analysis, and provide rapid reporting of test results in one facility.
 - Develop the ability to perform On-Site and Off-Site (remote location) testing.
 - Provide the ability to perform different dynamic environment tests (Transient, Sinusoidal, and Random Excitation) in a common facility.
5. Cryo-Structural Test Facility
 - Develop a combined environments test bed for small and large-scale cryogenic tanks.
 - Provide the ability to perform remote testing for hazardous testing operations including explosive and extreme temperature conditions.
 - Provide the capability for high heat flux testing, night operations and heavy lifting capabilities.
6. Composite Cryotank Health Monitoring
 - Develop advanced active sensing systems to monitor and characterize damage size and type.

- Develop sensing capability to detect impact damage (passive) and delaminations, microcrack density increase, debonding, and fiber cracking (active) that have occurred since baseline configuration.
 - Provide a sensing system capable of rapid installation, high sensing reliability and high sensor placement accuracy.
7. Composite Cryotank Material Repair
- Develop structural repair processing methods and advanced equipment for composite cryogenic tanks.
 - Provide capability to repair large damage areas with minimum work and touch-labor, on-location curing processes, and low-level/high-reliability inspection methods.
 - Develop repair methods and techniques for complex geometry joint areas that will minimize inspections, maximize joint repair strength, and provide quick on-location curing.

5. CRITICAL TECHNOLOGY ISSUES

The new generation of aerospace launch vehicles must meet critical requirements that are unrelated to aerodynamic performance. In fact to make the launch vehicle feasible it is essential that the system be able to "pay for itself." No government can afford to operate an aerospace launch system continuously without showing an economic return. It is true that the technology benefits of such systems are enormous and discoveries that occur during the development and operations of such systems frequently result in improvements in the quality of life for all of humanity. However, it is also true that the public in general does not know where these technologies came from and how they were developed is of little consequence to them. What is important is that the technologies are effective, efficient and affordable. Advanced technology development must answer all three of these criteria.

The United States' Space Shuttle is the prime example of an extremely sophisticated aerospace launch system that, although is the most successful and reliable human operated launch system in history, has reached a point where costs of operation have become a major part of the total cost per launch. In a launch vehicle design where development costs are constrained, weight becomes restricted. This in turn results in higher operational costs. Lessons learned from the Space Shuttle include [10]:

1. The assembly and processing (including checkout) of the launch vehicle must be developed to minimize touch labor and operational staff.
2. The vehicle must be designed so that there are very few launch constraints. Launch holds and scrubs are extremely costly with typical constraints related to high launch wind loads and dynamic pressure.
3. The launch vehicle, its launch profile and mission must be designed to accommodate the largest possible payload configuration and weight range. This will reduce the number of "tailored" launches that have to be developed by minimizing the detailed flight mechanics and loads analyses that must be performed.
4. Critical vehicle systems must go through extensive development to assure they are insensitive to ground, launch, space, re-entry, and landing environments. As examples, the Space Shuttle has two major systems that require extensive maintenance and hardware replacement in order to meet safety requirements. These are the Space Shuttle Main Engine (SSME) and the Orbiter Thermal Protection System (TPS) comprised of individual tailored heat protection tiles.

Thus, there is a mandatory requirement for any new launch system to avoid operational, maintenance and refurbishment problems by addressing these technological requirements at the very beginning of the development.

Cryogenic tanks for aerospace launch vehicles, payloads and satellites have been traditionally constructed from metallic materials, mostly aluminum alloys. In this new era of advanced computational and design tools, it is possible to design configurations and geometries that are superior to those developed just 20 years ago. However, to obtain these complex configurations the technical community has relied more and more on advanced composite material systems. For cryogenic tank development, these advanced materials pose a significant number of challenges that must be resolved in the very near future to make them economically and technically feasible.

Design and Fabrication Technology Issues

Cryogenic launch vehicle propellants, liquid oxygen (LO₂) and liquid hydrogen (LH₂), pose significant challenges when used in tank structures manufactured from advanced composite materials. Depending on the configuration and construction method, various types of challenges must be overcome to assure reusability and reliability of the tank. Cryogenic tank walls constructed with a honeycomb core material are very appealing due to

their light weight and high strength and stiffness characteristics. In expendable launch vehicles this type of construction is frequently used. In reusable systems, however, the effects of the operational environments associated with launch, reusability and refurbishment are not well characterized or even known for this type of construction.

A phenomenon known as cryopumping has emerged that is specific to honeycomb core/composite face sheet material systems. Cryopumping begins when the inner face of the tank wall comes into contact with the cryogenic liquid (see Figure 5.). Composite materials experience microcracking as a normal by-product of the manufacturing process. Although these minute cracks may not penetrate the entire thickness of the laminate they are nevertheless present. Initially the tank wall has a small amount of trapped air in the honeycomb core after bonding the inner and outer face sheets to the honeycomb core.

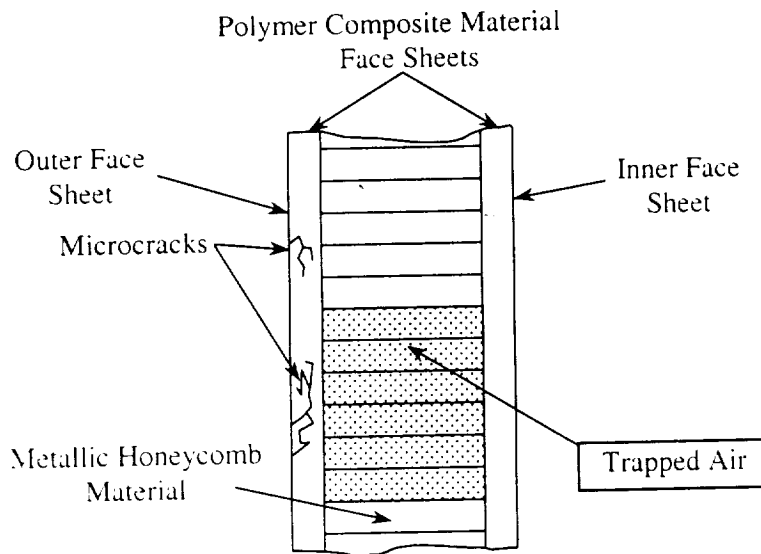


Figure 5.

When the tank is filled with the cryogenic liquid, this trapped air will condense and freeze on the honeycomb side of the inner wall (see Figure 6.). This in turn reduces the pressure within the honeycomb core allowing external air to penetrate through the external face sheet through the microcracks. As time proceeds more and more air is "pumped" into the honeycomb core. If the tank is filled with the cryogen for a long enough period of time it is plausible that the internal core pressure may reach equilibrium with the external atmospheric pressure. When the tank is drained of the cryogenic fluid the temperature increase in the core occurs fast enough that the air that has been "pumped" into the tank wall cannot escape fast enough through the microcracks. Pressure builds up inside the wall causing the bond between the inner or outer face sheets and the honeycomb core to fail thus causing tank failure by leakage or bursting (see Figure 7.).

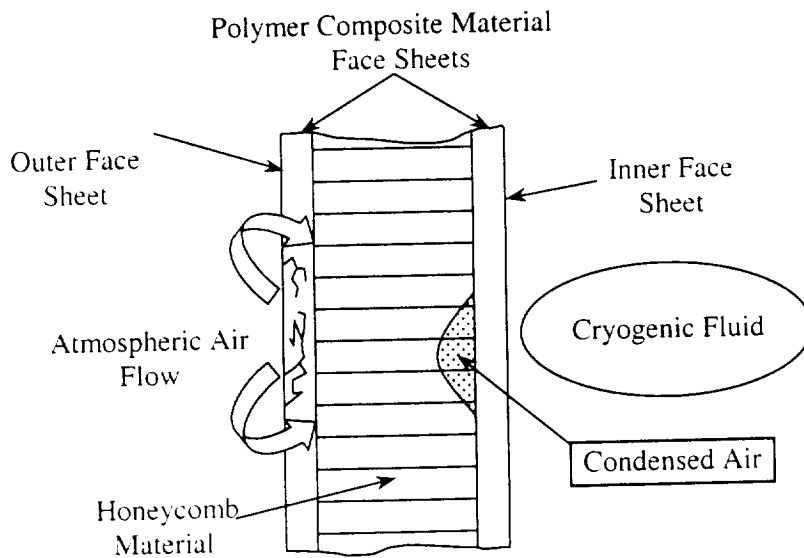


Figure 6.

The existence of the cryopumping phenomenon is an indication that several technologies must be developed that not only solve this problem but also allow the structural system to be robust enough to survive multiple uses

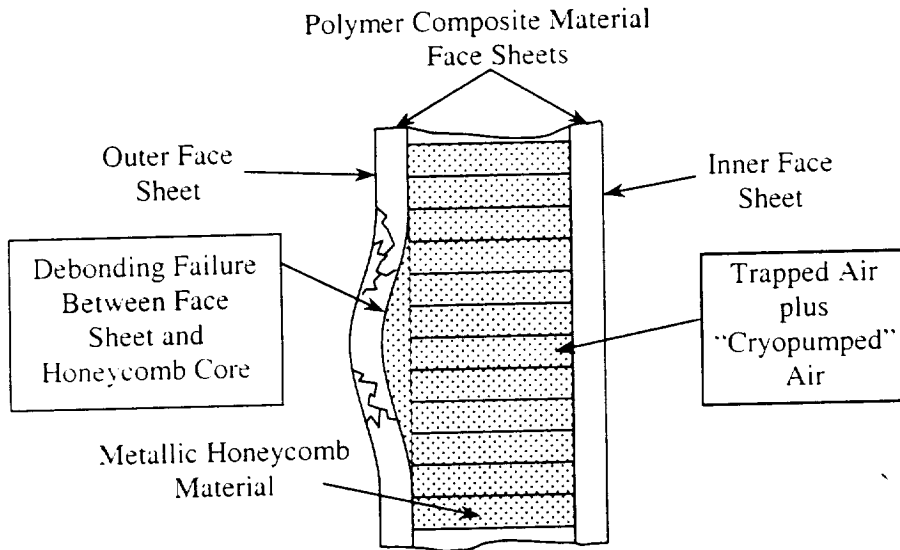


Figure 7.

with minimum repair and maintenance. By analyzing the cryopumping process and the events that cause it one can identify technology needs that must be worked on. By identifying the phenomenon that leads to hardware failure, a list of potential technology solutions can be developed.

Eliminate Microcrack Formation

This can be attributed to a problem with design and manufacturing. Technologies that prevent the infiltration of external fluids (such as cryogenic fluids or external air) are needed. Some possible scenarios are:

- Development of compliant and non-permeable interleaf films that can be inserted into the composite material face sheets during the manufacturing process. These interleaf sheets must also possess material properties that are compatible with or have the ability to accommodate the parent material properties.
- Development of a non-permeable inner-wall liner that can be co-cured with the parent composite material face sheet and can withstand multiple uses in an environment of extreme temperature differences at cryogenic temperatures.

- Development of a technology that can attach internal cryogenic insulation to both composite materials and metallic materials. This technology would allow localized repair and replacement of degraded or damaged insulation in a short period of time.
- Develop a technology that can evacuate the honeycomb core cavity so that air cannot accumulate during the cryopumping process. The technology should minimize or eliminate the need for added hardware or heavy mechanisms.
- Develop lower temperature curing composite material matrix systems and adhesives capable of high strain-to-failure and low coefficient of thermal expansion.

Eliminate Critical Bondline Failure

- Develop reliable manufacturing technologies that assure required pressure during curing in complex joint areas. This is needed to build high quality bonds and joints and assure that tolerance stack-up caused by inadequate composite material compression is minimized.

Enhance Non Destructive Evaluation Methods

- Develop technologies or processes that will minimize or eliminate the need for visual inspections for foreign object debris (FOD) during manufacturing.
- Develop a technology that will increase the bondline strength between the honeycomb material and the face sheet to a level that the minimum FOD size that will cause bondline failure increases significantly.
- Develop manufacturing technologies and process controls that assure high bondline strength with minimum requirement for inspection.
- Incorporate design technologies with manufacturing technologies such that high damage tolerance structural configurations are easily inspected.

Improve Sealing Methods

- Develop mechanical sealing technologies that can assure leak-free conditions over large areas in complex structural configurations.
- Develop new manufacturing methods that will assure no void content in polymer composite material systems. Such methods would be capable of including seals and barriers in the final structural configuration.

Improve Assembly Methods

- Develop new technologies for manufacturing support fixture design and assembly. Such technologies would allow the fixture to respond and react to deformations and forces as a result of the temperatures associated with the manufacturing process. In this manner the spring-back that normally results when the produced hardware is removed from the fixture is minimized.
- Develop technologies that combine design, analysis and manufacturing disciplines to eliminate residual stresses in post cured composite material structures.
- Develop real-time, quick-curing, impermeable repair technologies and processes.

6. SUMMARY

The impetus for the development of this book stems from the recognition that in the near future aerospace vehicles must no longer be isolated technological icons of mystery and marvel. Humanity has already demonstrated the ability to achieve space exploration as near as lower earth orbit and as far as the corners of the universe. The next step is to make space exploration accessible to all. The ability to do this rests on our resolve to place the right emphasis on developing the necessary technologies to: 1) reduce the costs of placing payloads in orbit and, 2) increasing the reliability and robustness of the launch vehicles charged with delivering such payloads.

Design Optimization and Design for Reliability must move from element and component level development to entire systems development. The new generation of primary design optimization constraints are not weight, stiffness, strength, and performance. The next generation of launch vehicles must be optimized for reliability, manufacturability, maintainability, reusability, operations, and safety. This first chapter has presented but a small portion of the challenges and requirements that are essential for the effective commercialization of such vehicles. It is imperative that the engineering community focus on changing the old paradigm of how aerospace vehicles are designed. For example, technologies that allow the design and manufacturing discipline requirements and limitations to be combined into an overall system model are needed. Hazelrigg [11], mentions that: "In the past, system design had been a process that was

largely disconnected from the manufacturing process.” Since manufacturing processes are not easy to describe in a physical design model the development of quantitative manufacturing models has been extremely slow and the models that exist are very few and far between. It is common in a conventional design optimization process to identify the thickness and shape of a structural plate as parameters to be optimized based on some strength and stiffness requirements. However it is a more complex matter to optimize the geometry of the same plate based on the most cost effective manufacturing process, the ability for the surface to be cleaned and reused without losing functionality, and the easiest way to replace the plate during refurbishment. “Much research needs to be done in this area in order to realize effective systems engineering models, but even approximate and rudimentary models offer the possibility of considerable gain.”[11]

Indeed the technical community has started identifying manufacturing models as a needed technology development. Rais-Rohani and Huo [12] have developed a model for aircraft structures wherein a wing spar has been optimized for strength, stiffness, manufacturability, and cost. They use simple mathematical models and identify manufacturability factors and cost elements that, when combined with the structural constraints produce critical information on the complexity and efficiency of the design and the effect of cost on the final design configuration.

A final thought on the need to develop technologies for effective reusability, manufacturing, maintainability, safety and reliability is that system level testing of the final configuration is often the only place where many components are tested for the first time. These tests however are often deleted because of the fear of over testing the final system, enormous costs of developing a facility to test the system, and confidence in the ability to perform analytical investigations of the final system. The effects of the new requirements on the final system configuration often cannot be verified by analysis and so cost effective new methods for testing at the system level are needed. Typically the effects of physical parameters such as temperature, weight and acoustic environment can be easily verified through traditional stress, thermal and dynamic analysis of the structural system. However, effects of reliability and robustness parameters such as repairability, reusability and maintainability are more difficult to quantify and verify. Technologies for final verification of complex systems are critical to determine the flaws and defects that cannot be verified through analysis such as those due to errors in workmanship.

“...the ship should not have been asked to demonstrate achievements when she had not had a chance to exhibit her weaknesses.” [13]

Robin Higham on the fatal crash of the British dirigible R-101 in 1930.

References

1. Eldred, Charles H.: Shuttle for the 21st Century. Aerospace America, Vol. 22, No. 4, April 1984. pp. 82-86.
2. Haefeli, Rudolf C., Littler, Ernest G., Hurley, John B., and Winter, Martin G.: Technology Requirements for Advanced Earth-Orbital Transportation Systems. Volume I. Summary Report. NASA CR 2867, June 1977.
3. Hepler, A.K., and Bangsund, E.L.: Technology Requirements for Advanced Earth Orbital Transportation Systems. Volume 2. Summary Report. NASA CR 2878, July 1978.
4. Calouri, Vincent A., Conrad, Robert T., and Jenkins, James C.: Technology Requirements for Future Earth-to-Geosynchronous-Orbit Transportation Systems. Volume II. Technical Results. NASA CR 3266, June 1980.
5. Taylor, A.H., Cerro, J.A., and Jackson L.R.: An Analytical Study of Reusable Flight-Weight Cryogenic Propellant Tank Designs. AIAA/ASME/ASCE/AHS 25th Structures, Structural Dynamics, and Materials Conference, Palm Springs, CA, May 14-16, 1984. AIAA Paper No. 84-0865.
6. Dixon, C.S., Tenney, D.R., Rummier, D.R., Wieting, A.R., and Bader, R.M.: Structures and Materials Technology Issues for Reusable Launch Vehicles. NASA TM 87626, October 1985.
7. Ryan, R.: Robustness, NASA TP 3336, March 1993.
8. Hernandez, S., Rodriguez, P., Smeltzer, S., and Vanderplaats, G.: Structural Optimization of Aerospace Vehicles with Emphasis on High-Reliability, "An International Workshop," AIAA/ASME/ASCE/AHS 39th Structures, Structural Dynamics, and Materials Conference, Long Beach, California, April 20-23, 1998.
9. Goldin, D. and Holstein, E.: "The New Economics of Space," in *LaunchSpace*, Vol. 5, Number 3, April 1, 2000.
10. Ryan, R.: Robustness, NASA Technical Paper 3336, March 1993.
11. Hazelrigg, G.A., Systems Engineering: An Approach to Information-Based Design. Prentice-Hall, Inc., 1996.
12. Rais-Rohani, M. and Huo, Z.: Analysis and Optimization of Primary Aircraft Structures based on Strength, Manufacturability, and Cost Requirements. AIAA/ASME/ASCE/AHS/ASC 40th Structures, Structural Dynamics and Materials Conference, St. Louis, Missouri, April 12-15, 1999.
13. Higham, D.R., The British Rigid Airship, 1908-1931, London, 1961, quoted in Ferguson, E.S., Engineering and the Mind's Eye, MIT Press, 1997.