Research and Technology 1996

Annual Report of the
Marshall Space Flight Center

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Space Administration

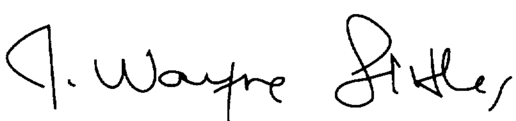
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

Introduction

As the world around us changes, new and complex technological challenges greet us at every turn. At the Marshall Space Flight Center, a talented team of scientists and engineers with a synergistic spirit rises to meet those challenges with faith in Marshall's credo: That our capabilities and successes are possible by a continuing emphasis on scientific research and the development of technology.

People across the country and around the world have benefited by our work in ways that once were only imagined, and it is that limitless imagination and the new ideas of the NASA "can-do" spirit that form the very cornerstone of our Nation's space program.

As we move toward the goal of increasingly accessible space transportation and the next generation of propulsion systems and launch vehicles, as well as long-term research aboard the *International Space Station*, our scientific and engineering teams continue to probe the vast frontiers of challenge and change. In the following pages, you will see a sample of the scope and diversity of the research and technology activities conducted here and catch a glimpse of stimulating future goals for the exploration of space.



J. Wayne Littles
Director
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To assist the reader, the MSFC contact, office code, telephone number, and e-mail address are included at the beginning of each article. The sponsoring organization and university/industry involvement are given at the end of each article. An abbreviations and acronyms list, an alphabetical index of contacts, and an index of key words are presented at the end of this report.

This publication can be found on the Internet at: http://techtran.msfc.nasa.gov/96R&T/index.html.

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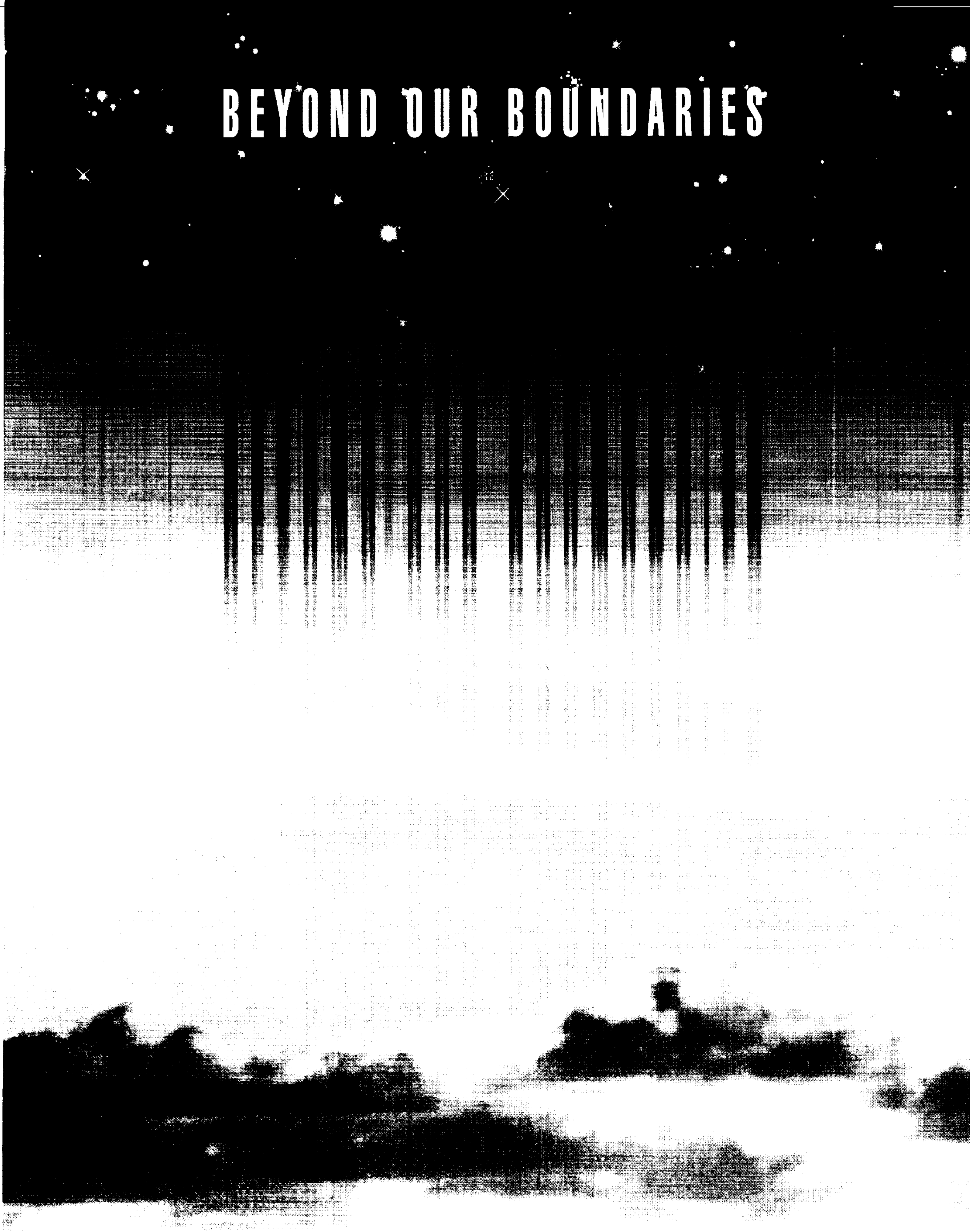
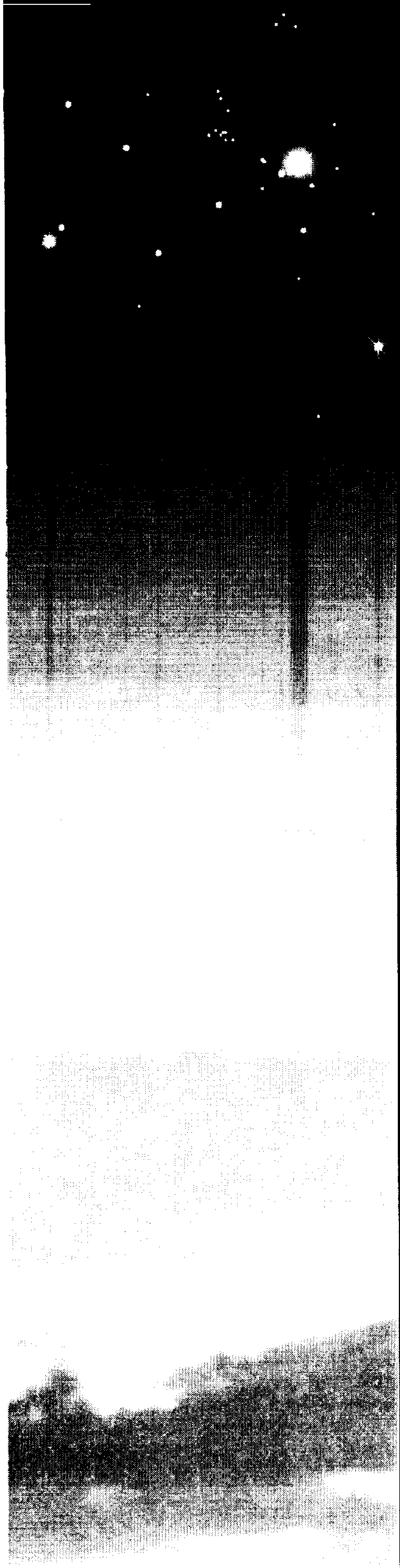
BEYOND OUR BOUNDARIES





This year's Research and Technology Report, "Beyond Our Boundaries," is about unveiling the secrets of other worlds. Thanks to the technological and scientific strides being made by NASA's Marshall Space Flight Center, other field centers and contractors, reaching beyond our boundaries, and sharing in the wealth of knowledge gained from worlds rich with possibilities, is no longer just a dream. We have already exceeded our ancestors' wildest dreams, and with new and exciting technologies at our fingertips, the door to other worlds is wide open...

The heat insulating properties of space aerogel are shown with help from a little Hershey Hug™.

At Marshall, three interrelated areas of focus—space transportation, microgravity research, and optics research—continue the strides that will take humanity beyond mere imagination in our quest for knowledge of the heavens and how that understanding can benefit our own world.

NASA's space transportation efforts build on current technologies to transport payloads, research facilities, and humans into space safely and efficiently. Marshall's vision is to help our country maintain its role as the world's leader in space transportation. In order to achieve that, we developed a space transportation strategic plan that directly supports the NASA Strategic Plan, and provides a 25-year transportation vision to support anticipated future Agency and national needs. To that end, NASA has begun concentrated efforts to balance current space transportation systems with investments in improved technologies, with the potential to significantly reduce these costs.

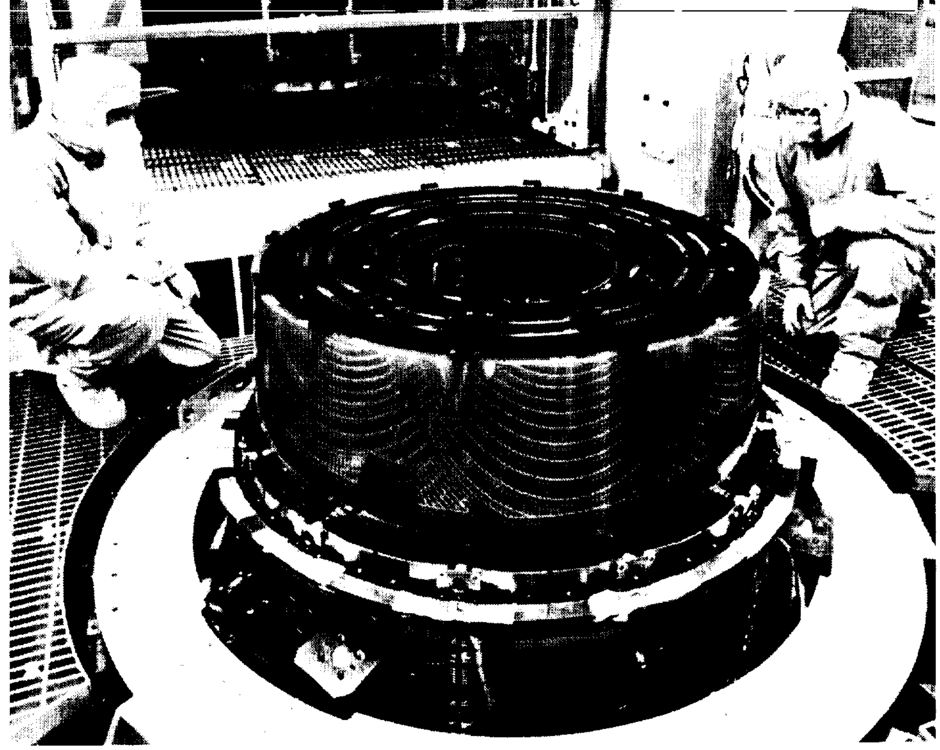
NASA has two strategic roles in these endeavors. The first is to provide the technology base required to satisfy long-term strategic plans for Space Science, Mission to Planet Earth, and the Human Exploration and Development of Space. The second is to perform the research and development necessary to enable the U.S. launch vehicle industry to compete globally in the ever growing space launch market. The Reusable Launch Vehicle (RLV) Technology Program and Advanced Space Transportation Program (ASTP) will develop and demonstrate the needed technologies and operational systems to meet these needs.

The ASTP and RLV programs are complementary space transportation technology development efforts. While the RLV program addresses the relatively near-term technology needs for a next generation reusable launch vehicle, the ASTP provides space transportation technologies for all other needs not addressed by the RLV effort. The RLV program will provide technology demonstrations in support of a national decision to either develop a new fully reusable spaceship or to upgrade the Space Shuttle for use far into the future. ASTP is a technology demonstration and validation program and has the charter for space transportation technologies from basic technology research to flight-system demonstrations.

The scientific research that will be accomplished once the *International Space Station* is in operation is being

An artist's concept of the X–33 RLV, a future Space Shuttle, depicting a solar thermal array launch.

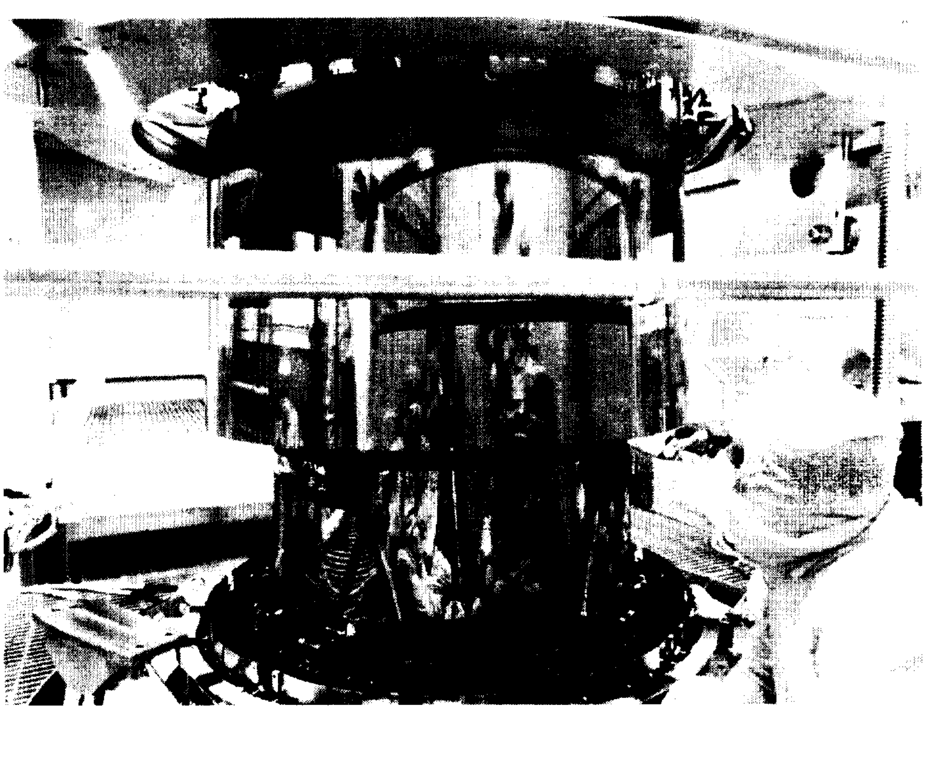
The High Resolution Mirror Assembly, with all four H mirrors installed and visible.



approached with the same practical strategies that will put the Station in orbit. Biotechnology and materials research conducted during Space Shuttle Spacelab missions have paved the way for investigations on the Space Station, with experiments already having yielded valuable results. Microgravity research facilities flown on the Shuttle represent an integrated program comprised of Government, academia, and private industry participation, and by using instruments developed by neighboring countries, this research helps broaden the basis for international cooperation in space.

As the Lead Center for Microgravity Research, Marshall is responsible for all microgravity integrated program planning and direction, program resource management, program assessment, and program outreach and education to the scientific and industrial communities, as well as the public. Commercially, the Microgravity program seeks to promote industry participation and to facilitate the use of space for commercial products and services. The industry-driven, high-technology program supports goals of implementing research and development to enable commercial space advances and expansion of current markets, and to enable U.S. industry to develop new, profitable space industries. It is this kind of concentrated effort and organization that brings us closer each day toward stable, long-term research on board the premier orbital laboratory, the *International Space Station*.

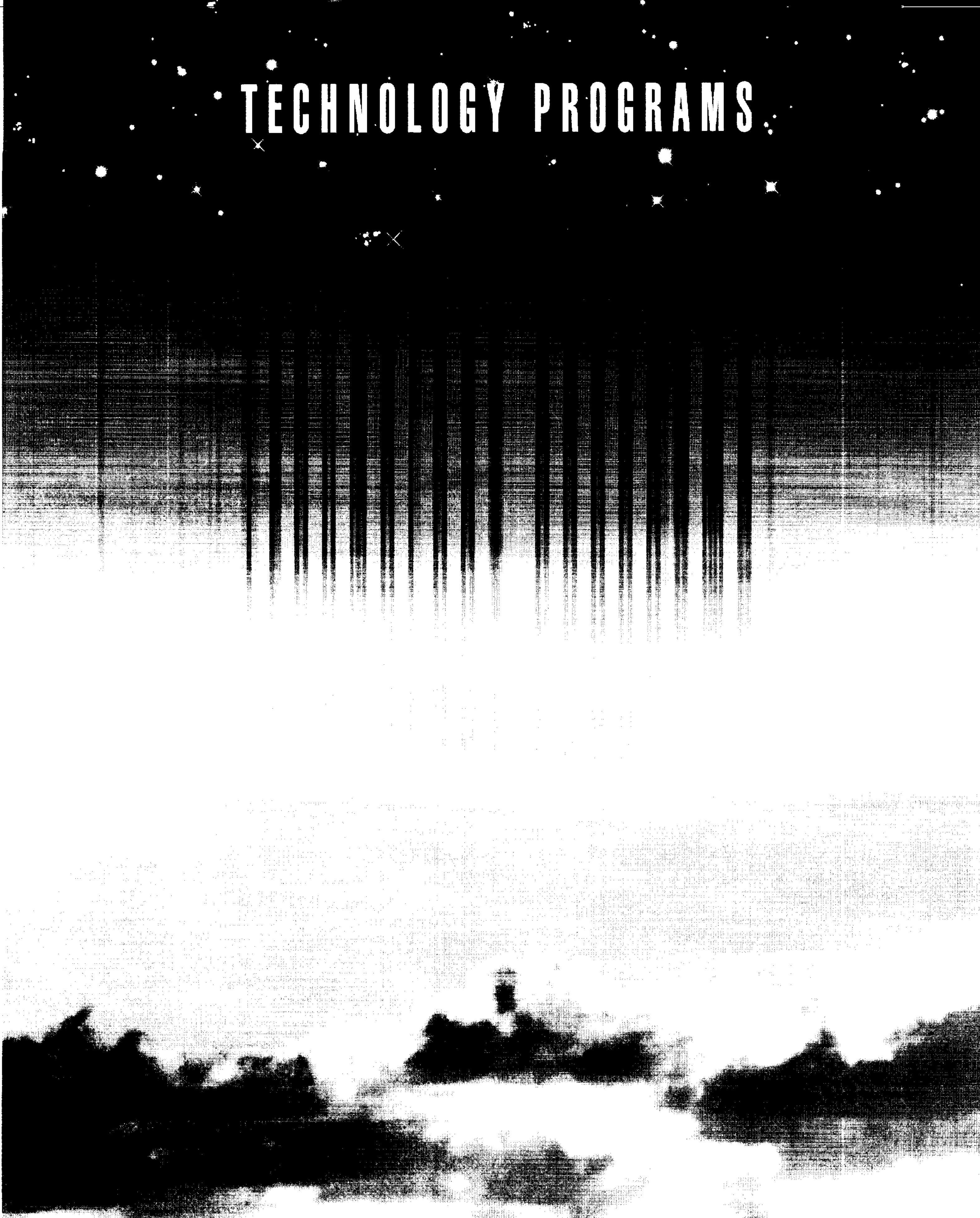
Telescopes and other scientific instruments already have given us an exciting glimpse into a universe filled with endless possibilities. Through the use of optics, Marshall provides support to NASA's Science Enterprise to examine the content, structure, origin, and evolution of our galaxy and the universe. In order to see vast distances in the universe in great detail, accuracies pushing beyond the existing capabilities will be required. Fabricating the next generation of optical and x-ray telescopes will require state-of-the-art delicate and precise cutting, grinding, shaping, and polishing tools for optical components. Special mirror coatings will also be needed for various astronomical applications. Optics work literally is in the details, and such precise operations require the finest "surgeons." At Marshall, a skilled team of scientific artisans are the caretakers of the equipment and the knowledge that will help us find the answers to never-ending questions about the final frontier.



The Marshall Center is steeped in tradition. The pride in excellence that was forged with NASA's inception remains a driving force behind the Agency's goal of providing a space program that satisfies the needs of the American public. MSFC is well equipped with the knowledge, courage, and a broad experience base to help reach our Nation's goal, but it is a limitless vision that will carry us beyond our boundaries and into another realm. At Marshall, we continue to dream. And what's more, we turn those dreams into reality.

AXAF H1 mirror and alignment system being lowered into place.

TECHNOLOGY PROGRAMS



As the Lead Center for Space Transportation Systems Development, MSFC plays a vital role in NASA's overall missions and long-range goals. To reach beyond our world and expand our destinations beyond where we thought possible is our primary focus.

Believing that strength concentrated in one particular area will provide the very best end product, Marshall serves as a Center of Excellence for providing cost-effective and reliable space propulsion technologies, thus assuring continued safe and efficient operation of the Nation's Space Transportation System.

Marshall's research into the advanced technologies for a Reusable Launch Vehicle will lead to an economical, safe, and robust launch system to meet the growing needs of placing a diverse range of payloads into orbit. The main goal of the Advanced Space Transportation Program led by MSFC is to dramatically reduce the cost of Earth-to-orbit transportation in order to spur commercial growth. The *International Space Station*, to which MSFC lends valuable support, will provide a permanent human outpost at the gateway to the last frontier. As the Lead Center for Microgravity Research, Marshall manages Spacelab missions which have already yielded Earth-based benefits, yet it has merely grazed the surface of the discoveries that await humankind on board the Space Station.

The series of articles that follow attest to years of education, training, and experience in technology programs under Marshall's capable direction. The Marshall team is committed to utilizing information from space exploration to improve life on Earth.

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Director
Science and Engineering

Advanced Space Transportation

Magnetohydrodynamics: H2OTSTUF

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Two activities are underway in the area of magnetohydrodynamics (MHD). The first, called H2OTSTUF, is an investigation of using high temperature water as the medium for an MHD generator and accelerator. The second called "Investigations of External MHD Slipstream Accelerator Technologies," investigates the use of external electromagnetic fields to accelerate the air flowing past the vehicle for propulsion.

Several studies have examined the use of MHD accelerators and generators to augment current chemical, nuclear, and solar thermal rockets. These studies have relied heavily on analytical models and numerical codes to calculate performance. Little experimental data is available to verify these predictions. Among the experimental works that have been performed are those of NASA Langley Research Center and Arnold Engineering Development Center. The work at these centers on MHD accelerators for accelerating air in a hypersonic wind tunnel was performed about 35 years ago.[1,2] During this same time Dr. Vadim T. Alfyorov started a program to develop an MHD augmented hypersonic test facility at the TSAGi research center. This work continues today, and a small-scale facility is operational. It produces very high velocity flows, but at temperatures too high to simulate the correct Mach numbers for hypersonic flow.[3]

While this work gives us a base point from which to begin, it does not provide the necessary experimental data to validate existing codes used to predict the performance of MHD accelerators and generators. Looking at the big picture of where MHD augmentation can be used, we see a broad range of propellant, pressure, and temperatures in which we would like to operate. A single rocket would not be capable of exploring this broad range of parameters. A facility is needed where varied propellants can be heated and fed into an MHD accelerator/generator.

Some key experimental data to be gained by this type facility are:

- A velocity profile at the exit of the accelerator/generator;
- Conductivity as a function of seeding ratio, temperature, pressure, and other plasma properties;
- Boundary layer voltage drop/electrical loss;
- Validation of friction and heat transfer models used in existing codes; and
- The quantification of nonuniform velocity profiles, pressure distributions, temperature distribution, etc. and their effect on the plasma flow.

The UAH Propulsion Research Center has proposed a facility that should be capable of obtaining most of this data without firing a rocket. They plan to use a microwave plasma generator to heat various propellants. A seeding system is being designed to seed these propellants with potassium. A vacuum system is in place that will allow simulation of orbital conditions for upperstage applications. Spectrometers are available to determine temperature, pressure, and species concentrations in the plume. Laser diagnostic equipment is being sought to obtain velocity profiles at the exit and within the plume. Also, a strain gage thrust stand is being designed to measure the thrust from which the exit velocity can be calculated.

The thrust of this research is directed at validating the performance of H2OTSTUF, a solar thermal/MHD water rocket. The data obtained from this detailed study of water will be directly applicable to the augmentation of or power generation by a lox/LH_2 rocket, as water or steam is the primary combustion product from this rocket. Other propellants will be tested under this program in an attempt to determine the best

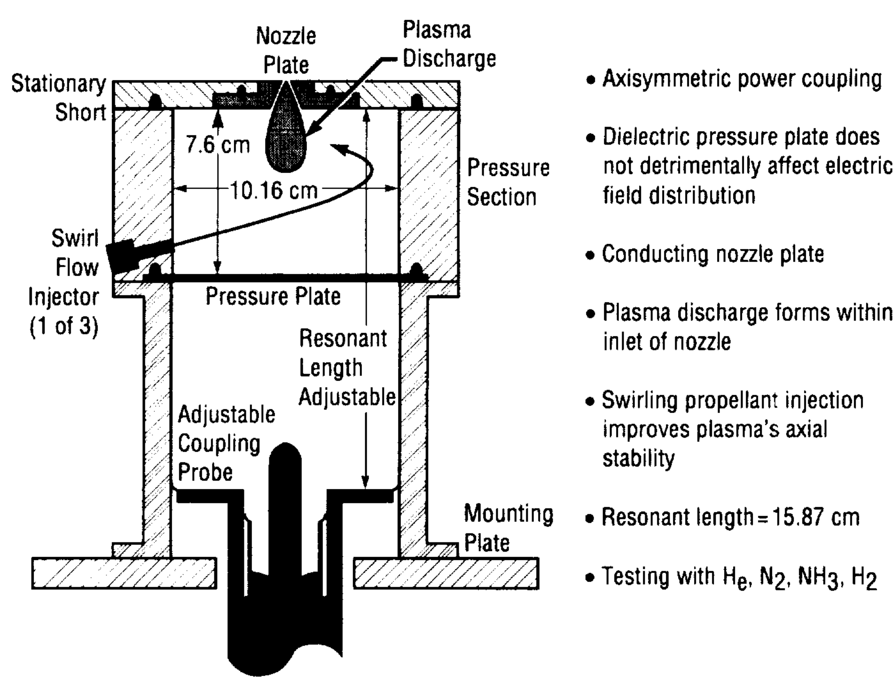

Figure 1.—Microwave cavity electrothermal thruster prototype design.

propellant combinations for MHD acceleration/generation. Other chemical rocket exhaust can be studied in the system by heating the products that would be obtained in their respective chemical reactions with the microwave plasma generator. Also, air could be heated and accelerated to verify necessary operational parameters in a ducted MHD rocket.

The development of this laboratory is the next logical step for the MHD program. With the experimental validation of existing MHD codes, an optimal system can be found through numerical simulation, thus allowing a prototype of this optimal system to be designed, built, and flown. The expertise to accomplish these tasks is available by combining the resources and personnel of the Marshall Center, the University of Alabama in Huntsville, and the University of Tennessee Space Institute.

Sponsor: Advanced Space Transportation Program

University Involvement: UAH Von Braun graduate fellow Jonathan Jones

Biographical Sketch: Tony Robertson, of the Component Development Division in the Propulsion Laboratory, has been serving as an advanced propulsion engineer and technical manager in several areas of advanced propulsion since 1995, including magnetohydrodynamics and magnetic levitation. Robertson provides support to Program Development and the Advanced Space Transportation Program in these and other advanced propulsion areas. Robertson earned a B.S. in physics and mathematics from the University of North Alabama in Florence, AL, 1982; earned a master's in operations research from the University of Alabama in Huntsville, AL, 1993; will soon complete a second master's in engineering management from the University of Alabama in Huntsville, AL, (mid-1997); and plans to seek a Ph.D. in engineering management.

Magnetohydrodynamics: Investigations of External MHD Slipstream Accelerator Technologies

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Electric propulsion systems, like the external MHD slipstream accelerators, have excellent prospects for greatly improving the specific impulse of advanced rocket-based combined-cycle engines designed for high-performance, reusable launch vehicles (RLV's) for Earth-to-orbit applications of the future. These MHD thrust augmentation systems will require high-performance rocket-driven MHD generators, as well as special electromagnetic slipstream ionization systems that can enhance the electrical conductivity of slipstream air at the lower hypersonic flight Mach numbers; beyond Mach 18, naturally occurring conductivities may suffice.

Current solid chemical-fueled rocket-driven MHD generators have a propellant utilization efficiency of 0.5 KJ/Kg, whereas 2.0 KJ/Kg may be feasible with advanced liquid fuels. In contrast, utilization efficiencies of laser-heated hydrogen-fueled, rocket-driven MHD generators promise to be several orders of magnitude higher (e.g., 300 to 800 KJ/Kg), which could elevate specific impulses for such advanced beam-boosted RLV engines into the range of 6,000 to 16,000 sec—i.e., truly revolutionary advances.

To pursue this cutting-edge research, it is necessary to understand the physics of the complicated hypersonic flow phenomena created within MHD slipstream accelerators and air ionization systems. Since there is practically no data available in the open literature on this technology, it is proposed to conduct a combined experimental, theoretical, and computational investigation of the hypersonic flow for such MHD thrust augmentation systems. A CFD algorithm to model this flow will be necessary for simulating the MHD slipstream accelerator (and air spike) performance along a transatmospheric trajectory to orbiting velocity (i.e., Mach 25).

The proposed research program will be carried out at Rensselaer Polytechnic Institute in Troy, NY, and will involve hypersonic testing of two different MHD slipstream accelerator models (one perhaps incorporating an air spike, an air ionization device).

Five major goals for this research project include:
- To demonstrate the ability to control slipstream electrical conductivity;
- To prove that external MHD thrust production is possible;

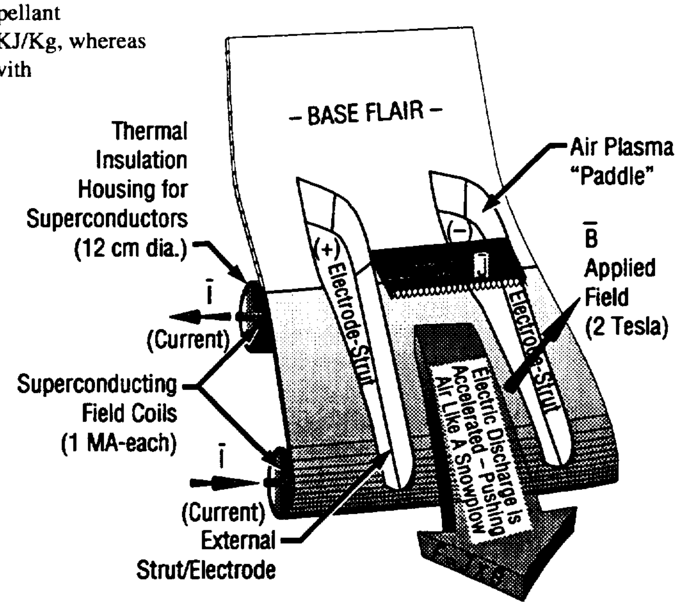

Figure 2.—External MHD accelerator.

- To determine the necessary levels of applied magnetic field and plasma current density for efficient MHD acceleration;
- To annihilate the bow shock wave with external MHD forces, and confirm this accomplishment with Schlieren photos; and
- To measure pressures (and perhaps heat transfer rates) across the powered and unpowered hypersonic models (i.e., with, and without the MHD accelerator operating).

Both slipstream accelerator experiments will utilize Rensselaer's Mach 25-class hypersonic shock tunnel (2-ft diameter test section) at Mach numbers of 8.5 to 25 and stagnation temperatures up to 4,100 K.

Sponsor: Advanced Space Transportation Program

University Involvement: Principal Investigator: Leik N. Myrabo, Ph.D., Associate Professor of Engineering Physics, Rensselaer Polytechnic Institute; Troy, NY. Co-Investigator: Professor Henry T. Nagamatsu, Ph.D., Active Professor Emeritus, Rensselaer Polytechnic Institute; Troy, NY.

Biographical sketch: Tony Robertson, of the Component Development Division in the Propulsion Laboratory, has been serving as an advanced propulsion engineer and technical manager in several areas of advanced propulsion since 1995, including magnetohydrodynamics and magnetic levitation. Robertson provides support to Program Development and the Advanced Space Transportation Program in these and other advance propulsion areas. Robertson earned a B.S. in physics and mathematics from the University of North Alabama in Florence, AL, 1982, and earned a master's in operations research from the University of Alabama in Huntsville, AL, 1993. He will soon complete a second master's in engineering management from the University of Alabama in Huntsville, AL, (mid-1997), and plans to seek a Ph.D. in engineering management.

Solar Thermal Propulsion Absorber/Thruster

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In-house studies at MSFC show reduced costs for orbit transfer using solar thermal propulsion (STP) systems. STP uses concentrated sunlight inside an absorber cavity to heat hydrogen (to 2,700 K) and expel it from a conical nozzle. STP systems are low thrust (4.4 to 44 N) and require about a month to transfer payloads from low-Earth orbit to geosynchronous-Earth orbit. Cost savings are primarily from reduced weight and high specific impulses (800 to 900 sec). A ground demonstration STP absorber/thruster has been designed and fabricated with two main objectives:

- Develop a STP fabrication procedure; and
- Verify expected STP performance with simulated ground tests.

The design (fig. 3) of MSFC's first STP absorber/thruster is cylindrical for simplicity and operates under the "direct gain" principle (focused sunlight provides immediate thrust). The inner cavity is highly reflective close to the front opening (833-K surface temperature) and more absorbing deep inside (2,700 K surface temperature) to control light distribution of high-energy solar wavelengths. Heat transfer of solar energy energizes the propellant, hydrogen.

Tungsten ($4/N) is the refractory metal with the highest melting point and was selected for the first thruster. Rhenium ($133/N) has the next highest melting point, but is very costly. Tungsten is brittle and very difficult to machine at room temperatures. A procedure has been developed that fabricates inner and outer tungsten shells which, when joined, creates an absorber cavity with helical flow channels and a nozzle. The procedure involves vacuum plasma spraying tungsten over a graphite mandrel with an outer surface designed to meet requirements of the inner surface of a tungsten shell. The graphite is removed with a drill bit and plastic bead blaster. Shell length is cut using a brass wire electric discharge machine (EDM). A hone device using polyurethane pads, diamond powder, and a glycerin slurry was used to polish the tungsten surface inside the absorber to 75 percent reflectivity. Figure 4 shows an outer shell made of tungsten. The tungsten shells are brazed to a nickel face plate, which has hydrogen inlet lines.

Insulation is made of a rigidized graphite felt to lower temperatures on the thruster's outer surface to 444 K. Graphite diffuses into tungsten at high temperatures. A protective coating of tantalum carbide (TaC) or niobium carbide (NbC) is required at each material interface to minimize a buildup of tungsten carbide.

The next STP absorber/thruster will be made of a tungsten/rhenium alloy ($44/N) which has better ductility. The fabrication procedures developed from the first thruster greatly reduces the time and cost associated with expensive material.

Sponsors: Advanced Space Transportation Program; Aerospace Industry Technology Program; Center Director's Discretionary Fund (CDDF)

Industry Involvement: Rockwell International Rocketdyne Division

Biographical Sketch: Harold P. Gerrish Jr. is an aerospace engineer for MSFC's Propulsion Systems branch. He is principal investigator for the STP project funded by CDDF and leads a small team charged with thruster design/fabrication and activation of special test equipment for ground demonstrations. His 10 years in propulsion cover solar thermal propulsion, nuclear thermal propulsion, and hypergolic combustion engines. He received a B.S. in aerospace engineering from Auburn University, and an M.S. in aeronautics and astrnonautics from Purdue University.

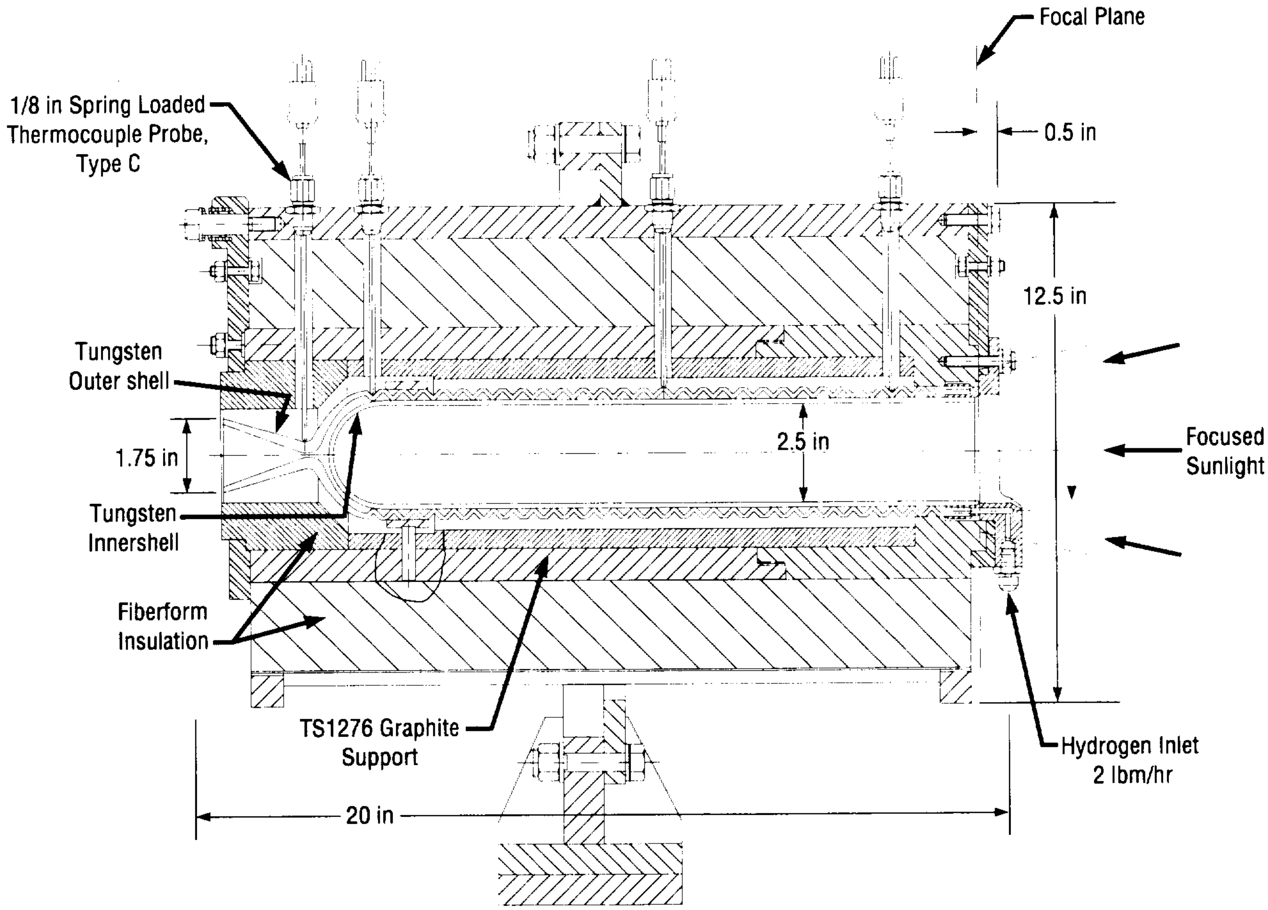

FIGURE 3.—Phase I solar thermal propulsion absorber/thruster design.

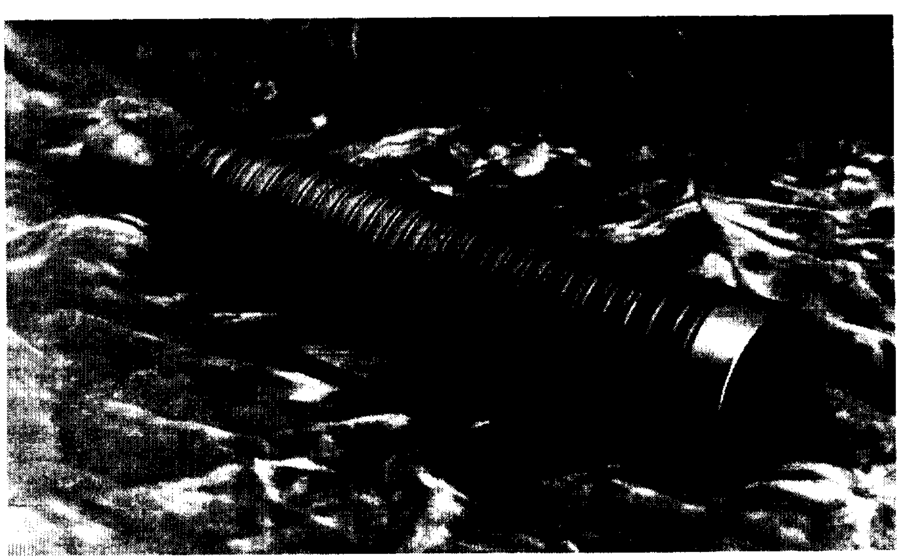

FIGURE 4.—Tungsten outer shell with helical flow channels and nozzle.

Low-Cost Booster Propulsion System Test Article

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The propulsion test article (PTA) provides a flexible test-bed environment to evaluate low-cost hardware RP–1/lox options for use on a future small payload expendable boosters. The test-bed will be in a stacked configuration as shown in figure 5 and will be tested in the B–2 test stand at Stennis Space Center (SSC). The major components of the PTA include the support structure, the lox and RP–1 tanks, the RP–1 and lox feedlines, the pressurization system including a heat exchanger, flight type avionics and test instrumentation and the 60-klbf thrust MSFC Fastrac engine. The Fastrac engine is scheduled for use on the X–34 program, therefore establishing this test-bed as the engine development and verification facility for the X–34 engine.

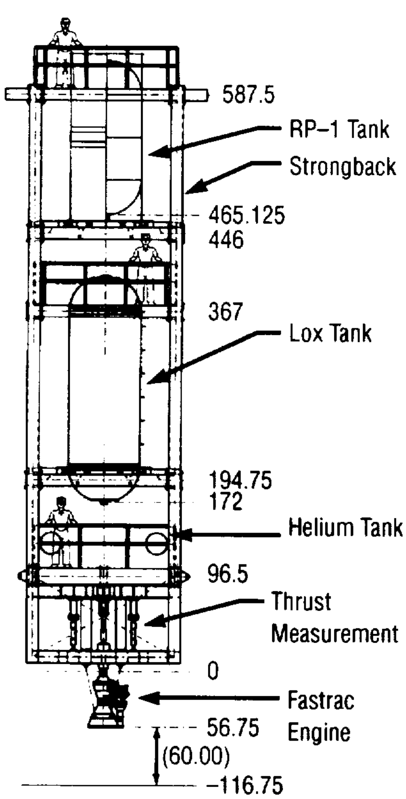

Figure 5.—The propulsion test article.

The PTA design began in May of 1996 and had as one of its fundamental requirements the necessity to fire the engine and propulsion system by January of 1998. The major milestones of the project are the systems requirements review held June 27, 1996, the preliminary design review held August 20, 1996, the critical design review scheduled for December 16, 1996, cold flow checkouts in November of 1997 and the first hot fire in January of 1998.

The PTA will provide a system test-bed to evaluate low-cost propulsion system components developed by NASA, traditional and nontraditional industries, as well as universities. The traditional industries refer to the classic space contractors possessing years of experience with flight hardware. The nontraditional industries are those business concerns which produce components and materials which are applied to commercial areas (i.e., gas bottles for hospital use, gasoline storage tanks for service stations). The heart of the low-cost booster technologies program lies in this canvassing of all of these groups to develop and test, both at a component and at a system level components and materials which could eventually be applied to use on commercial launch vehicle, developed by industry, which would have an extremely low-cost payload capability ($/lb).

The PTA design is being led by members of MSFC and the SSC. The design approach has entailed the use of the product development team (PDT). The project design is centered around four PDT's. They are the engine PDT, the Systems Integration PDT, the Avionics PDT and the PTA PDT, which has responsibility for the coordination and integration of the hardware into the PTA and the test stand. The test operations personnel for the SSC serve as part of the test team. This close working relationship ensures the concurrent engineering required to complete this task in the aggressive schedule which has been undertaken. When the design is complete and the hardware is procured, it will be sent to SSC integrated and tested in the B–2 test stand.

Figure 6.—The Fastrac engine.

The PTA will provide development data on a wide range of propulsion hardware which will allow the future development of an extremely low-cost launch vehicle. This capability will most likely be utilized in the launch of small payloads to a wide range of potential orbital inclinations. These small payloads could include scientific and engineering payloads in the areas of medicine, materials and space manufacturing. The design is based around a 72-in-diameter tank set and would be representative of a booster with a 220-lb capability to low-Earth orbit.

The PTA will provide a flexible test-bed with the ability to test various propulsion components in a system environment, allowing NASA and industry to evaluate these components, with the perspective of their use in a low-cost booster, providing less expensive access to space.

Sponsor: Advanced Space Transportation Program Office

Biographical Sketch: Mark Fisher is member of the Propulsion Systems Branch in MSFC's Propulsion Laboratory. He has been an employee of NASA since 1990. Fisher leads the PTA product development team, an interlaboratory, intercenter team charged with the design, development and test of the PTA system. He received a B.A. degree in mathematics from Edinboro University of Pennsylvania, and a B.S. and an M.S. degree in mechanical engineering from Pennsylvania State University.

Integrated Propulsion Technology Demonstrator

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Improved propulsion system integration methods are the answer to reduced flight cost of any propulsion system. The propulsion system is a significant factor not only in weight, but in both turnaround time and operations cost of any reusable launch vehicle. Historically, the design of such systems has considered weight and "hardware" as the primary technical challenges. This type of approach has been demonstrated again and again resulting in uncoordinated and inefficient operations. Bottom line: You have good designs and reliable hardware, but you can't launch it on time and at low cost! The integration technology needs are basic and focus on two areas: First, develop hardware designs based on operational efficiency, and second, implement automation for all operations. Technology developed in both of these areas will result in well-integrated, highly efficient, and low-cost test/launch operations. The integrated propulsion technology demonstrator (IPTD) charter is to provide a platform to make significant advancements in both of these areas.

The overall goal of the IPTD program is to enable NASA and industry to jointly develop system requirements and validate integrated vehicle, engine, and subsystem requirements in the advanced conceptual design phase of a program through the preliminary design phase. This early validation of requirements with empirically derived integrated performance and operational data is necessary to enhance the credibility of operational cost projections for the next launch vehicle program. Advancements in integrating propulsion systems, focused on operations costs and efficiency of launch and test operations, will enable the United States to provide reliable and repeatable low-cost access to space.

MSFC, through a cooperative agreement (NCC8–47) with Rockwell International, developed this integrated propulsion system test-bed known as the IPTD. Figure 7 illustrates the IPTD Phase I test configuration. Five major propulsion system technologies were implemented and evaluated during Phase I IPTD testing. The majority of Phase I testing focused on demonstrating complex facility/vehicle checkout and launch operations which could be integrated and automated to provide "on-time" launches at reduced cost. Component/system technologies were also evaluated during the course of Phase I testing.

Automation of LO_2 component checkout and propellant loading was successfully demonstrated utilizing one operator, computer hardware, and expert software. Following are details of the specific accomplishments and their benefits.

LO_2 and LH_2 component checkout software was co-written by a small government/industry team in G2 (expert system software) and executed within the propulsion checkout and control system (PCCS) architecture to conduct automated checkout tests. Five Shuttle checkout tests were chosen for automation demonstrations where operation improvements could be quantified by comparing to existing Shuttle timelines and manpower estimates. A reduction in manpower of 266 man-hours (Shuttle) to 6 man-hours and a reduction in actual clock time of 77 hr (Shuttle) to 1.5 hr was demonstrated for LO_2 system checkout/retest. These quantified results and technical expertise obtained during IPTD testing provide the basis for implementing significant cost savings via automation on existing or future launch systems and facilities.

The IPTD team successfully demonstrated the total automation of LO_2 loading and launch operations including real-time facility and vehicle reconfiguration upon anomaly detection. The demonstration consisted of one control workstation and operator automatically configuring the

MSFC west test area facility and the IPTD for LO_2 actual loading, simulated launch, safing, and securing. During this test, the automated control and evaluation software detected a limit violation during terminal count and automatically proceeded to scrub safing which immediately safed the IPTD LO_2 module and facility. The limit was reset and LO_2 flow was restored automatically within minutes. After loading was re-entered, the software automatically proceeded to and through the appropriate chilldown and loading phases and advanced to terminal count. Terminal count and simulated launch was successfully demonstrated and was followed by module and facility safing and final securing. This major IPTD milestone demonstrates that, low-cost and very time-efficient vehicle and launch facility operations can be achieved by implementing highly "integrated" propulsion health monitoring and control systems.

A full-scale 12-in-diameter composite feed line was successfully integrated and tested in the LH_2 propulsion module (PM). The feed line and composite flanges performed as designed when subjected to two cryogenic cycles at LH_2 temperatures. This was a first major milestone with full-scale hardware that demonstrated composite feed lines and flanges can potentially be used in some cryogenic MPS systems applications for significant weight reduction.

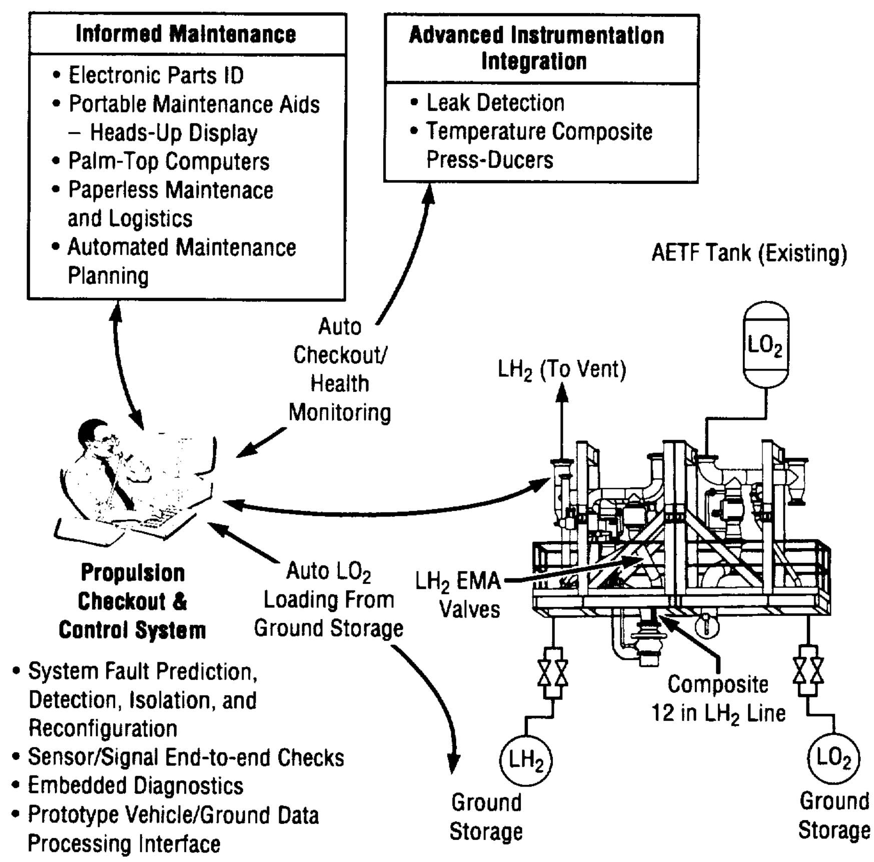

FIGURE 7.—IPTD Phase I testing configuration.

Electromechanical actuator (EMA) technology was evaluated by integrating and testing two EMA's in the LH_2 module. A MOOG, Inc.-designed EMA was installed in the LH_2 bleed line and a NASA-designed EMA was installed in the LH_2 fill and drain line. Both actuators were successfully cycled during LH_2 testing. These EMA tests were the first to test EMA technology in a full-scale cryogenic propulsion system environment, allowing engineers to assess the potential operation improvements/issues related to implementing EMA technology in existing and/or future vehicles.

An MPS hazardous gas leak detection method which could potentially identify leaks at a zone/component level was demonstrated during LH_2 testing. The method utilized mass spectrometry with real-time gas sampling at multiple locations (zones) in an enclosed compartment. The leak detection system performed as designed and provided engineers with preliminary data for improving current state-of-the-art leak detection methods.

Industry designed and manufactured close-coupled cryogenic pressure transducer technology was evaluated during Phase I LO_2 and LH_2 testing. A TABER 2211LT pressure transducer was installed on the LO_2 module and another on the LH_2 module to provide data at both cryogenic temp ranges. Both sensors tracked pressure changes very well, but exact magnitudes were slightly off. Integration and evaluation of these commercial transducers is a classical example of industry/Government partnership developed during IPTD testing to benefit each party involved.

Rockwell's informed maintenance techniques were demonstrated throughout IPTD testing. These demonstrations were the first steps toward proving that well-designed software can detect errors, generate an error report, recommend corrective action, schedule work, and provide a work order with associated procedures for component repair or replacement. This type of "in-the-loop" hardware operations testing will continue to help develop and validate the tools required for eventually implementing "airline"-type operations for launch vehicles and support systems.

Sponsor: X–33 Program

Biographical Sketch: Joe L. Leopard has been with MSFC's Propulsion Laboratory since 1990 working in several areas including engine testing, analysis, and expert systems design for test and flight operations. While working in Propulsion Laboratory's Propulsion/Systems Branch, he served as NASA's principle investigator on the IPTD project directing the day-to-day implementation of each technology demonstration. He currently works in Propulsion Laboratory's Engine Design and Analysis Branch.

Uni-Element Injector Testing

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In order to develop improved injectors for liquid rocket engines, a low-cost, time-effective method for evaluating injector characteristics is needed. A new methodology and test facility are being developed for this purpose at MSFC.

Historically, large subscale hardware at the 40,000-lb thrust level has been used for this purpose. This test hardware is approximately 5 to 15 percent of typical full-scale hardware for launch vehicle applications. Because of the expense and limited data quality of this test approach, injector development programs using it are typically limited to evaluating a small number of injector designs. These designs are usually similar to injectors with an established performance data base.

An alternative method for characterizing injectors is to use a small combustion chamber with windows to conduct extensive evaluation of a single or a small number of injection elements. Quantitative, as well as qualitative, data can be obtained using a combination of advanced optical diagnostic methods and conventional methods. A facility has been established at MSFC for this type of advanced injector development.

The combustion chamber currently being used, known as the uni-element injector test article, is on loan from Aerojet TechSystems. The combustion chamber, which has a 3.42-in inner diameter, is designed to accommodate windows with a viewing diameter of 1.125 in. Three sets of windows provide optical access to the combustion chamber at axial distances of $x = 0.5$, 2.25, and 4.0 in from the injector face. At each axial location, windows are at four circumferential positions: 0, 150, 180, and 270 degrees. This configuration allows for a variety of optical techniques that require the light source and receiving optics to be oriented at different angles.

The uni-element hardware was used to examine an oxidizer-rich swirl injection element. The injection element was provided by the Pennsylvania State

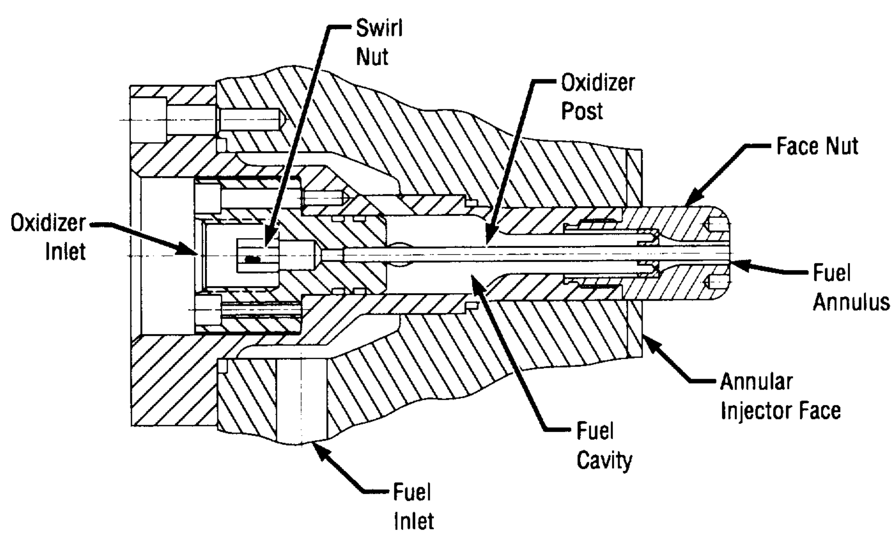

Figure 8.—Oxidizer-rich swirl injection element.

University's Propulsion Engineering Research Center (PERC), and it is identical to elements that have been tested at PERC. A cross-sectional diagram of this element is shown in figure 8. The central oxidizer post has an inner diameter of 0.135 in and an outer diameter of 0.165 in. Angular momentum, or "swirl," is imparted to the oxidizer flow as it passes through the slotted openings in the swirl nut at the head end of the injector. The fuel annulus which surrounds the oxidizer post has an outer diameter of 0.280 in.

Liquid oxygen (lox) and gaseous hydrogen (GH_2) were used as the propellants. The lox mass flow rate was fixed at 0.25 lb_m/sec or 0.40 lb_m/sec. The GH_2 mass flow rate was varied to provide mixture ratios (O/F) over the range of 50 to 175. Gaseous nitrogen (GN_2) was injected through the annular injector circuits (both fuel and oxidizer). Additional GN_2 was used in the film coolant circuit at the injector periphery. The GN_2 flowing into the chamber contributed significantly to the total chamber pressure. The mass flow rate of GN_2 was adjusted to set the steady-state chamber pressure at approximately 400 or 800 psia.

Several combustion diagnostic techniques are being applied or are being developed for application to this problem. For example, ultraviolet (UV) images have been taken with an intensified charge coupled device (CCD) camera and a UV filter. Figure 9 shows a series of these individual images taken at a gate speed of 3 μsec. These images were taken at the first window position (x=0.5 in), and the direction of flow is from left to right. White pixels indicate regions of high flame intensity. The instantaneous flame structure in these images is quite complex, and significant variation can be seen from frame to frame. The final frame in this sequence is an average of 35 individual images. This average image shows a spray cone with remarkable symmetry, with the region of highest flame intensity located very close to the injector face (<0.5 in).

Other diagnostic techniques under development include the phase doppler particle analyzer (PDPA) system and Raman spectroscopy. PDPA is an established method for measuring the important characteristics of a liquid spray, in particular droplet size and velocity distributions. Refinement of this technique for rocket engine injection elements is underway at PERC, and collaboration between PERC and MSFC will continue in this area. Recent experimental studies indicate that Raman spectroscopy is a promising technique for gathering local data on major species and temperature with reasonable levels of accuracy. MSFC's approach is to apply a spontaneous Raman scattering technique

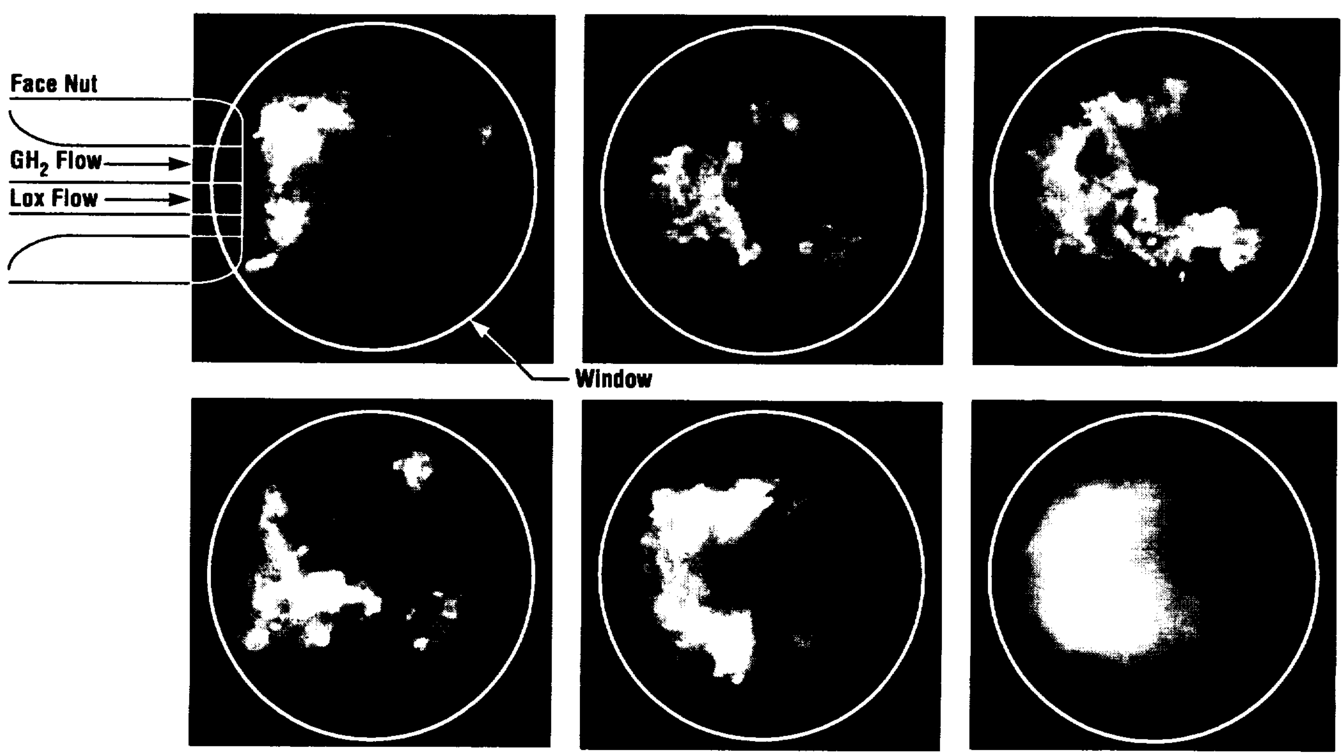

Figure 9.—Ultraviolet images of combustion zone at first window position (x=0.5 in).

developed at ambient pressure to pressures of interest for rocket engine applications (>1,000 psia). This previous work demonstrated a temporal resolution of 20 ns and a spatial resolution of 0.4 mm. Comparable levels of resolution are expected at MSFC.

A new approach for assessing the performance of liquid rocket engine injection element designs at MSFC has been established. The test facility and test hardware are operational, and a range of combustion diagnostic techniques to characterize important physical processes are being developed.

Hutt, J.J.; and Cramer J.M.: "Advanced Rocket Injector Development at the Marshall Space Flight Center." AIAA 96-4266, 1996 AIAA Space Programs and Technologies Conference, Huntsville, AL, September 24–26, 1996.

Sponsor: Office of Space Access and Technology; Space Transportation Division

University/Industry Involvement: Aerojet Tech Systems; University of Alabama in Huntsville—Propulsion Research Center; Pennsylvania State University—Propulsion Engineering Research Center

Biographical Sketch: John Cramer and John Hutt are aerospace engineers in the Combustion Physics Branch of the Propulsion Laboratory. Cramer is a graduate of Purdue University and the University of Wisconsin–Madison. Hutt is a graduate of the University of Alabama, Tuscaloosa, and the University of Alabama in Huntsville.

Thin Membrane Fresnel Lens for Solar Thermal Propulsion

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Solar concentrators made from deployable thin membranes offer a significant size and weight savings as a propulsion power source for spacecraft upper stages. A membrane cast into a fresnel lens can collect and focus the sun into a thermal cavity so that the energy absorbed there by a fluid creates a low thrust but a high initial specific impulse (Isp). MSFC is developing a demonstration in space of this solar thermal technology with the shooting star flight experiment.

A polyimide developed by Langley Research Center can be cast into an ultra-thin, strong membrane tolerant of space environments. Work has been ongoing since 1988 at MSFC on fabrication and testing of membrane reflectors with this polyimide[1]. The material has been produced into specimens that are 0.001-in thick and 8-ft wide. Although originally spin cast on flat plates, the material can be molded on a mandrel to produce a groove pattern. The polyimide membrane can be folded and stowed, then recover its shape when released and supported.

The shooting star flight experiment will use a deployable 6-ft-diameter f/1.25 fresnel lens to concentrate sunlight. A fresnel lens focuses light with a series of small concentric circular prismatic wedges instead of a curved surface, and can be molded into the polyimide membrane. A 12-in-diameter scale model was made to test and prove the concept, specifically the fabrication technique and the optical performance.

The optical prescription for the fresnel lens was designed and converted into a groove pattern compatible with the tooling controller on the Moore M-40 diamond turning machine at the MSFC Optics Branch. An aluminum blank was attached on to the machine and the grooves cut in the blank to make the mandrel. The mandrel was sent to United Applied Technology as part of a SBIR Phase 2 contract who cast the lens by pouring the dissolved polyimide onto the mandrel and spinning it in a temperature and humidity controlled environment. The cured lens was returned to MSFC where it was optically tested. The lens was fully illuminated by a collimated laser beam and the focused spot was observed and compared to the design value. The lens was also attached to a heliostat and the size and power distribution of the solar image was measured. Four lenses were produced and studied.

The lenses showed the casting and production process to be consistent. The measured optical performance was nominal, and the lens proved itself suitable as a concentrator. The focal length and solar image size were observed to be as predicted, but there were noticeable transmission losses through the lens due to the scattering from the very small groove pattern.

The success of this model allows the continuation of fresnel research and manufacturing to scale up to the full-size lens for the flight experiment. By making and testing a thin membrane fresnel lens from the polyimide, this investigation has expanded the data base and developed better expertise to understand the fabrication techniques and technology to make larger solar concentrators for upper stage propulsion. New designs and materials such as this are essential to further advance space deployable optics.

[1]Huegele, V.B.: "Thin Film Electrostatic Controlled Reflector." *MSFC Research and Technology Report 1991.*

Sponsor: Office of Space Access and Technology

Industry Involvement: United Applied Technology

Biographical Sketch: Vinson Huegele is an optical physicist in the Optics Branch and is the optics lead for the shooting star flight experiment. Huegele has been with MSFC since 1980. He received his B.S. in physics from David Lipscomb University and his M.S. in engineering from the University of Tennessee Space Institute.

Nuclear Fission Propulsion

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Missions to Mars will almost certainly require propulsion systems with performance levels exceeding that of today's best chemical engines. A strong candidate for that propulsion system is the Nuclear Thermal Rocket or NTR. Solid core NTR engines should have specific impulses in the range of 925 sec as opposed to chemical lox/hydrogen engines with specific impulses in the range of 450 sec. NTR's operate by using a nuclear reactor to heat hydrogen propellant to high temperatures and then expelling the resulting exhaust through a nozzle to produce thrust.

In the early 1970's, a nuclear rocket program was instituted called ROVER/NERVA which demonstrated a 75,000-lb thrust class engine. This engine was tested in the Nevada desert by allowing the hot hydrogen propellant exhaust to escape directly into the atmosphere. Such testing would not be permitted in today's regulatory environment; therefore, the current emphasis is on much smaller nuclear engines with thrust levels of less than 15,000 lb. These engines are small enough to be tested in current closed-loop test facilities, thus avoiding the expense of constructing large, expensive test facilities that would be required for the larger engines. High values of thrust can be attained, at the expense of specific impulse, by injecting and burning oxygen in the supersonic portion of the nozzle. Investigations are also being pursued for using these engines in "dual mode" operation—the engine reactor could be used both for thrust and power production. Figure 10 illustrates a nuclear thermal engine. Research is underway with LeRC and LANL to understand the benefits and problems with oxygen augmentation and dual-mode use.

Another nuclear thermal engine concept that is being investigated is the gas core nuclear rocket. This engine concept offers the possibility of even higher performance levels than the solid core nuclear rocket with specific impulses in the order of 1,500 to 5,000 sec. These engines use a fissioning uranium plasma to heat hydrogen gas to ultra-high temperatures before being expelled through a nozzle. The technical difficulties associated with constructing a gas core NTR are formidible. Before a gas core nuclear engine can be constructed, it will be necessary to answer fundamental feasibility questions related to maintaining uranium plasma stability, minimizing uranium plasma loss through the nozzle, and maintaining separation of the hydrogen propellant from the uranium plasma while maximizing their energy exchange. Research is being conducted with LANL to answer some of these gas core issues.

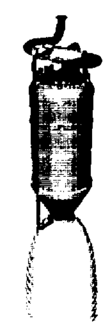

FIGURE 10.—Nuclear thermal engine.

Sponsor: Advanced Space Transportation Program

Biogaphical Sketch: Bill Emrich is an AST Aerospace Flight Systems engineer. He serves as a project engineer for advanced propulsion systems, developing analytical and design techniques for advanced propulsion systems and defining ancillary propulsion system elements. Emrich received his B.S. at Georgia Institute of Technology, his M.S. at Massachusetts Institute of Technology, and conducted his post graduate work at Princeton University.

Fusion Propulsion

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One of the great deterrents to the large-scale exploration of the solar system has been and continues to be the tremendous cost associated with putting the massive amounts of equipment and infrastructure into space to support such endeavors due to the relative low specific impulse available from chemical engines. Ideally, for solar system exploration, one would want a vehicle with specific impulses in the range of 10,000 to 200,000 sec and at least moderate levels of thrust. Fusion engines, if they can be built in reasonable sizes, match these requirements quite closely and would be most suitable as the primary propulsion system for an interplanetary vehicle. Such a vehicle would be quite capable of accomplishing manned missions to any planet in the solar system.

Several manned missions to various planets have been analyzed to determine fuel requirements and launch windows for vehicles employing such propulsion systems. For all cases studied, the fuel weight remained a minor component of the total system weight regardless of when the missions commenced. In other words, the use of fusion propulsion virtually eliminates all mission window constraints and effectively allows unlimited manned exploration of the entire solar system. Missions employing vehicles with fusion-based main propulsion systems may begin and end at times convenient to meeting the mission objectives rather than being artificially constrained by launch window considerations. These vehicles also mitigate the need for large space infrastructures which would be required to support the transfer of massive amounts of fuel and supplies to lower a performing spacecraft.

Efforts are currently underway to examine the various fusion concepts that have been developed over the years to determine which configurations are most suitable for use as propulsion systems. Three concepts currently being studied for possible use as propulsion systems include the gasdynamic magnetic mirror, the colliding conical theta pinch, and the field reversed configuration. Other concepts will also be considered if evaluations appear to show their viability as propulsion systems. Figure11 illustrates a vehicle design based upon a Gasdynamic Mirror Fusion Engine.

Sponsor: Advanced Space Transportation Program

Biographical Sketch: Bill Emrich is an AST, aerospace flight systems engineer. He serves as a project engineer for advanced propulsion systems, developing analytical and design techniques for advanced propulsion systems and defining ancillary propulsion system elements. Emrich received his B.S. at Georgia Institute of Technology, his M.S. at Massachusetts Institute of Technology, and conducted his postgraduate work at Princeton University.

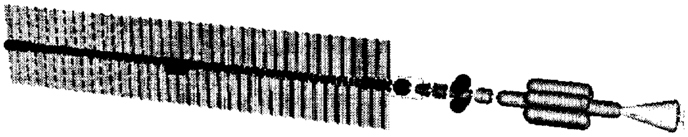

FIGURE 11.—Interplanetary vehicle using a gasdynamic mirror fusion propulsion system.

Components for Beamed Energy Transportation

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The Beamed Energy Transportation (BET) program is a component of the Advanced Space Transportation (AST) program. The objective is to exploit recent R&D advances such as high average power lasers, atmosphere compensating beam directors, and high specific impulse space propulsion in order to achieve the capability of transferring large amounts of power over great distances. Such a capability would remove from the launch vehicle and space transfer stages those systems needed to generate power, thus improving the overall mass fraction. In addition, the availability of large amounts of energy to propulsion systems enables more efficient high specific impulse propulsion technologies. Microwave rectenna power transmission, while limited in range, may be a useful augmentation for Earth-to-orbit transportation. The development of laser-photovoltaic power transmission may also provide the basis for new capability in supporting orbiting spacecraft propulsion from the ground. A spinoff for NASA will be a capacity to support scientific, life support, and other housekeeping operations for space stations and lunar bases. Also, long distance high-bandwidth communications will be made possible. Initially, within the next 20 years or so, the technology will be used to transmit power from the ground, where it is relatively plentiful and inexpensive to obtain, to space where power generation is one of the major design constraints on orbital systems. As access to space becomes more routine and less expensive, the power generation capabilities will be available in orbit, and the transmitters will also be based in space.

The current program goals of the BET are to provide a demonstration before the year 2000 which verifies that beamed energy can be used to remotely power a space transportation system, and to follow that demonstration with an initial operational capability of a launch system by 2004 and a space transfer stage by 2006.

The technologies being developed will be critical to the transport of payloads to space and in space using transportation systems of low mass and cost.

At MSFC, the BET program is going forward in three main thrust areas: Efficient high average power lasers, economical large aperture beam directors with adaptive optics, and innovative propulsion concepts.

MSFC is leading the development of an efficient high-power laser based on the concept of building an array of many small semiconductor laser diodes (SLD's) similar to those used in compact disk players and bar code scanners. Two approaches are being pursued. MSFC, in conjunction with USAF Philips Laboratory and the University of Alabama in Huntsville, has been engaged in the development of a method of phase-locking fiber optic device that can efficiently coordinate a large array of SLD's. In conjunction with the Lawrence Livermore National Laboratory, the production of higher power and more compact, but less efficient incoherent diode arrays are being researched. In the future, research into free electron lasers and efficient microwave generators is anticipated.

MSFC is also sponsoring the testing of innovative beam-energized "accelerator-class" advanced engine concepts with Dr. Leik Myrabo of the Rensselaer Polytechnic Institute in Troy, NY, utilizing the high-energy laser system test facilities at White Sands, NM. A variety of experimental apparatus are being used in these tests including dynamic impulse pendulums, a fully instrumented static impulse plate (equipped with numerous piezoelectric pressure transducers) to measure time-resolved pressures, several parabolic receiving mirrors and 0.5 Tesla permanent magnets. This experimental data will be compared with theoretical predictions for engine performance, and engineering implications for a flight demonstration drone will be determined.

Karpinsky, John; Lindsey, Randall: "Final Report: Demonstrator for an Innovative Mirror Segment Edge Sensor." SY Technology, Inc., Contract Order #H-25794D, Huntsville, AL.

Sponsor: Advanced Space Transportation Program; Office of Space Access and Technology; Advanced Concepts; Center Director's Discretionary Fund

Biographical Sketch: Edward Montgomery is an Advanced Space Transportation (AST) aerospace engineer at the Marshall Space Flight Center. He earned a B.S. degree in aerospace engineering at Auburn University, and received a master's degree in science and engineering from the University of Alabama in Huntsville.

Advanced Reusable Transportation Technologies Project

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The primary goal of the Advanced Reusable Transportation Technology (ARTT) project is to reduce by a factor of 100 over today's costs the payload transportation cost to low-Earth orbit by maturing technologies beyond X–33 for medium class launch vehicles (fig. 12). In doing so, the project's technology goals focus on combined cycle rocket-based propulsion systems and advanced materials (e.g., structures, tankage and TPS). These rocket-based combined cycle (RBCC) engines transition from an initial air-augmented rocket mode takeoff to ramjet mode, then to a scramjet mode and finally to an all rocket mode for orbital insertion.

The state-of-the-art all rocket single stage to orbit vehicle must have approximately 90 percent propellant and 10 percent inert mass. This inert mass must include the vehicle structure, propulsion hardware and the vehicle's payload. Modern operational engines, such as the SSME and the RD–0120, are essentially at the technical limit of rocket propulsion; further technology gains will only increase rocket performance (Isp) slightly. The use of RBCC propulsion may provide Isp gains of approximately 50 to 150 sec. These types of increases in mission average Isp would result in doubling the allowable launch vehicle inert mass fraction available for launch vehicle design. This additional margin could be utilized as increased operating margin by making the design more robust or to reduce the overall launch vehicle size. Either or both of these approaches would directly contribute to a major reduction in both operational costs and cost of payload to orbit.

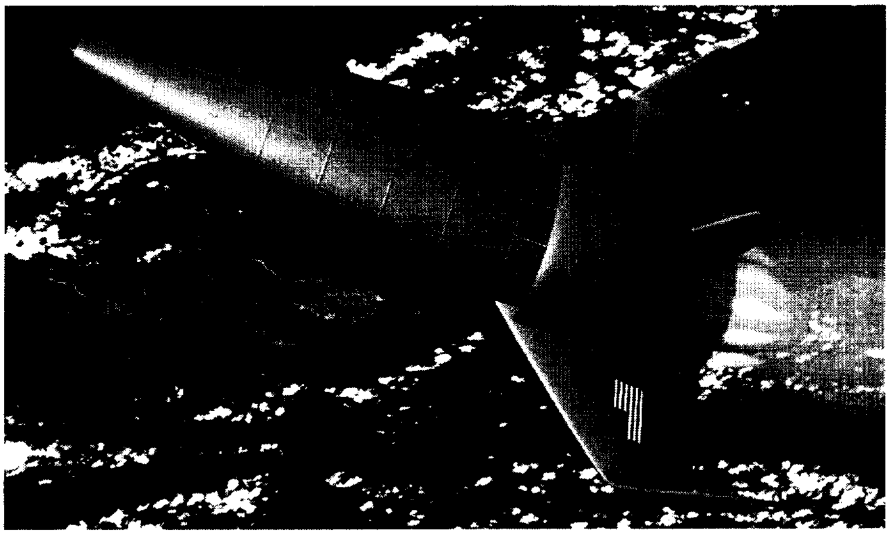

FIGURE 12.—Artist's concept of RBCC flying through atmosphere.

The ARTT project currently in progress focuses on ground testing those technologies deemed critical for the successful demonstration of an RBCC engine. Attention is being focused on the ability to design, fabricate, install and demonstrate small rockets in a carrying structure. These rockets will be required for the initial takeoff and low-speed operation of the launch vehicle. The rockets will then be turned off as the engine transitions to ramjet and scramjet modes. The rockets will finally be turned back on and the engine inlet closed for orbital insertion. The results of this testing will be incorporated with flow path work currently ongoing. The engines will be subscale, on the order of 1/6 scale, and will be flight-like but not flight-weight. Tests will include direct connect and freejet testing of these rockets in various test facilities, both industrial and government, in this country.

The incorporation of a supercharging fan increases the operability of a RBCC vehicle by adding a self-ferrying capability and additional abort-mode option. Technology issues associated with a supercharging fan will be addressed and tested in the ARTT project.

A large percentage of the launch vehicle cost reduction goal will be achieved by incorporation of RBCC propulsion. However to achieve a 1/100 reduction in the vehicle recurring cost, additional technologies will be required. Along with the RBCC technologies, advanced vehicle technologies will also be pursued. The main focus of this activity will be on primary structures, cryogenic tankage and thermal protection systems, and avionics.

Sponsor: Office of Aeronautics and Space Transportation Technology

Biographical Sketch: Jim Turner is the chief engineer for the Advanced Reusable Transportation Technologies Project. He holds a bachelor's degree in chemical engineering and a master of materials engineering from Auburn University, and has worked for MSFC for 14 years.

Solar Thermal Propulsion Flight Experiment

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One of the space transfer technologies of promise in the Advanced Space Transportation Program is solar thermal propulsion. This type of propulsion system could be used for advanced upper stages that could provide low-cost transportation of payloads from low-Earth orbit to geosynchronous-Earth orbit and beyond. Solar thermal propulsion requires large lightweight concentrators, high-temperature materials for the engine, integrated controls and pointing, and long-term storage of cryogenic hydrogen. Several of these technologies are being matured to support solar thermal propulsion including a flight experiment to demonstrate a solar thermal propulsion system in space operation. This experiment is called the shooting star experiment (SSE) and will be flown in FY99. Deployed configuration is shown in figure 13.

The shooting star experiment will demonstrate the deployment of a lightweight inflatable support structure, precise sun acquisition and collection, high-temperature engine operation resulting in high specific impulse (Isp). The experiment is designed to concentrate solar energy with a fresnel lens that will be connected to an inflatable torus which will be supported by three inflatable struts. The concentrated solar energy will be focused into a thermal storage engine where stored propellant will be used to provide a small thrust. The inflatable concentrator system will be launched deflated and packaged in a container to protect it during pre-launch processing and launch environments and to reduce the launch vehicle payload volume.

The spacecraft bus is the physical structure to which all the subsystem components will be attached and will interface to the launch

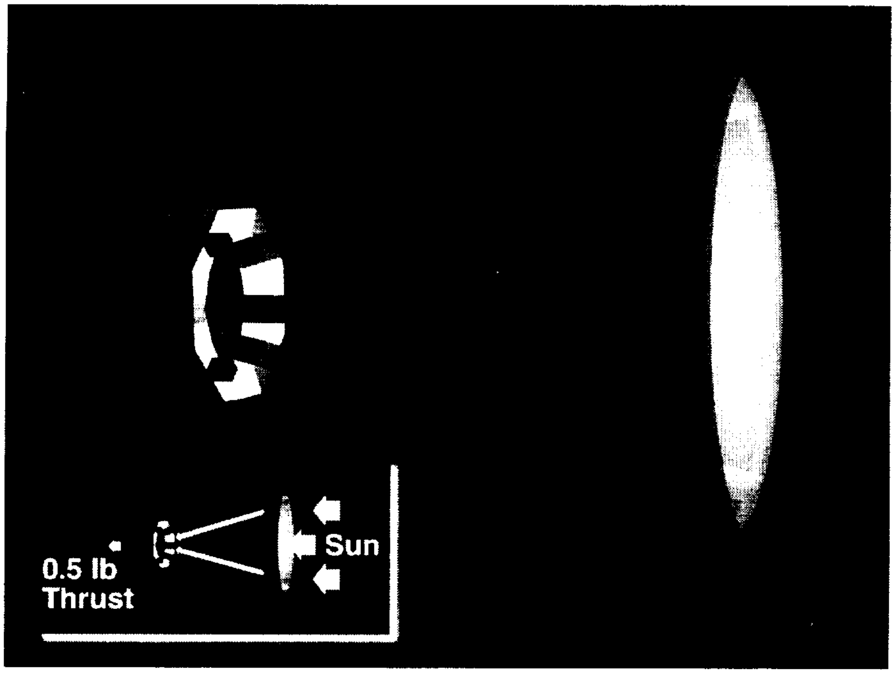

FIGURE 13.—Deployed flight configuration of shooting star experiment.

vehicle via the payload adapter interface. It also provides the thermal protection to all subsystems from the thermal engine module. The thermal engine assembly is designed to convert the solar energy focused into the engine inner cavity, store it as heat and transfer the energy to a gaseous propellant injected into the engine heat exchanger, resulting in an increased Isp over that obtained by just flowing the monopropellant through the engine nozzle. For SSE, the engine is operated in pulse mode, (i.e., it is thermally charged and then discharged by injecting the propellant when the operating temperature is reached). During the experiment operation, multiple cycles will be attempted, at increasing start-point temperatures. The final goal is 2,760 °C. At this temperature, it is estimated the resulting Isp should approach 800 sec.

There will be a Sun-centering detector system to direct the focused solar flux into the engine cavity. The cavity diameter is about 3.8 cm. Part of the Fresnel lens will be dedicated to provide a light ring at the approximate outer diameter of the bus where four optical detectors will be located. The centering processor will forward commands to the guidance and control software for corrections to keep the energy centered. A lost Sun mode has been baselined in order to reorient the SSE lens from any orientation back toward the Sun.

The electronic heart of the SSE is the on-board computer system (OBCS), (fig. 14), and the inertial measuring unit (IMU). The OBCS contains and executes the programmed sequential and housekeeping software and the IMU provides navigational and stability measurements. All experiment functions are controlled in flight by the OBCS. There is no capability for ground control after launch.

The successful space demonstration of several key technologies in this flight experiment will help mature solar thermal propulsion to the point where full-scale development of an upper stage using this technology could be undertaken.

Sponsor: Advanced Space Transportation Program

University/Industry Involvement: University of Alabama in Huntsville; United Applied Technologies; Plasma Processing, Inc.

Biographical Sketch: Leslie A. Curtis serves as manager for the Space Transfer Technologies project in the Advanced Space Transportation Program office. She has responsibility for in-space transportation technology including upper stages, transfer stages, and on-board propulsion systems. Curtis has worked for NASA at MSFC for 13 years.

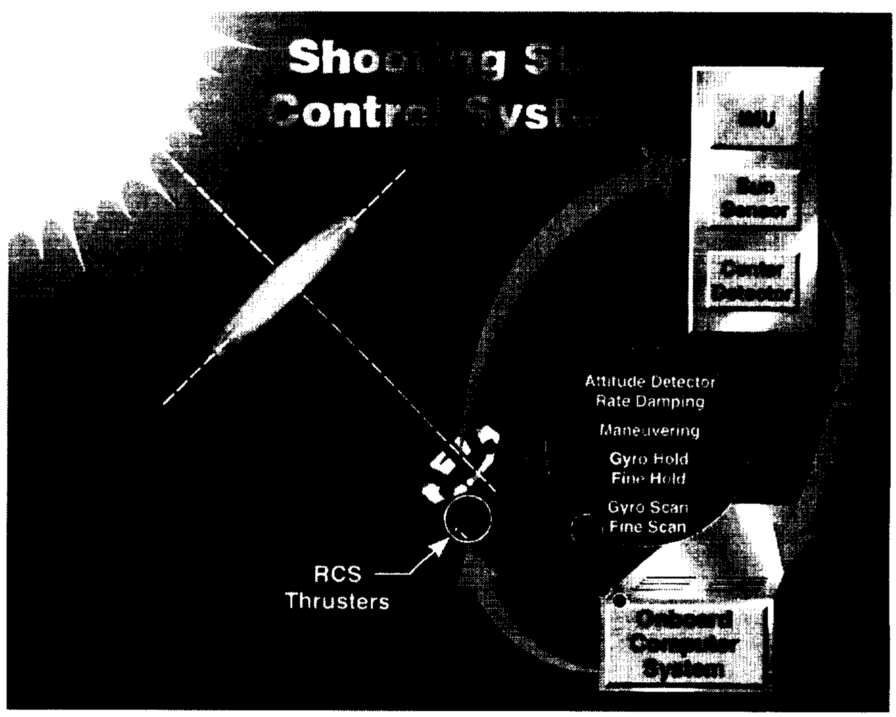

FIGURE 14.—Shooting star control system.

Magnetic Lifter

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Achieving an affordable and reliable launch infrastructure for low-cost, routine access to space is one of the enduring challenges of the space age. In a marketplace dominated by expendable launch vehicles grounded in the technology base of the 1950's and 1960's, diverse innovative approaches have been conceived since 1970 for reducing the cost per pound for transport to low-Earth orbit. For example, the Space Shuttle—a largely reusable vehicle—was developed in the 1970's with the goal of revolutionizing Earth-to-orbit transportation. Although the Shuttle provides many important new capabilities, it did not significantly lower space launch costs. During the same period, a variety of other launch requirements (e.g., for vehicle research and development and microgravity experiments) have been met by relatively expensive, typically rocket-based solutions (e.g., rocket sleds and sounding rockets).

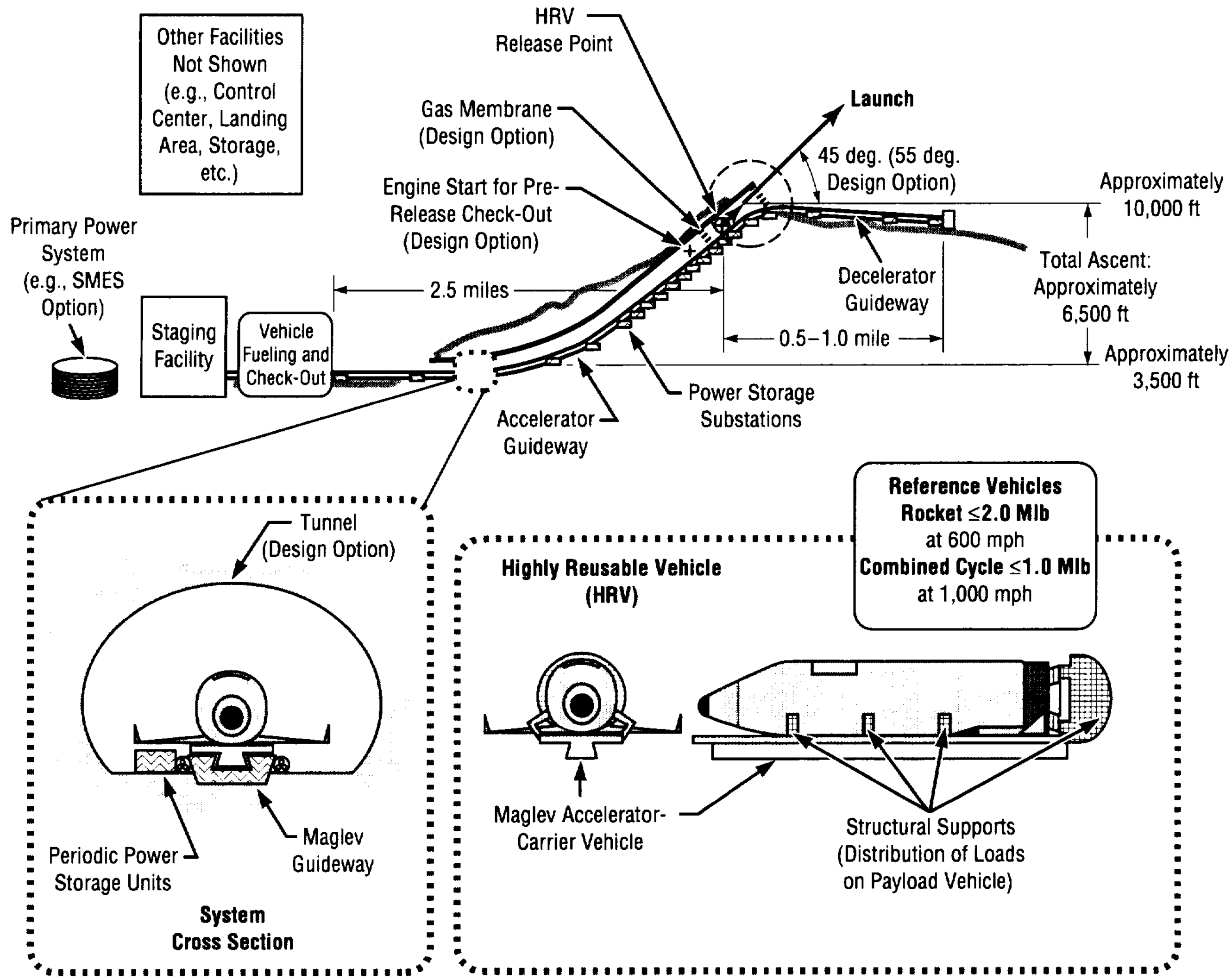

FIGURE 15.—MagLifter Space Launch System (configuration "i"): Notional, full-scale system concept. This version of MagLifter is configured for a highly reusable vehicle that does not involve the use of aerodynamic lift during launch (i.e., a ballistic ascent trajectory).

There are several basic strategies for cost reduction, including: (1) reducing the cost of hardware expended in launcher systems per pound of payload, (2) increasing the reusability per flight of highly reusable vehicles, and (3), for both of these, reducing the cost of launch operations. A variety of space launch concepts is still under study in this context, ranging from single-stage-to-orbit vehicles to "big, dumb boosters," and from air-breathing hypersonic Earth-to-orbit vehicles like the National Aerospace Plane to advanced rocket concepts such as space nuclear thermal propulsion. Some exotic concepts involving "gun-type" systems have also been studied.

However, past analyses of launch systems involving electric propulsion have been largely limited to electromagnetic versions of "cannons," such as rail guns and coil guns. Despite significant theoretical advantages, these systems have had both technical and programmatic difficulties in maturing beyond research and development and prototype-level demonstrations.

A new approach, involving the use of superconducting, magnetically levitated ("maglev") and propelled vehicles, has been

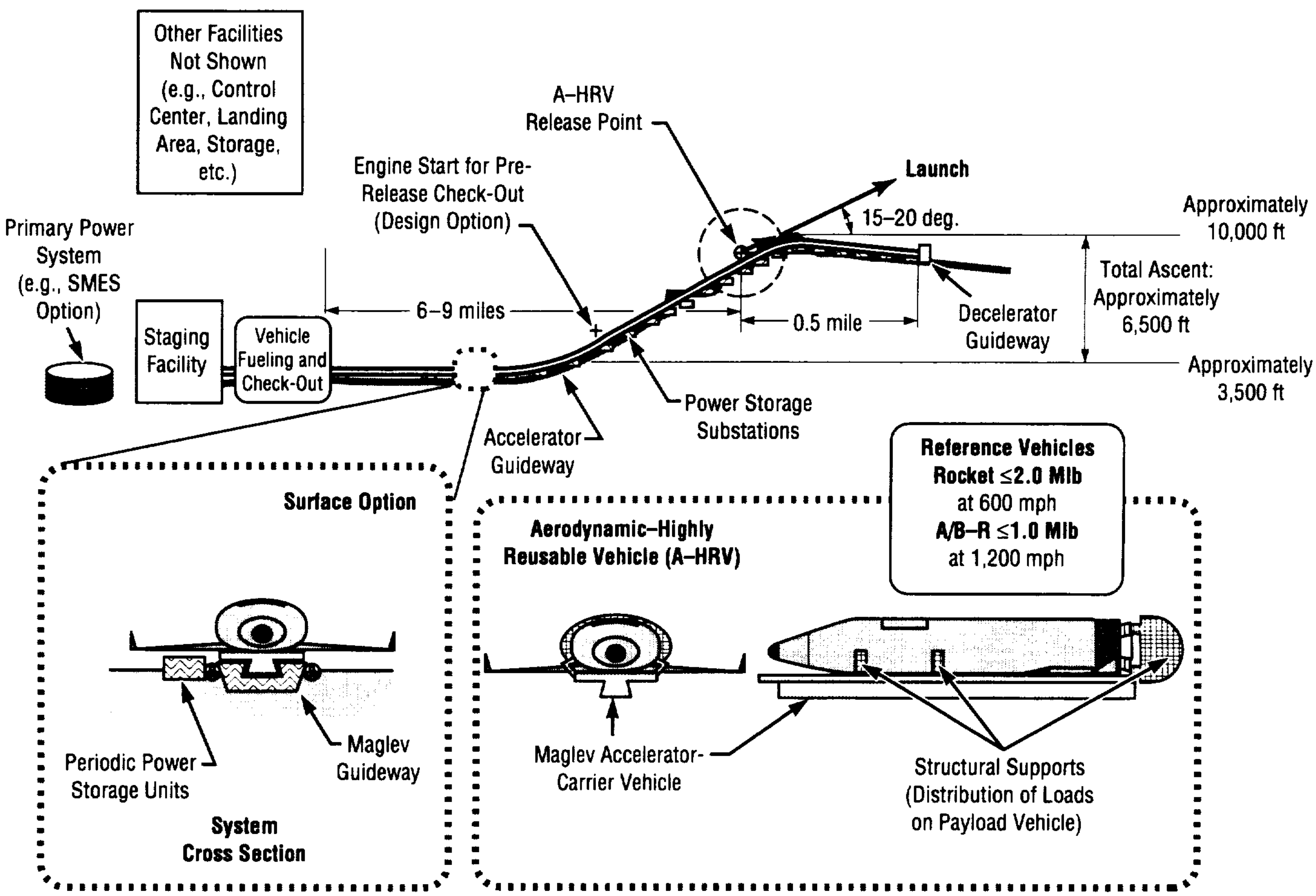

Figure 16.—MagLifter Space Launch System (configuration "j"): Notional, full-scale system concept. This version of MagLifter is configured for a highly reusable vehicle that does involve the use of aerodynamic lift during launch.

developed. Three configurations of the MagLifter concept shown in figures 15, 16 and 17 combine the technology base of maglev systems being proposed and demonstrated for terrestrial applications with the best planned improvements in expendable launch and/or highly reusable vehicle systems. Together, the results suggest dramatic improvements in Earth-to-orbit costs may be possible. The MagLifter draws on a heritage of electromagnetic launch concepts and technical literature, but embodies several new technical characteristics which have not been thoroughly considered to date.

The Magnetic Launch assist shown in figure 18 depicts the goal of a magnetic launch assist concept, potential developing technologies, maglev testing and flight demonstration. A strong synergism exists between the magnetic lifter technologies and the multi-use technology applications involving other Government agencies and private industries.

Sponsor: Office of Space Access and Technology; Advanced Space Transportation Program

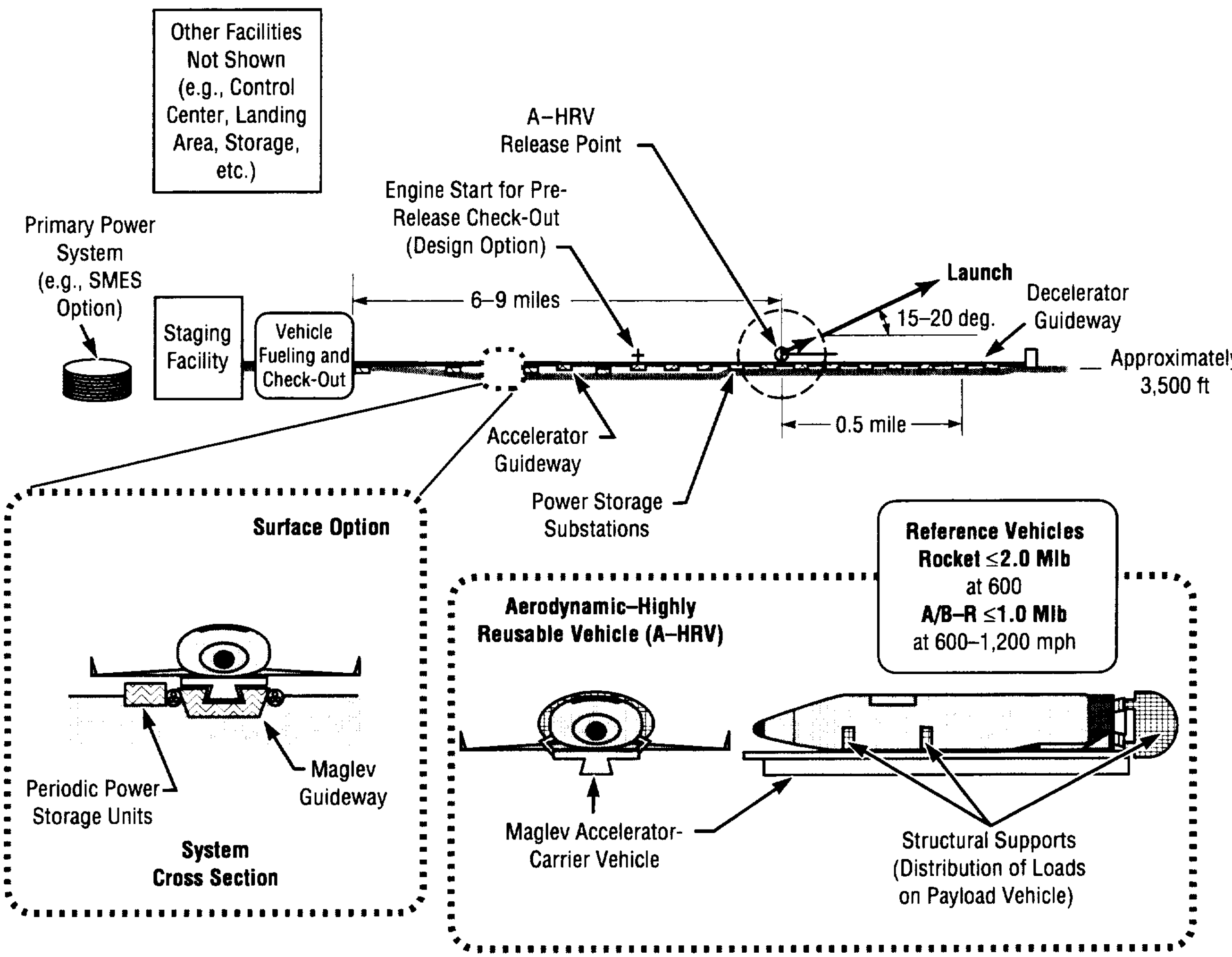

FIGURE 17.—MagLifter Space Launch System (configuration "k"): Notional, full-scale system concept. This version of MagLifter is configured for a highly reusable vehicle that does involve the use of aerodynamic lift during launch and runs horizontally—0-degree inclination—at release of HRV.

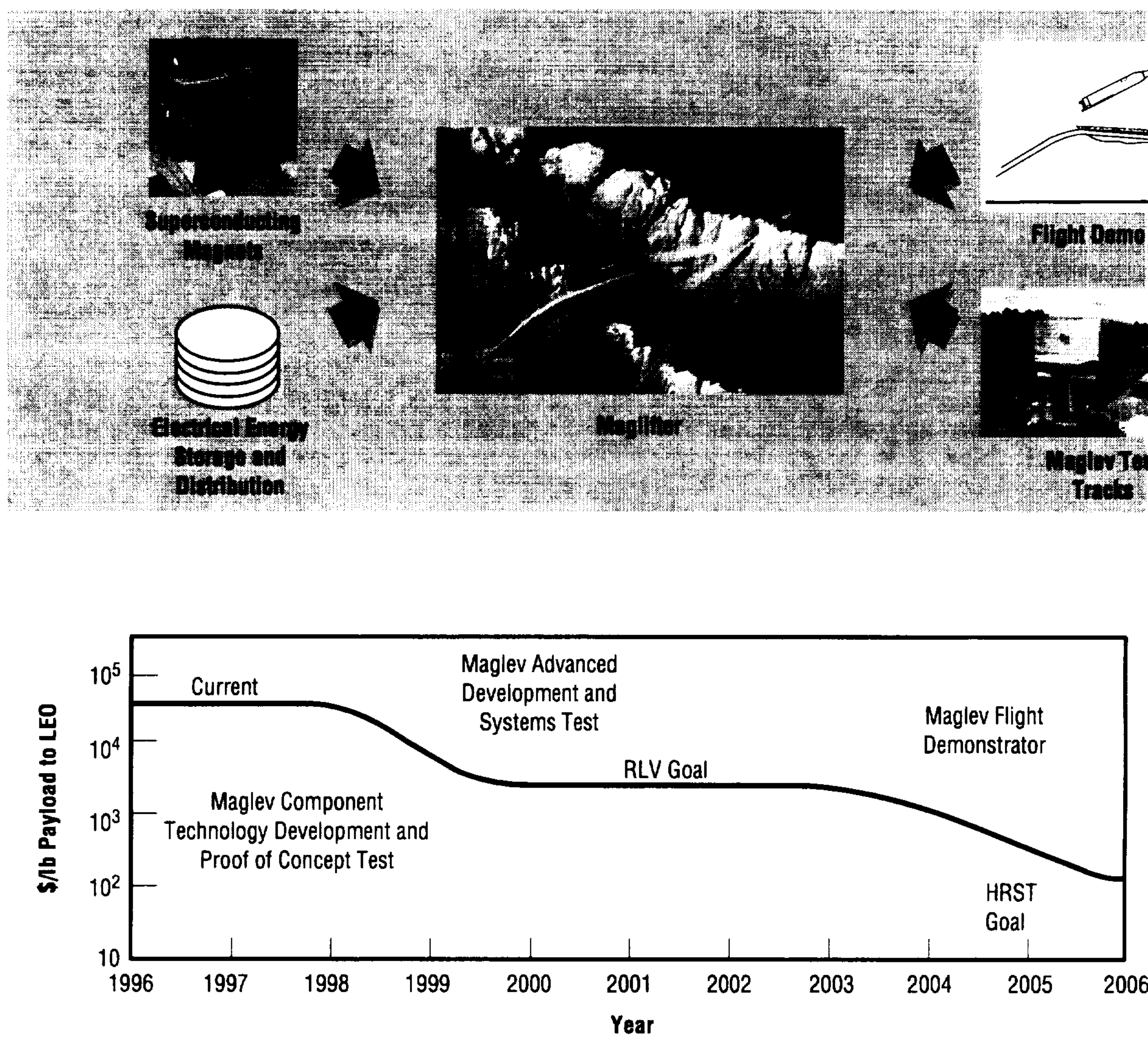

Figure 18.—Magnetic launch assist, technologies, and goal.

Biographical sketch: Joe T. Howell is an aerospace engineer. He serves as a project lead with responsibility for performing advanced systems planning involving conceptual and preliminary design definition studies, and analyses of space systems for advanced concepts. Howell attended Auburn University, earning a B.S. in mechanical engineering. He received a master's in engineering science at the University of Tennessee.

Superconductor Interactions With Gravity

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NASA's Advanced Space Transportation Program (ASTP) is charged to investigate technologies and concepts which will result in future reductions in the cost of space travel. The program has established an area of investigation in breakthrough propulsion physics. These basic investigations focus on ideas which are beyond our present capability to implement, yet offer some theoretical or experimental basis to warrant further research.

One of these areas involves the possible gravitomagnetic effects of high-speed rotating superconductors in strong magnetic fields. Published reports[1] indicate a possible gravity shielding effect with such an apparatus. Podkletnov devised an experiment in which a large disk of high-temperature ceramic superconducting material was magnetically levitated and rotated at high speed (up to several thousand r/min) in the presence of an external magnetic field. In the course of the tests he noted that objects above the rotating disk showed a variable but measurable loss in weight (variable from less than 0.5 to around 2 percent). He had no explanation for this effect and went through a self-described rigorous effort to eliminate systematic or other possible sources of error. Having done so, he found that the effect remained. The effect, while small, offers significant potential for propulsion, if real.

Dr. Ning Li, University of Alabama in Huntsville (UAH), has established a theory which establishes a theoretical basis for such gravity-superconductor interactions.[2,3,4] Based upon the reported experimental data and the Li theory, MSFC and UAH are preparing a cooperative experiment to determine, with scientifically supportable rigor, whether the reported effect is real and measurable.

The test apparatus consists of a disk of high-temperature superconducting ceramic (YBCuO material) levitating and rotating in a magnetic field. Measurements will be taken of the local gravity field surrounding the disk before, during, and after operation. Several independent methods will be used to monitor the gravity field. As the properties of this material are highly variable and very dependent upon processing, considerable effort will be expended characterizing both the superconducting material and disk processing.

[1]Podkletnov, E.; Niemanen, R.: "A Possibility of Gravitational Force Shielding by Bulk YBa2Cu3O7-x Superconductor." Physica C 203, pp. 441–444, 1992.

[2]Li, N.; Torr, D.G.: "Effects of a Gravitomagnetic Field on Pure Superconductors." Physical Review D, pp. 457–459, 1991.

[3]Li, N.; Torr, D.G.: "Gravitational Effects on the Magnetic Attenuation of Superconductors." Physical Review B, vol. 46, no. 9, pp. 5489–5495, 1992.

[4]Torr, D.G.; Li, N.: "Gravito-electric Coupling via Superconductivity." Foundation of Physics letters, vol. 6, no. 4, pp. 371–383, 1993.

Sponsor: Advanced Space Transportation Program; Center Director's Discretionary Fund

University Involvement: University of Alabama in Huntsville

Biographical Sketch: Ron Koczor is chief engineer for the Advanced Systems and Technology Office at MSFC. He has a degree in physics and has been with NASA for 8 years.

Pulse Detonation Rocket Engines

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The pulse detonation engine (PDE) is an innovative concept for producing thrust for an aerospace vehicle. The PDE injects low-pressure fuel and oxidizer into a tube and initiates a detonation. The detonation wave, which travels through the tube at a very high velocity (~Mach 4 to 6), compresses the combustion products behind it. This high-pressure gas acts on the closed, head end of the tube to produce thrust. By operating at a high repetition rate, the PDE generates a quasi-steady thrust.

Because the propellants are injected at low pressure, the PDE feed system hardware is less complex than that of a conventional liquid rocket engine. The transient nature of the PDE combustion process means that the tube walls are exposed to hot gases for only a small fraction of each cycle, unlike a conventional engine that is continuously exposed to hot gases. Because of these short exposure times to hot gases, active cooling of the the detonation tube may not be required. These simplifications should result in a significant reduction in development and production costs of a PDE.

Another potential advantage of the PDE involves the nature of the combustion process. A conventional rocket engine burns propellants continuously at constant pressure. Thermodynamic cycle analysis shows that the constant volume combustion process of the PDE is inherently more efficient than constant pressure combustion. However, the actual efficiency improvement suggested by this analysis is yet to be demonstrated.

Although advanced development of the PDE has focused on air-breathing applications in recent years, a similar concept can be applied to rocket engines. MSFC has

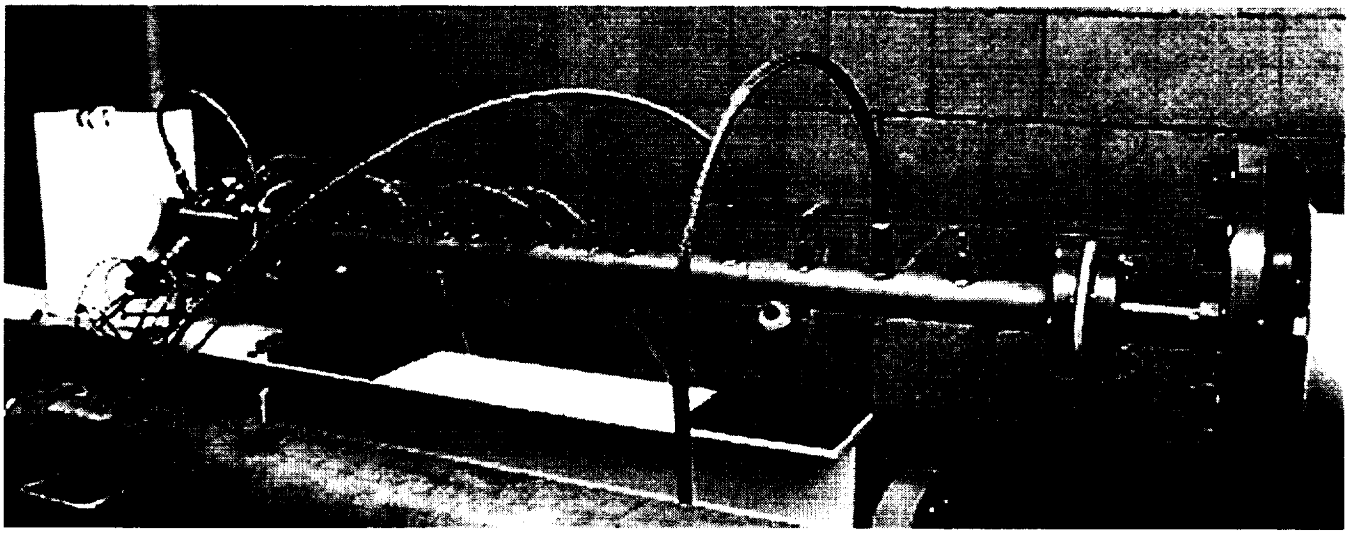

FIGURE 19.—Prototype hardware for a pulse detonation engine.

conducted a rocket engine system design study to identify potential PDE configurations for applications such as upper stage engines and small-scale booster engines. The study has identified the key technology issues, and it has defined a technology development plan for addressing these issues.

A technology development program is underway to address the major technical issues. In FY97 MSFC will begin testing subscale PDE hardware provided by one or more contractors. The product of this task will be a prototype PDE that will generate approximately 1,000 lbf of thrust by FY99. The next step in the advanced development program will be to develop and test a PDE at the 10- to 20,000-lbf thrust level.

Eidelman, S.; Grossmann, W.; Gunners, N.E.; Lottati, I.: "Progress in Pulsed Detonation Engine Development." AIAA 94–2721, 30th Joint Propulsion Conference, Indianapolis, IN, June 27–29, 1994.

Sterling, J.; Ghorbanian, K.; Humphrey, J.; Sobota, T.; Pratt, D.: "Numerical Investigations of Pulse Detonation Wave Engines." AIAA 95–2479, 31th Joint Propulsion Conference, San Diego, CA, July 10–12, 1995.

Bussing, T.; Pappas, G.: "An Introduction to Pulse Detonation Engines." AIAA 94–0263, 32nd Aerospace Sciences Meeting, Reno, NV, January 10–13, 1994.

Sponsor: Advanced Space Transportation Program

University/Industry Involvement: Adroit Systems Incorporated (ASI); Advanced Projects Research Incorporated (APRI)

Biographical Sketch: John Cramer is an aerospace engineer in the Combustion Physics Branch of the Propulsion Laboratory. He is a graduate of Purdue University and the University of Wisconsin—Madison.

Propulsion and Fluid Management

Advanced Gas/Gas Injector Technology

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To provide a rocket engine injector technology base for supporting the Reusable Launch Vehicle (RLV) engine development, a study of high-performance injectors associated with various engine cycles has been performed by MSFC and Pennsylvania State University (PSU) under the NASA Research Announcement (NRA) Cooperative Agreement NCC8–46. The recent effort in this activity focused on the advanced gas/gas injector. Based on the results of previous investigations on other injector types, it was suggested that a swirl coaxial injector may provide effective propellant mixing; hence it was selected for this study. Three variations of the swirl coaxial injector, having oxidizer swirl angles of 60, 75, and 95 degrees, were fabricated and tested in a hot-fire environment. Detailed dimensions of the three injectors are summarized in table 1. The injectors were designed for a gaseous oxygen/hydrogen propellant system at an oxidizer/fuel mixture ratio (MR) of six with the chamber pressure of 1,000 psia. The purpose of the experiments is to evaluate the mixing/combustion processes and the injector face heat transfer characteristics.

TABLE 1.—*Swirl coaxial injector dimensions.*

	GO_2 Post Diameter (d_0)	GH_2 Annulus Inner Diameter (d_{Fi})	GH_2 Annulus Outer Diameter (d_{Fo})
60° Swirl	0.210 in (5.33 mm)	0.250 in (6.35 mm)	0.290 in (7.37 mm)
75° Swirl	0.277 in (7.04 mm)	0.317 in (8.05 mm)	0.357 in (9.07 mm)
90° Swirl	0.370 in (9.40 mm)	0.410 in (10.4 mm)	0.450 in (11.4 mm)

The experiments were conducted with a 2- by 2-in square uni-element combustor equipped with helium-cooled windows. The windows allow optical access into the combustion chamber for laser-based diagnostic techniques. Raman spectroscopy was used to measure the major species at 3.5 in downstream of the injector face. The species Raman signals were calibrated and presented in terms of the species mole fraction, as shown in figure 20, for the test results of the 60-degree swirl-angle injector. The measured data indicate uniform distribution of species in the radial direction, which suggests that the gaseous propellants were well-mixed and combusted at this axial location. The other two derivative injectors also behaved in a similar manner.

Injector face temperature was measured with the aid of a type "K" thermocouple silver brazed at a location 0.425-in from the injector center line. The temperature measurements, sampled at 200 Hz for the 2-sec duration rocket firings, as plotted in figure 21, show that the injector face temperature is lowest for the 60-degree oxidizer swirl angle injector and nominally the same for the 75-degree and 90-degree swirl injectors. The high temperatures indicate that the energy release for the swirl coaxial injector is close to the face, and hence, the possible use of this type of injector for actual rocket engines will require face-cooling schemes.

In conclusion, the results of this investigation suggest that the generic swirl injector for a gas/gas propellant system will have efficient propellant mixing/combustion characteristics. However, actual implementation of this type of injector will require a tradeoff between injector face temperature

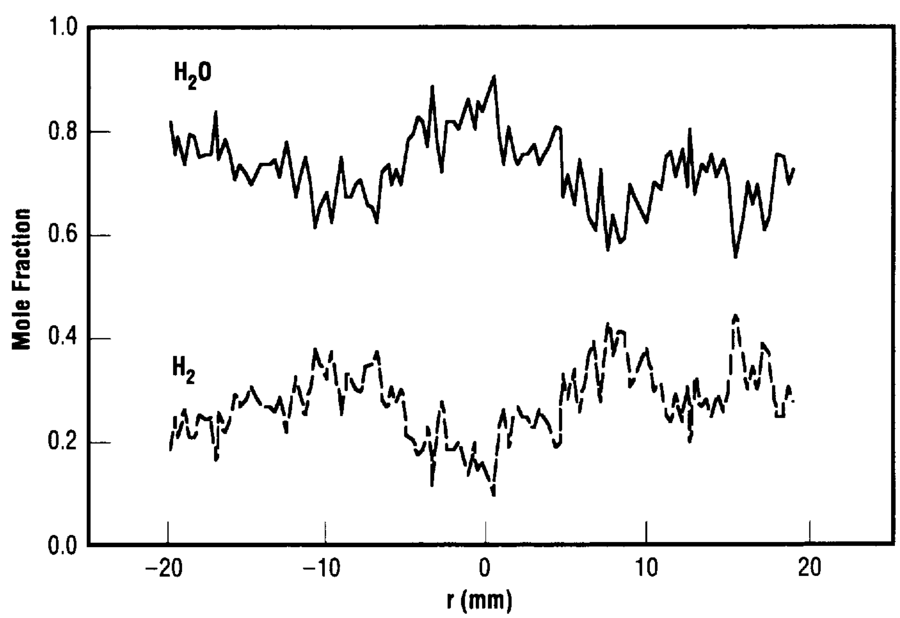

FIGURE 20.—Average GH_2 and H_2O mole fraction for a 60° swirl inject or at pc=993 psia.

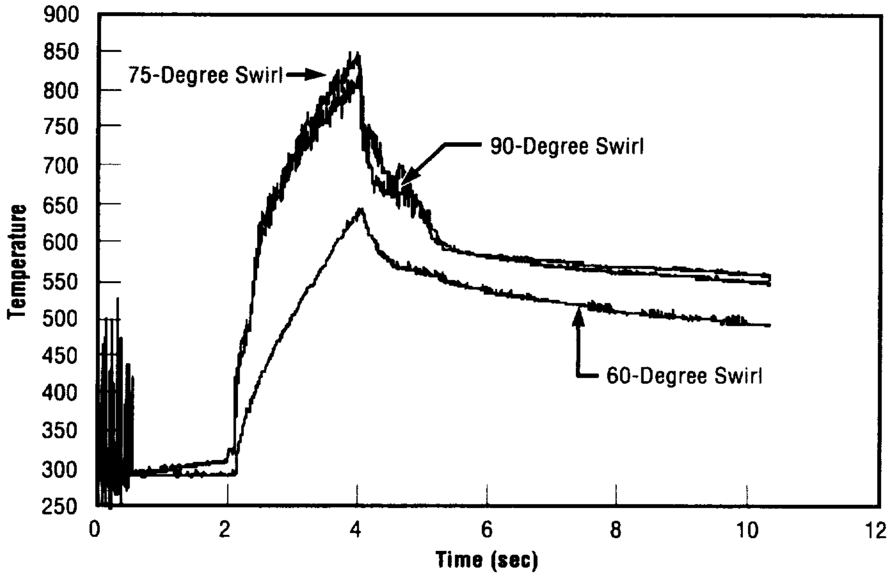

Figure 21.—Injector face temperature for the three coaxial injectors having 60-, 75-, and 90-degree swirl angles.

requirements and mixing/combustion efficiency.

Sponsor: Office of Space Access and Technology

University/Industry Involvement: Robert J. Santoro and Charles Merkle, The Propulsion Engineering Research Center of the Pennsylvania State University.

Biographical Sketch: Huu P. Trinh has worked in the area of liquid rocket engine combustion at MSFC since 1987. He has used computational and analytical models to analyze rocket engine performances. Currently, he monitors a project of providing technologies for main chamber and preburner injectors. The effort is conducted under a PSU NRA cooperative agreement to support the RLV program. In addition, he evaluates injector performance of the Fastrac engine and analyzes proposed Bantam main and gas generator injectors.

Tripropellant Effervescent Injector Study

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To advance the state-of-the-art with respect to the development of injection elements for the Reusable Launch Vehicle (RLV) engine, Pennsylvania State University (PSU) has designed an effervescent atomizer, as shown in figure 22. This design has a potential application on a tripropellant RP–1/oxygen/hydrogen rocket engine. The injector type is similar to a shear coaxial element. The major difference is that both fuels, RP–1 and gaseous hydrogen, share the center post. The gaseous hydrogen flow enters the liquid RP–1 through three holes located upstream of the center post-exit plane and forms the effervescent fluid. The inside diameter of the center post is 0.15 in, whereas the inner and outer diameters of the gaseous oxygen annulus are 0.18 and 0.5 in. Drop-size measurements and photographic visualizations of the flowfield for cold flow conditions, using gaseous nitrogen and water as simulants, indicate that for high gas-to-liquid volumetric flow ratios, the flow exiting the injector is an extremely dense cloud of small liquid drops.

A hot-fire test series was conducted using a 2- by 2-in square combustor equipped with windows on the chamber walls for the purpose of using a laser-based diagnostic technique. These windows were cooled with a nitrogen purge. To identify the injector performance, the experiments were set up to measure RP–1 drop size and combustion efficiency (C^*) for hydrogen mass flow rate additions from 2 to 10 percent with chamber pressures (Pc) from 230 to 500 psia. This pressure range covers the sub-, trans-, and super-critical regimes of RP–1 propellant. Performance enhancement due to hydrogen addition is also evaluated from this study. An overall optimum mixture ratio of oxidizer to fuel was based upon an established mixture ratio of

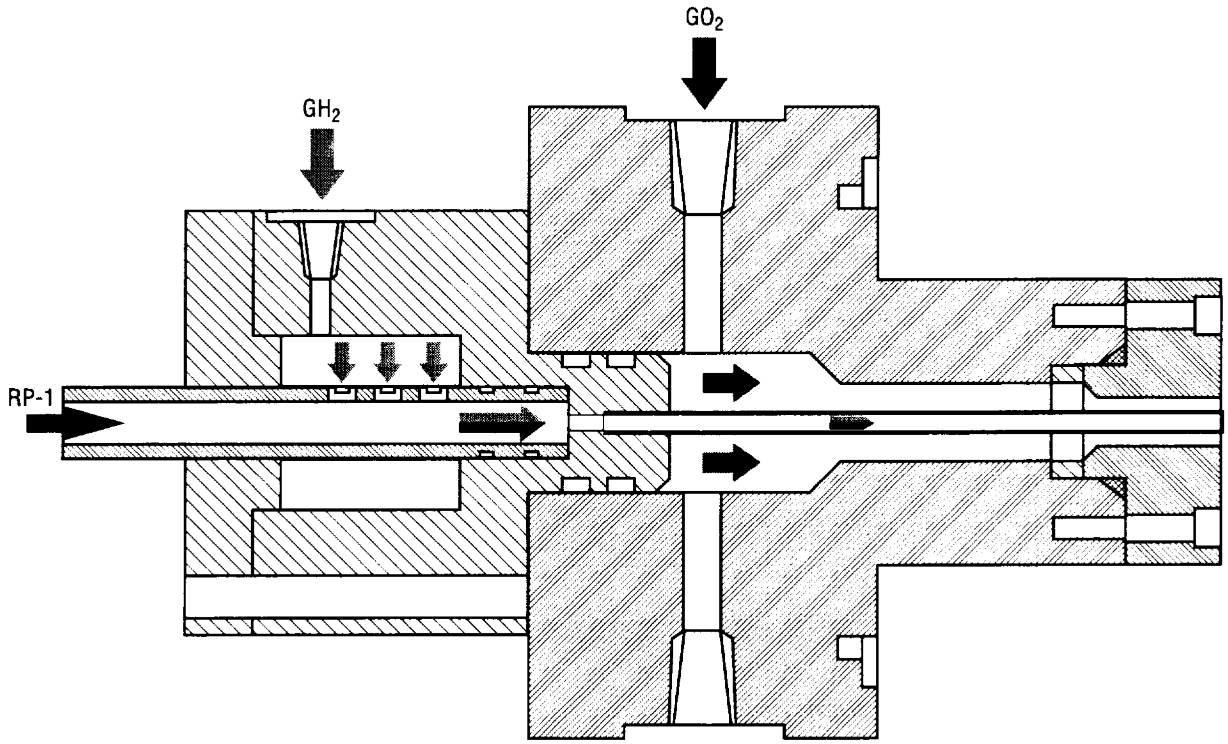

FIGURE 22.—Schematic of effervescent injector element used for RP–1/GH_2/GO_2 tripropellants.

oxygen/RP–1 of 2.4 (yielding high performance) together with the stoichiometric mixture ratio for oxygen/hydrogen of 8.0 (producing the maximum temperature).

The RP–1 drop sizes in the combusting flowfield were measured using phase Doppler interferometry. Measurements at a location (x = 6 in and r = 0.2 in), as shown in figure 23, are compared for three chamber pressure conditions of 230, 320, and 500 psia. The results show that drop sizes could be measured at both transcritical (320 psia case) and super-critical conditions (500 psia case).

The effects of hydrogen mass addition on C* efficiency for subject injector are presented in figure 24 for three chamber pressure cases. For comparison purposes, the C* efficiencies at a chamber pressure of 500 psia were calcualted both with and without the nitrogen purge. The results clearly show that the combustion efficiency increases with the increase of hydrogen mass flow rate. The measurements are

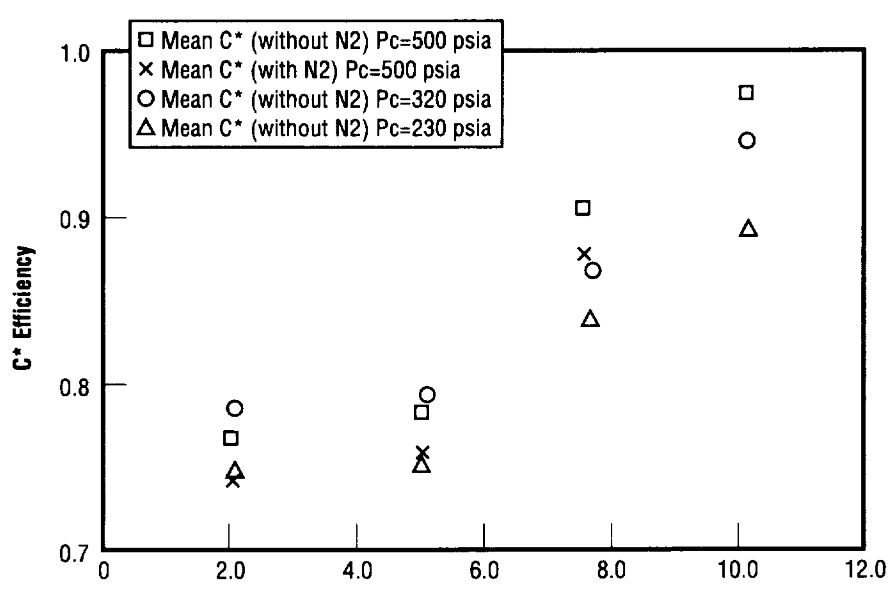

FIGURE 23.—RP–1/GH_2/GO_2 rocket C* efficiency for increasing flow rate of GH_2 (percentage of RP–1 flow).

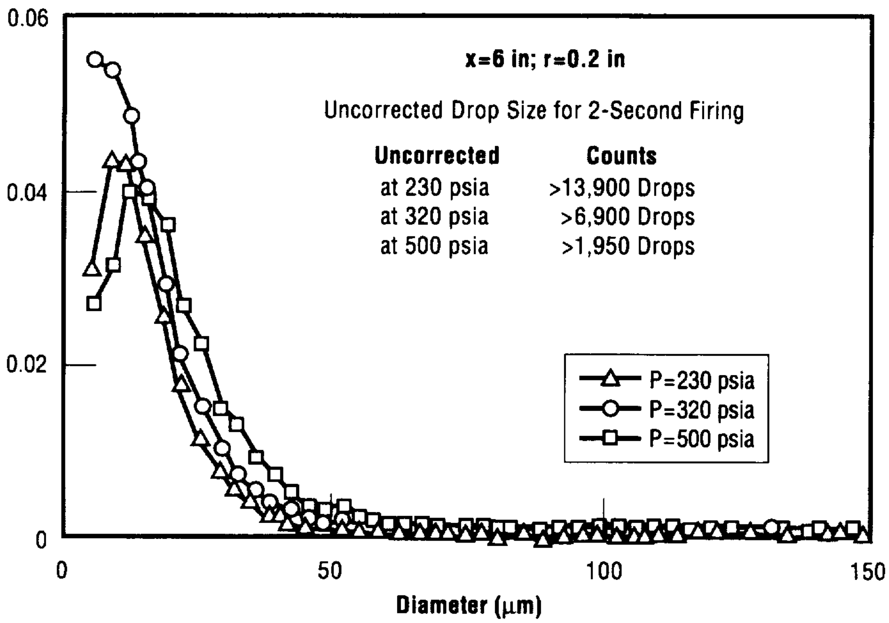

FIGURE 24.—Measured RP–1 drop size probability density functions for three chamber pressure conditions. GH_2 flowrate equal to 10 percent of RP–1 flowrate.

consistent for the tested chamber pressures of 230, 320, and 500 psia. For the effervescent injector, atomization is clearly improved with the addition of hydrogen. The fast reaction rate of hydrogen/oxygen as compared to that of RP–1/oxygen translates to a high-temperature oxidizer-rich environment near the injector face. Consequently, the two aforementioned effects would enhance the combustion efficiency.

Sponsor: Office of Space Access and Technology

University/Industry Involvement: Robert J. Santoro and Charles Merkle, The Propulsion Engineering Research Center of the Pennsylvania State University.

Biographical Sketch: Huu P. Trinh has worked in the area of liquid rocket engine combustion at MSFC since 1987. He has used computational and analytical models to analyze rocket engine performances. Currently, he monitors a project of providing technologies for main chamber and preburner injectors. The effort is conducted under a PSU NRA cooperative agreement to support the RLV program. In addition, he evaluates injector performance of the Fastrac engine and analyzes proposed Bantam main and gas generator injectors.

Pintle Injector Study for Liquid Bipropellant Engines

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As a part of advancing the injector technology base in support of the Reusable Launch Vehicle (RLV) engine development and other future rocket engines, an effort of studying a pintle injector for a liquid bipropellant engine system has been performed at Pennsylvania State University (PSU) under a NASA Research Announcement (NRA) cooperative agreement with MSFC. A typical pintle injection element has design characteristics as shown in figure 25. For this study, RP–1 fuel is injected into the combustion chamber from the central post, whereas liquid oxygen

$$\theta = f\,(\mathrm{TMR},\ \mathrm{BF})$$

$$\mathrm{TMR} = \frac{(\mathrm{Mdot} * U)_{RP}}{(\mathrm{Mdot} * U)_{Lox}}$$

$$\text{Blockage Factor (BF)} = \frac{\Sigma\ \text{Width of Slots}}{\text{Perimeter of Tube}}$$

$$\text{Effective Momentum Ratio (EMR)} = \frac{\mathrm{TMR}}{\mathrm{BF}}$$

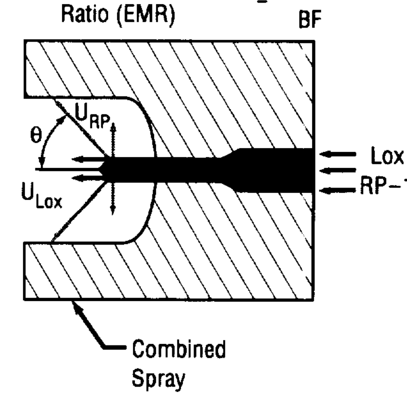

Figure 25.—Pintle injector design characteristics.

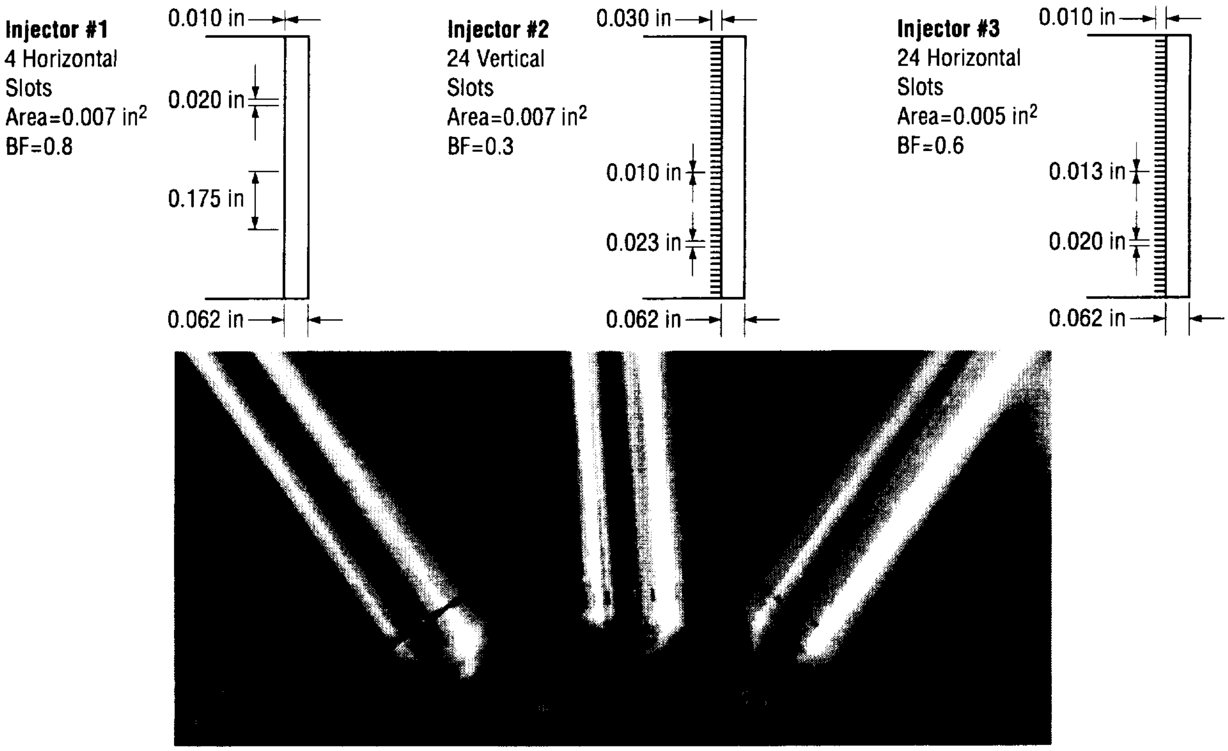

Figure 26.— Pintle injector tip designs for three injector elements.

(lox) is issued from the outer annulus. Since the design of the central post is crucial for achieving good mixing and combustion, three variations of subject injector configuration, as shown in figure 26, are being examined.

Cold-flow tests, using water as a propellant simulant, were conducted for the three injectors. The matrix of 3 by 3 images from the test results, as shown in figure 27, were captured using a 35 mm camera. The three images in the first column were taken by positioning the camera directly beneath the pintle tip with flow only ejected through the central post. The first image for injector one shows four liquid sheets emanating from the four horizontal slots, whereas the next two images show 24 liquid jets. The middle and last columns of images were taken by positioning the camera such that the line of sight is perpendicular to the injector axis. The middle column of images for the same central and outer annular flows display the effects of the injector geometry on the resulting spray field. The spray cone angle for the first injector, which has 4 horizontal slots, is larger than the one from the 24-slot injectors. Finally, the last column of images shows the spray field for flow conditions

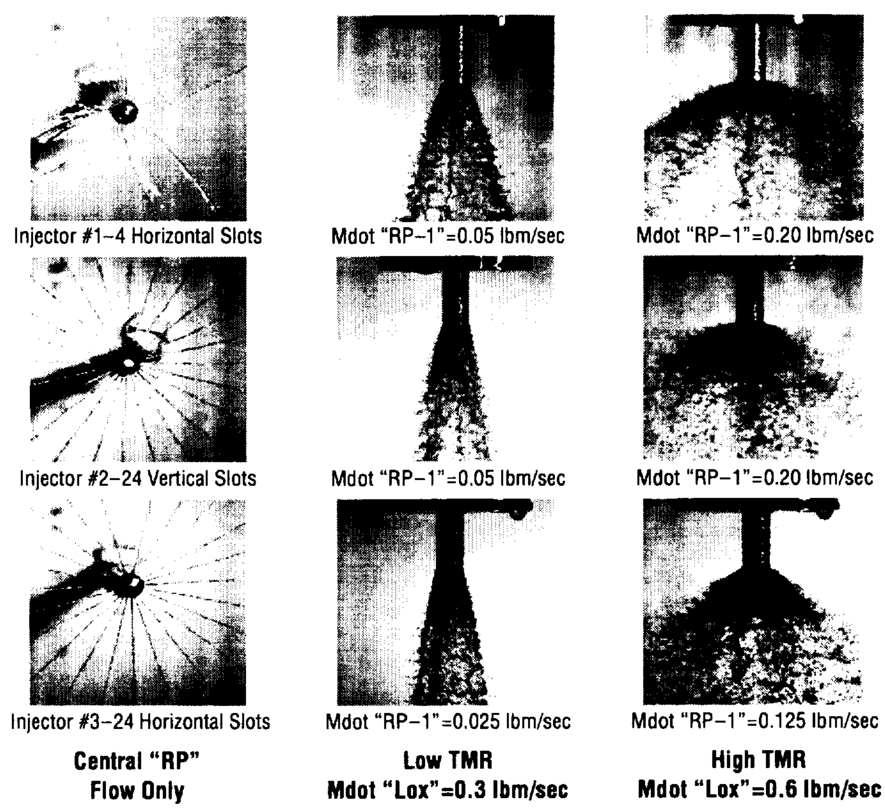

Figure 27.— Cold flow visualizations for three Pintle injectors.

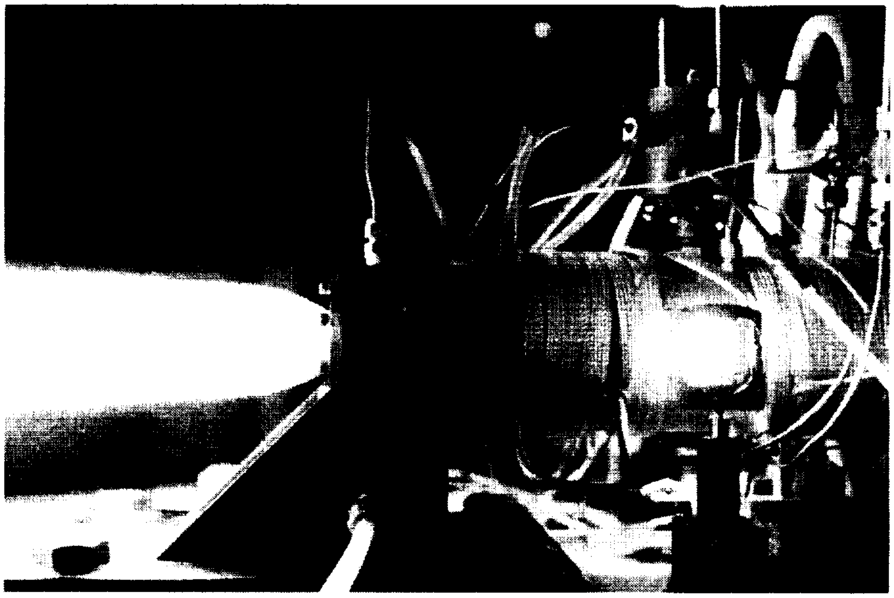

FIGURE 28.— Panoramic photograph of RP–1/lox rocket firing for Pintle injector.

where the central to outer annular mass flow rate ratios are higher than that for the images shown in the center column.

The initial series of hot-fire tests for this injector was also conducted with an optically accessible unielement combustor. A panoramic photographic image of a rocket firing is shown in figure 28. The flame luminosity of RP–1/lox combustion is extremely high as evidenced by the light level that passed through a neutral density filter positioned in front of the window.

At present, PSU continues performing parametric hot-fire tests to provide details of the combustion flow field and injector performance characteristics of this injector type.

Sponsor: Office of Space Access and Technology

University/Industry Involvement: Robert J. Santoro and Charles Merkle/The Propulsion Engineering Research Center of the Pennsylvania State University.

Biographical Sketch: Huu P. Trinh has worked in the area of liquid rocket engine combustion at MSFC since 1987. He has used computational and analytical models to analyze rocket engine performances. Currently, he monitors a project of providing technologies for main chamber and preburner injectors. The effort is conducted under a PSU NRA cooperative agreement to support the RLV program. In addition, he evaluates injector performance of the Fastrac engine and analyzes proposed Bantam main and gas generator injectors.

Solid Rocket Motor Asbestos-Free Insulation

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Substantial progress has been made to further develop and qualify an asbestos-free internal case insulation design for NASA's reusable solid rocket motor (RSRM). The presently used asbestos/silicon dioxide-filled, acrylonitrile butadiene rubber internal case insulation material is being replaced due to health hazard concerns and decreasing availability of all materials containing asbestos. The primary objective is to develop and qualify an asbestos-free internal case insulation design that will demonstrate similar or better erosion performance at a reasonable cost.

The first full-scale test with the two candidate materials was conducted on November 16, 1995, at the Thiokol Corporation Space Operations test facilities located in Utah. The RSRM flight support motor-5 (FSM–5) was used for this test. Aramid-filled, ethylene propylene diene monomer (EPDM) was utilized for both candidate materials. Both the 7 percent and 11 percent aramid-filled materials were installed in the high-impingement aft dome area. The 7 percent aramid-filled insulator was installed starting at the forward end of the aft dome and terminated 85 in forward of the nozzle boss (cylinder area). Erosion performance prevented the sole use of either candidate material in the high-impingement aft dome area adjacent to the submerged nozzle. The erosion performance of the 11 percent aramid-filled material was superior to that of the 7 percent material, as was anticipated from analysis of the subscale 48-in test motor data. In order to achieve the desired safety factors in the aft dome, it was necessary to use the present RSRM sandwich design with the 11 percent aramid-filled material replacing the substrate asbestos material next to the case wall. The currently used carbon fiber-filled EPDM adjacent to the propellant has a high cure shrinkage thus limiting the amount that can be installed.

Manufacturing and accurate analysis become much more difficult with the use of multiple layers of insulation. It is impossible to determine the exact prefire thickness of each of the multiple materials. Each material will undergo a different percentage of shrinkage during the cure cycle. A relatively large erosion data base is currently available with the presently used surface material thus enhancing reliability and confidence. The substrate material erosion rate must be estimated based on the one (FSM–5) full-scale motor test. If the substrate material is occasionally penetrated during the test, any statistical analysis is of little value. It is impossible to determine the exposure times or exact erosion for each material.

Analysis of the 7 percent aramid-filled material in the cylindrical area of the FSM–5 test indicated that this material will perform satisfactorily as a sole insulator for the entire motor except for the aft dome. Erosion performance was predicted for the untested portion of the motor using ratios from previous RSRM data. The erosion performance predictions for both of the asbestos-free materials will be evaluated with three additional full-scale motor tests prior to the first Shuttle flight.

Data evaluation methodology with a limited data base remains an undesirable and somewhat unique situation. The cost of full-scale testing precludes an adequate number of tests for standard statistical evaluation. Subjective decisions are necessary to determine which analysis technique will produce a reasonable design with an acceptable risk. Thiokol and NASA engineers agreed that erosion performance analysis using median material losses plus three standard deviations would be a reasonable approach to establish initial design thickness limits. It was further stipulated that the minimum design thicknesses would be no less than the maximum losses (with appropriate safety factors) experienced at any measurement station.

Erosion performance data for the two asbestos-free internal case insulation materials described above should be useful information for anyone associated with solid rocket motor design and performance evaluation. All component systems will have to be asbestos-free in the near future. The subjective nature of the methodology is unavoidable due to the unique circumstances. Further static testing and subsequent Space Shuttle flight evaluation will verify the validity of the analytical technique utilized.

Sponsor: Space Shuttle Projects Office

Industry Involvement: Thiokol Corporation Space Operations

Biographical Sketches: John Funkhouser is a NASA aerospace engineer in the Marshall Space Flight Center Propulsion Laboratory. He is responsible for the NASA space shuttle RSRM internal case insulation design and verification.

Charles Martin is a NASA aerospace engineer in the Marshall Space Flight Center Propulsion Laboratory. He is responsible for the NASA Space Shuttle RSRM ballistics analysis and statistical evaluation of all applicable motor systems.

Revolutionary Reusable Technology Turbopump

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The revolutionary reusable technology turbopump (RRTT) is a NASA/MSFC technology program intended to demonstrate a substantial reduction in the time and cost to produce reusable turbomachinery. A reusable liquid oxygen turbopump sized for a full-flow staged combustion cycle engine at a thrust of 400,000 lbf was selected as the demonstration turbopump. The goals of the program were: (1) to define the design, perform the required analyses, fabricate the hardware, and assemble the turbopump within 18 months; and (2) to limit the recurring fabrication and first unit cost to less than $600,000. This is a factor of three reduction in schedule and a factor of five reduction in cost from traditional rocket engine turbomachinery. Rocketdyne was selected as the contractor for the program which began in September 1995.

To achieve the aggressive schedule goal, a document called a product and process plan of action (PPPOA) was jointly written between Rocketdyne and NASA/MSFC. It combined an engineering design and analysis plan, a manufacturing plan, a quality plan, and a product validation plan into a single document which was approved by both Rocketdyne and NASA prior to initiation of the design phase. The PPPOA also defined, in detail, all of the ground rules, assumptions, and the required level of analysis for each part.

A product development team (PDT) was established with members from all of the appropriate disciplines at Rocketdyne, NASA/MSFC, and the appropriate vendors. Each team member was an active participant in the design phase to ensure the schedule and cost goals could be achieved while still meeting the design requirements. The manufacturing and inspection process

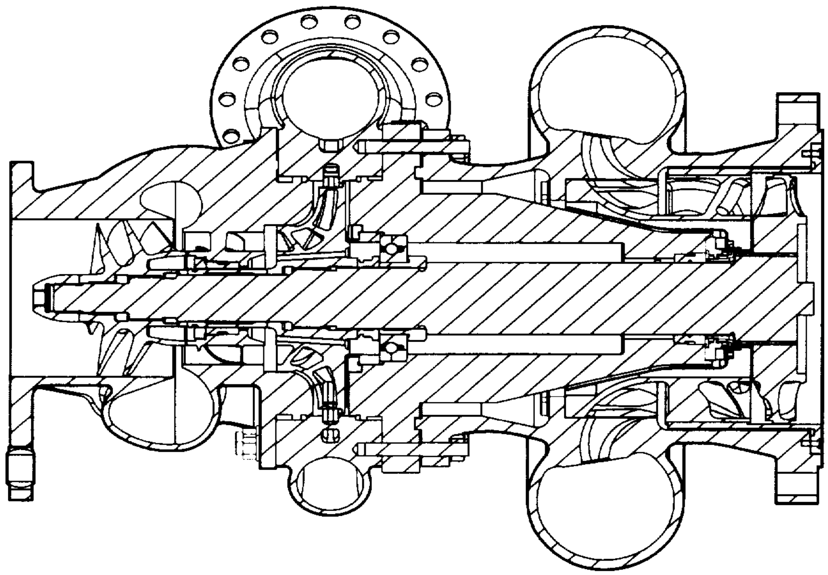

FIGURE 29.—**Revolutionary Reusable Technology Turbopump (RRTT) cross section.**

development was begun concurrently with the design process to minimize schedule and cost risk. With this approach, the process development is an essential element of the design itself. In addition, the three-dimensional computer aided design (CAD) models were electronically linked with stress and thermal analysis packages to enable rapid design generation and iterations. The vendors were part of the electronic drawing transfer as well. The three-dimensional models were used to produce rapid prototype casting patterns. This process was significantly cheaper and quicker than fabricating conventional hard tooling to produce wax patterns. The electronic drawings were also downloaded to the vendor numerically controlled (NC) machines.

A cross section of the turbopump is shown in figure 29. The turbopump consists of a high-pressure liquid oxygen pump driven by a single stage turbine using an oxygen-rich working fluid. The fluid requirements for the turbopump are shown in table 2. The RRTT is not man-rated flight hardware but is typical of future reusable turbomachinery. The life requirements for the RRTT were derived from the number of tests necessary to characterize the turbopump and to validate the processes used during the design and fabrication.

Considerable effort was spent during the design and analysis phase on the turbine design. The design was challenging due to the requirements of an oxygen-rich turbine. Materials were carefully chosen for oxygen compatibility and extensive material testing was performed to validate the material selection.

The RRTT hardware is currently in fabrication. To date the program is only one month behind and 6 percent over the cost goal. The assembly of the turbopump is currently planned to be complete by April 1997.

Sponsor: Long-term, high-payoff project

Biographical Sketch: Mary E. Koelbl has been a design engineer in the Turbomachinery Branch of Propulsion Laboratory at Marshall Space Flight Center for 10 years. She works on SSME fuel turbomachinery as well as turbomachinery technology programs.

TABLE 2.—*RRTT fluid conditions.*

	Pump	Turbine
Fluid	Lox	Oxygen-Rich Steam ($O_2 + H_2O$)
Inlet Pressure (psia)	200	5,034
Inlet Temperature (deg R)	169	1,145
Discharge Pressure (psia)	6,404	3,315
Flow Rate (lbm/sec)	922	860

Electromechanical Actuator Testing at IPTD

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Electromechanical actuation technology is currently being investigated and is considered the likely candidate for future replacement of the hydraulic systems utilized in most aerospace actuation applications today. Marshall recently demonstrated the maturity of the electromechanical actuator (EMA) technology by integrating a simplex valve EMA into a system-level test of the Rockwell International X–33 Phase I Integrated Propulsion Technology Demonstrator (IPTD).

The Simplex Valve EMA used in this demonstration was originally designed for and tested as an EMA technology "proof of concept." The design (fig. 30) consists of a three-phase brushless motor that drives a 120:1 reduction harmonic drive. The harmonic drive is directly mated to the actuator output spline. Position feedback is provided by a resolver, which is mounted on the output of the harmonic drive. Breadboard control electronics for the EMA were developed by the Astrionics Laboratory. The electronics utilize both motor current and actuator position to provide actuator control. The actuator was designed to meet the performance requirements of the Space Shuttle Main Engine's main oxidizer valve (MOV) actuator. Several years after the EMA had successfully completed laboratory performance testing, MSFC's Propulsion Laboratory was provided with the opportunity to integrate this component into a higher systems level test.

Rockwell International and NASA under an X–33 Phase I task agreement developed a propulsion system test-bed (IPTD) for the demonstration and development of propulsion technologies and operations concepts. System level integration and operation of MSFC's EMA was identified as a viable test for IPTD. The actuator was installed on an SSME main fuel valve which had been integrated into a 4-in fill and drain line on the liquid hydrogen side of the propulsion module (fig. 31). The control electronics and the power source for the actuator were remotely located on the test stand to protect against the environment. The cable length from controller to actuator was approximately 40 ft. The actuator was remotely controlled from the blockhouse by the Rockwell Propulsion Checkout and Control System (PCCS), which also provided for remote monitoring of the position feedback during checkout and test.

Before testing, redlines were developed for operation of the EMA. The presence of the EMA introduced an order of magnitude increase in electrical power (100 Vdc/ 100 A) previously seen in the potentially explosive environment of the IPTD. Activation of the EMA was therefore based on the absence of hydrogen in the area. In addition, the actuator was bagged and purged with nitrogen to prevent hydrogen accumulation and moisture from entering the EMA or electrical connections. Temperature redlines were also set on the actuator to prevent overheating and damage to the motor. Motor current redlines were

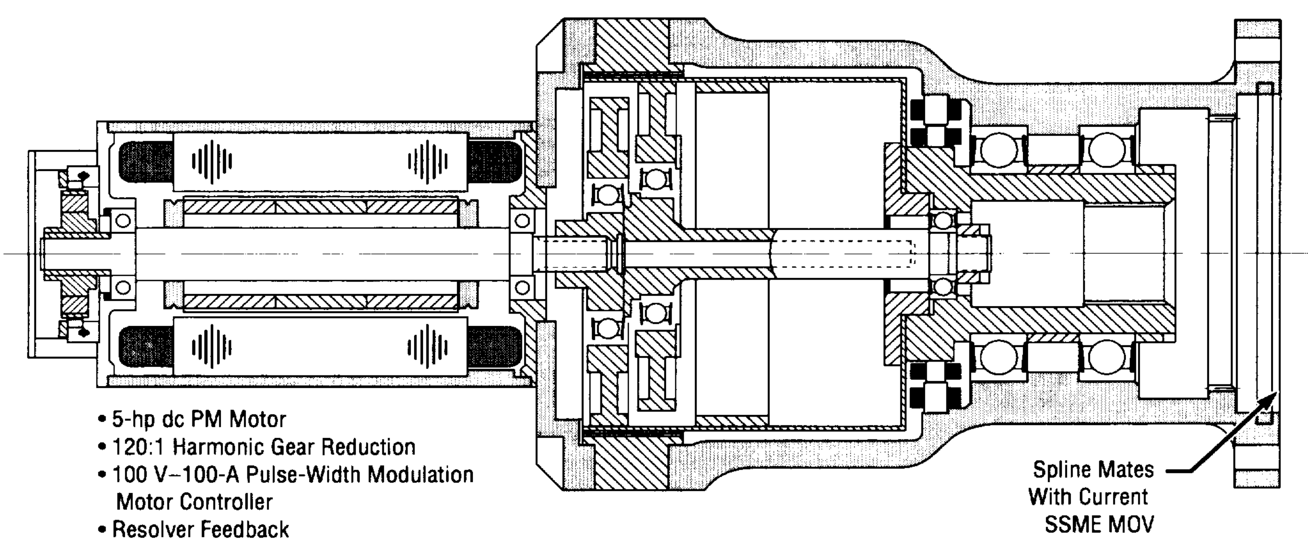

Figure 30.—MSFC Simplex Valve EMA.

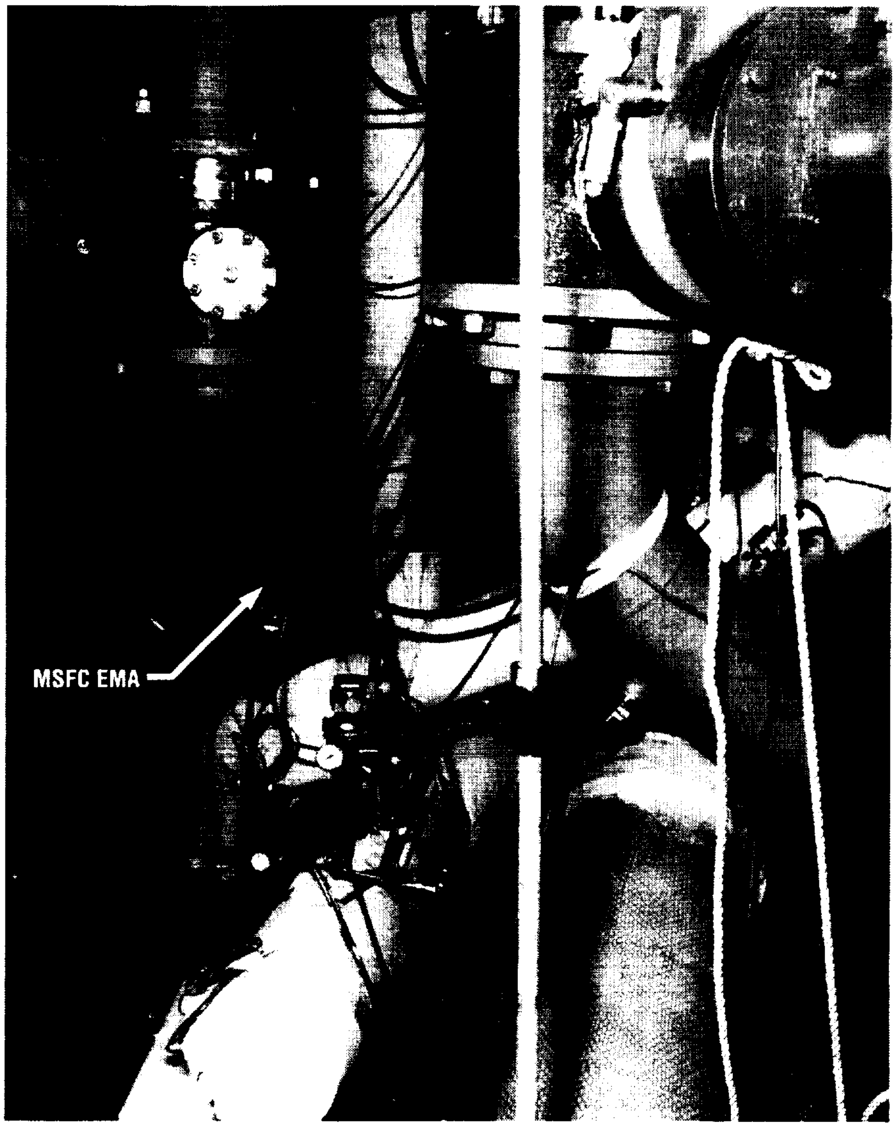

Figure 31.—EMA integrated into the IPTD.

also established. During actual test, position error was monitored in order to provide information for manual cut of actuator power from the blockhouse in case of actuator failure.

Actuator testing consisted of remotely cycling the actuator after liquid hydrogen (LH_2) cold shock of the system and later cycling during LH_2 flow (approximately 500 gal/min) using the PCCS. During actuator operation, the valve temperature was −130 °F. The EMA had not been designed for operation under the cryogenic condition presented by the presence of LH_2, and the possible reduction in performance due to temperature was a concern for these tests. Both a thermal isolator between the valve and EMA and a heater blanket around the throat of the EMA were utilized to alleviate performance degradation due to the environment. A similar procedure is followed on the SSME with the hydraulic actuator. During both the cold shock and flow tests, the actuator performed without anomalies, successfully demonstrating the EMA technology at a systems level, under cryogenic conditions.

Demonstration of this technology in a propulsion system environment was not the only benefit of these tests. A valuable integration and operations data base was generated which will be directly applicable to future testing and vehicle implementation of EMA's. Possible design improvements and considerations for operations in flight-type environments (such as placement of electrical components away from thermal paths and dry lubrication for cryogenic operations) were noted as well as integration and operation issues established for use in the design of EMA's and of the systems in which EMA's will be utilized.

Sponsor: Reusable Launch Vehicle Program

Biographical Sketch:
Rae Ann Weir is an electrical engineer in the Turbomachinery and Control Mechanisms Branch of MSFC's Propulsion Laboratory. She received a B.S. electrical engineering degree from the University of Tennessee in 1989. She has been employed by NASA since that time and has 7 years experience in the field of electromechanical actuators.

Propulsion System Design Reliability Modeling

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The Propulsion Laboratory of MSFC currently supports several propulsion system design efforts. In response to both internal and industry partner requirements, the propulsion systems operability and performance team has been tasked to develop and maintain a propulsion systems hardware design reliability analysis capability. This design reliability analysis capability will support design trades, provide an assessment of design against reliability requirements, and focus reliability-related design modifications to high-risk design elements. Recent research and development efforts supporting this task have focused on the development of a methodology for failure environment analysis which includes failure propagation logic modeling and time domain analysis. Propulsion system design failure propagation models have been developed to demonstrate the applicability of this design reliability analysis approach.

Design failure propagation logic models represent the propagation logic of failures from initiation to system events of interest, including failure mitigating factors, such as safety system functions, and correlation between system failures. The models developed may be used for qualitative and quantitative analysis. Qualitative models, operating with true and false states, are used in two ways. One is to determine what effects given failure initiation events may have on the overall system. The other is to determine what failure initiation events may cause a given system effect. Applications of qualitative models include the identification of common causes of failure, effect of dual point failures, and minimum cutsets, as well as improving communication among design and reliability organizations. Quantitative models represent failure propagation logic with probabilities of occurrence assigned to failure initiation events. Quantitative model logic propagates the failure initiation event probabilities to the probability that a system event will occur, such as system premature shutdown. These probabilities of occurrence may be either point probability estimates or probability distributions. Applications of quantitative models include identification of design/operational characteristics that may adversely affect reliability, determination of design reliability metrics, and providing input to performance and cost models. Failure logic models may also be used to determine the effect of operation time on system reliability by assigning failure probability verses time distributions for parts and components. The model logic, from these inputs, constructs system event probability verses time distributions by a incremental sampling of the inputs. These time-domain models may be used in analyzing component/part life requirements and operations planning.

To better illustrate the modeling approach, consider the segment of a full-flow engine cycle schematic shown in figure 32. Hot fuel-rich gas from the fuel gas generator drives the fuel turbine before being burned in the main combustion chamber. A portion of the hot gas flow is diverted around the fuel turbine and is controlled by the fuel turbine bypass valve. Since the power delivered by the fuel turbine is determined by the hot gas flow through the turbine, the fuel turbine output may be controlled by controlling the flow of diverted hot gas. Consider the failure modes where the fuel turbine bypass valve suddenly fails partially closed or fully closed. Closure of this valve has two effects. One is an increase in hot gas flow through the turbine, thereby tending to increase fuel pump output and fuel flow to the main combustion chamber. The other effect is a temporary increase in engine fuel flow resistance, which tends to reduce the fuel flow to the main combustion chamber. The net result of these opposite effects on main combustion chamber fuel flow rate depends on the degree of valve closure and the time required for the fuel pump to respond to the valve closure. Since changes in the main combustion chamber fuel flow rate affect combustion mixture ratio, it is important to be able to predict the failure propagation path for these failure modes. Figure 33 shows the failure propagation logic for these failure modes, including failure mitigating effects of the engine safety system. This model assumes that when the fuel turbine bypass valve fails fully closed, the fuel flow reduction due to increased resistance is greater than the fuel flow increase due to increased turbine hot gas flow, and when the bypass valve fails partially closed, the fuel flow reduction due to increased resistance is less than the fuel flow increase due to increased turbine hot gas flow. The fully closed failure mode includes partially closed conditions which have the same affect as a fully closed failure. Assignment of probabilities to these failure modes are based on a probabilistic prediction of the degree of valve closure and the timing of failure propagation. When the models are completed and each of these failure modes are assigned the probability of occurrence, the probabilities of inadequate

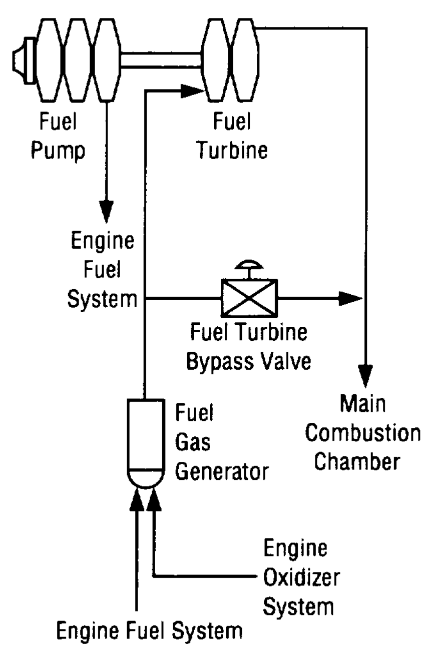

Figure 32.—Full flow engine cycle (partial schematic).

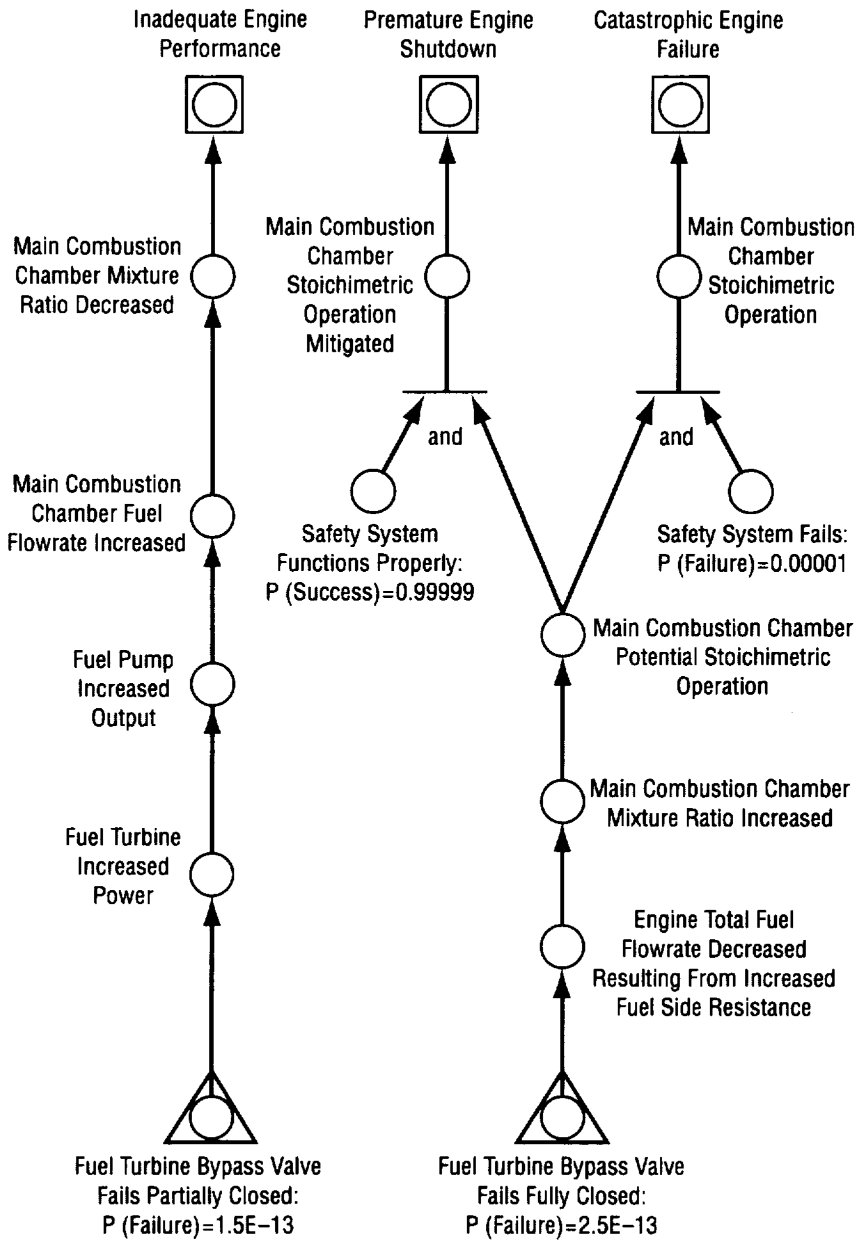

FIGURE 33.—Fuel turbine bypass valve partial failure propagation logic model.

engine performance, premature engine shutdown, and catastrophic engine failure are determined.

Recent efforts have focused on developing failure logic models for reusable launch vehicle (RLV) and electromechanical actuator concepts. These efforts demonstrate the applicability of the failure propagation modeling approach and have identified information resources needed for propulsion system model development.

Failure logic incorporated into these models was acquired from system configuration information, engineering expertise, description of health management functions, applicable failure reports, and existing failure assessments. Quantification of these conceptual design failure logic models was from four data sources: test data, quality data, operational data derived from systems similar to the conceptual design, and a priori estimates made from an engineering assessment of the conceptual design and related existing systems. Currently, additional data sources and applicable reliability metrics are being identified. Propulsion system concept design failure propagation logic models developed to date have demonstrated the feasibility of using these models for design reliability assessment and have resulted in the incorporation of this approach into current propulsion system development plans.

Propulsion system design reliability models will benefit NASA and the aerospace industry by providing designers a tool to better understand the failure environment of their designs, to assess the design against reliability requirements, and to focus reliability related design modifications to high-risk design elements. This capability will result in more reliable and dependable propulsion systems.

Sponsor: Reusable Launch Vehicle Program Office

Industry Involvement: Sverdrup Technology Incorporated, Huntsville Office

Biographical Sketch: Michael Whitley is a propulsion engineer in the Propulsion and Mechanical Systems Division of MSFC. He is responsible for the development of propulsion system design reliability assessment methodologies. Whitley earned his B.S. in mechanical engineering from the University of Alabama and his M.S. in computer science from the University of Alabama in Huntsville. He has worked for NASA for 14 years.

Magnetically Actuated Propellant Orientation

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In a low-g environment, acquisition of vapor-free propellant is complicated by the indeterminate location of bulk liquid with respect to the tank outlet. Proper design of engine feed or propellant transfer systems requires methods to control liquid orientation and an understanding of fluid motion in response to disturbances and imposed accelerations. Traditional approaches for controlling and positioning cryogenic liquids, such as periodic thruster firings and capillary retention devices, exhibit several drawbacks that could be mitigated by employing systems which exploit the inherent paramagnetism of liquid oxygen (lox) and diamagnetism of liquid hydrogen (LH_2). With the advent of lightweight, high-temperature superconductors and high-flux density, rare-Earth magnets, the use of magnetic fields to control large fluid quantities in microgravity appears feasibile, and could enable low-g settling, venting, fill and acquisition without the need for capillary retention systems or propulsive firings. Some of these potential applications are shown in figure 34.

This project is currently evaluating the feasibility and practicality of magnetically actuated propellant orientation (MAPO) for spacecraft applications. The scope has been restricted to lox primarily because:

- Control of lox offers the nearest term application of MAPO technology;

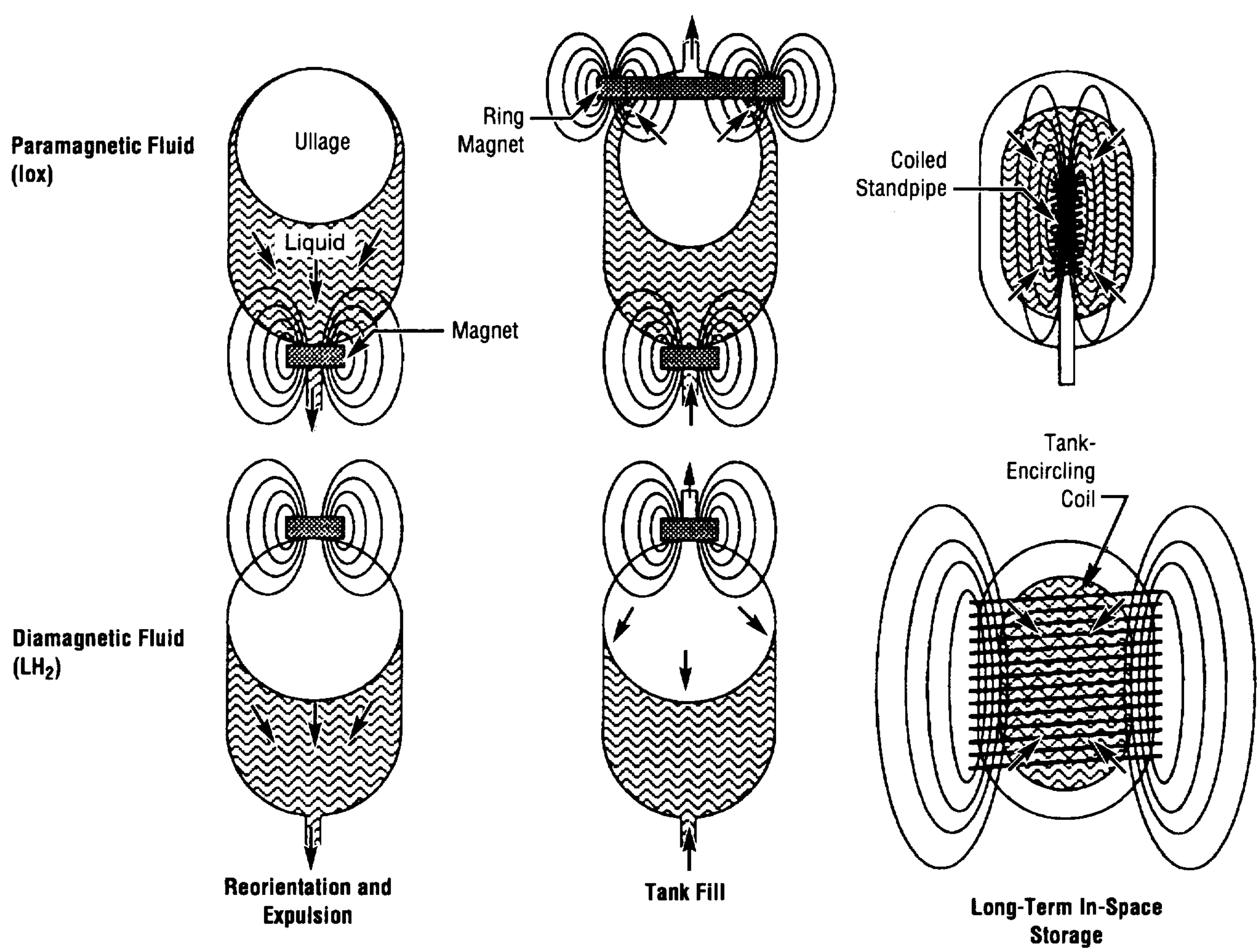

Figure 34.—Low-gravity fluid orientation concepts using magnetic fields.

- The magnetic properties of paramagnetic fluids are well known; and
- Lox behavior has been tested before in low-g on a laboratory scale.

One of the primary objectives is to determine the range of magnetic field strengths required to perform reorientation and maintain liquid orientation during tank fill and expulsion. This range will provide a basis for evaluating whether these magnetic field requirements fall within the capabilities of current or anticipated superconducting magnet technology.

The project involves low-g experiments using NASA's reduced gravity workshop (a KC–135 aircraft). All experiments employ several subscale hardware setups, one of which is shown in figure 35, and a noncryogenic ferrofluid that simulates the paramagnetic behavior of lox. The ferrofluid is a commercially available water-based solution containing a suspension of extremely fine ferrous particles. Several properties of this fluid (i.e., particle density, viscosity and surface tension), along with tank diameter, flowrates and magnetic field intensities, are being scaled to model lox behavior in a spacecraft-type application. Design and assembly of the test articles has been completed and one flight aboard the KC–135 was made in September 1995. Three other flight tests will be conducted in September and October 1996 and February of 1997.

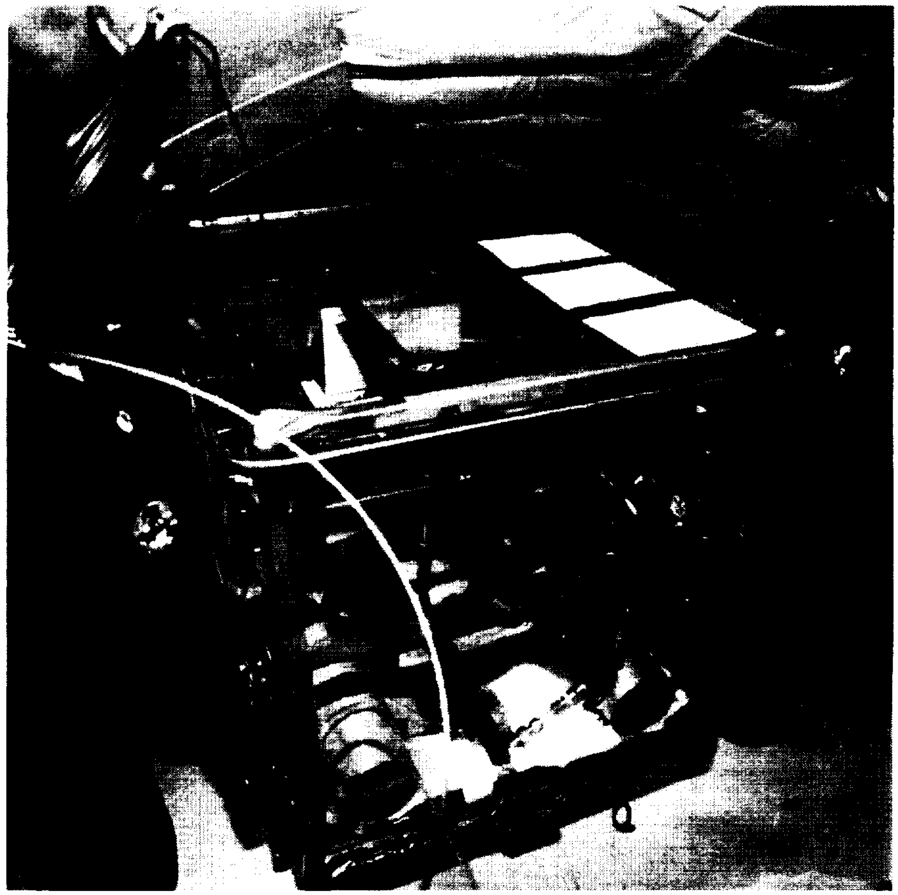

FIGURE 35.—Low-gravity fluid orientation and transfer tests aboard KC–135 aircraft.

Scaling analyses have shown that magnets in the size range of 1 to 10 Tesla should be adequate for propellant reorientation in a full-scale lox application. These results, however, are rather limited since the fields can typically assume very complicated geometries, which are difficult to characterize in terms of dimensionless groupings. Consequently, another aspect of this activity is focused on modifying an existing computational fluid dynamic (CFD) to include the body and surface forces arising from the interactions between the fluid and magnetic field. This will provide a more rigorous means of assessing fluid behavior, and will enable the modeling of more complicated field geometries and advanced concepts, such as liquid hydrogen. Videotaped recordings of fluid motions taken from the low-g tests will be used to validate the revised CFD model.

Sponsor: Center Director's Discretionary Fund

Biographical Sketch: Dr. George Schmidt is a lead engineer in the Systems Evaluation and Analysis Branch of MSFC's Propulsion Laboratory. He received a B.S. and M.S. in mechanical engineering from Stanford University in 1981, an M.S. in aerospace engineering from the University of Washington in 1985, and a Ph.D. in mechanical engineering from the University of Alabama in Huntsville in 1993. His team is responsible for research and development of advanced propulsion and fluid management technology. Prior to joining NASA 7 years ago, Schmidt worked on a variety of spacecraft programs, including the *International Space Station*.

James J. Martin is an aerospace engineer in the Systems Evaluation and Analysis Branch of MSFC's Propulsion Laboratory. He received a B.S. and M.S. in aerospace engineering from the University of Missouri at Rolla in 1989. Since 1989, he has been employed by NASA and has accumulated 7 years of experience in the development and testing of cryogenic fluid management systems.

Multipurpose Hydrogen Test-Bed

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The development of high-energy cryogenic upper stages is essential for the efficient delivery of large payloads to various destinations envisioned in future programs. A key element in such upper stages is cryogenic fluid management (CFM) advanced development/technology. Due to the cost of and limited opportunities for orbital experiments, ground testing must be employed to the fullest extent possible. Therefore, a system level test-bed termed the multipurpose hydrogen test-bed (MHTB), which is representative (in size and shape) of a fully integrated space transportation vehicle liquid hydrogen propellant tank, has been established. The MHTB is currently being implemented to evaluate CFM technology in support of the solar thermal propulsion.

The MHTB tank is ASME coded, is 10 ft in diameter by 10 ft long, has a 639 ft^3 capacity, and is made from 5083 aluminum. The tank design is based on enabling accommodation of various CFM concepts as updated or alternate versions become available. Major accommodations include: a 24-in diameter manhole; 1-in diameter pressurization and 2-in diameter vent ports; a 1-in diameter fill/drain line (through tank top); the Rockwell pressure control system enclosure interface provisions; a 3-in diameter drain at the tank bottom for future growth; a liquid-level capacitance probe; two liquid temperature rakes; wall temperature measurements at selected locations; ullage pressure sensors; pressure control/relief safety provisions; internal mounting brackets for future equipment and structural "hard points" for temporary scaffolding, ladder, etc; and low heat leak structural supports.

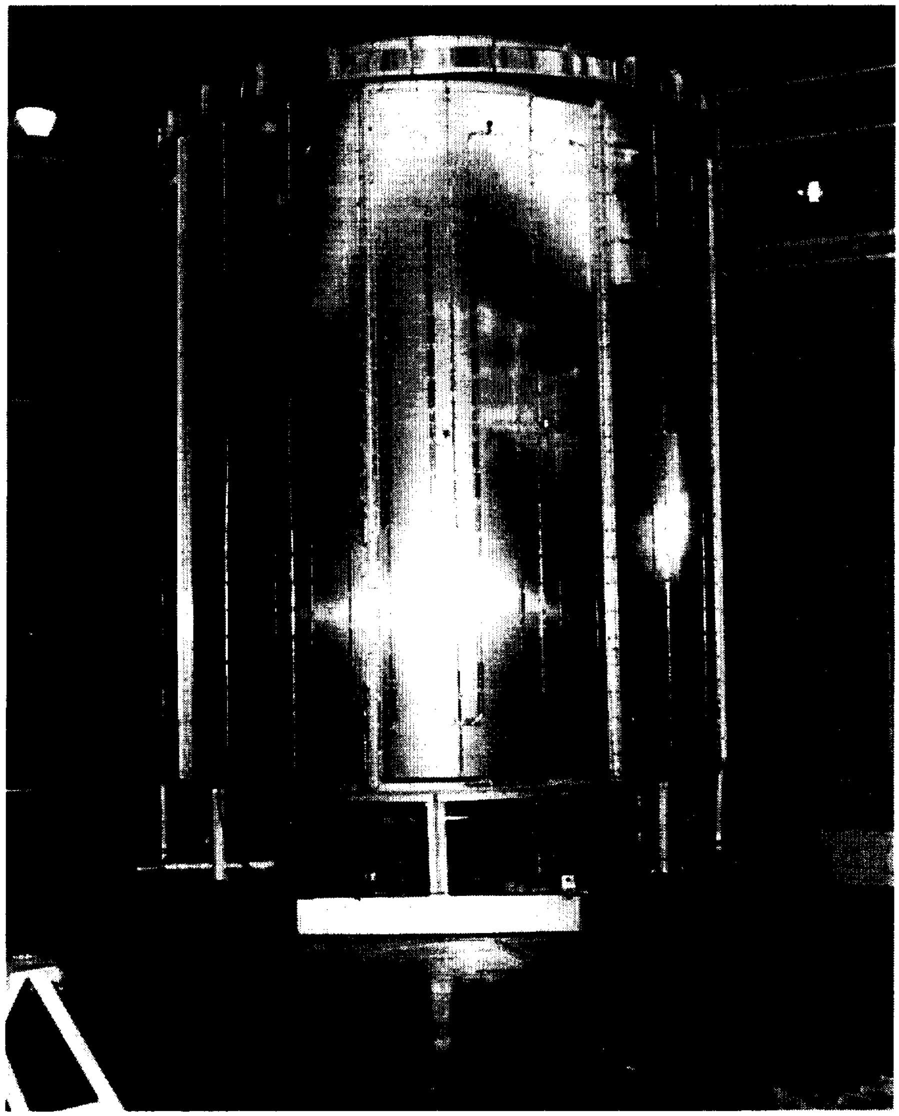

Figure 36.—Assembled multipurpose hydrogen test-bed.

Upper stage studies have often baselined the foam/multilayer insulation (FMLI) combination concept; however, hardware experience with the concept is minimal and it was therefore selected for the MHTB. The foam element is designed to protect against ground hold/ascent flight environments, and to enable a dry nitrogen purge as opposed to the more complex/heavy helium purge subsystem normally required with MLI in cryogenic applications. The MLI provides protection in the vacuum environment of space and is designed for an on-orbit storage period of 45 days. The foam component consists of an isofoam SS-1171 layer, with an average thickness of 1.3 in, bonded to the tank wall.

The MLI consists of a double aluminized mylar (DAM) MLI blanket with an average layer density of approximately 25 layers/in, which is composed of 45 radiation shields

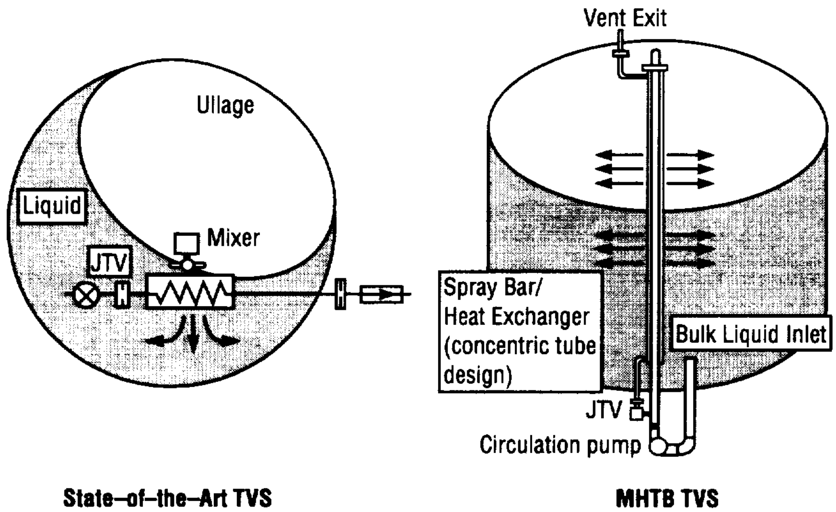

Figure 37.—MHTB TVS concept—spray bar with external active components.

with coarse Dacron net spacer material. Unique features of the MLI concept include a variable density MLI (reduces weight and radiation losses) and fewer but larger perforations for venting during ascent to orbit. The tank barrel section MLI was installed utilizing a commercially established roll-wrap process. It is estimated that the roll-wrap approach will save about 2,400 man-hours, compared with the standard blanket installation process, on a 10-ft diameter LO_2/LH_2 tank set. The process reduces heat leak due to the lack of seams and is less susceptible to structural damage during ascent flight.

Thermal performance testing was conducted during three test series conducted between September 1995 and May 1996. Preliminary results indicate that the orbital boiloff was reduced by 40 to 50 percent compared with the best MLI previously tested, i.e., boiloff losses were about 0.11 percent per day with a warm boundary temperature of 520 °R. The foam evidently performed as expected but further evaluation is required to quantify its reusability characteristics.

Thrusters have traditionally been used to settle the liquid prior to orbital tank venting with penalties in performance and operational complexity (Centaur and Saturn/S-IVB). The thermodynamic vent system (TVS) concept enables venting without resettling, but its utilization is constrained by a lack of on-orbit experience. The TVS concept selected for the MHTB differs from those previously tested in that the active components (a Joule-Thompson (J-T) expansion valve, subsystem pump, and isolation valve) are located external to the tank, as opposed to inside the tank, in a stainless steel cylindrical enclosure which is attached to the bottom of the MHTB tank. Such an approach enables modification or changeout of TVS components without entering the tank. In the mixing mode, fluid is withdrawn from the tank by the pump and flows back into the tank through a spray bar positioned along (or near) the tank longitudinal axis. The fluid expelled radially into the tank through the spray bar forces circulation and mixing of the tank contents regardless of liquid and ullage position, assuring destratification and minimum pressure rise rate. When pressure relief eventually becomes necessary, a portion of the circulated liquid is passed through the J-T valve (expanded to a lower temperature and pressure) then through the heat exchanger element of the spray bar, and finally is vented to space. The vented fluid thereby cools the fluid circulated through the mixing element of the spray bar and removes thermal energy from the bulk liquid. In an orbital propellant transfer scenario the spray-bar concept can also be utilized to assist tank refill. By filling through the spray bar/heat exchanger the inflowing fluid can be cooled and used to mix the tank contents, thereby assuring the accomplishment of a "no-vent fill" process. The zero-g vent subsystem testing was completed in October 1996 and the data evaluation is in progress.

Sponsor: Office of Aeronautics

Biographical Sketch: Leon Hastings, currently assigned to the MSFC Propulsion Laboratory, received his B.S. in mechanical engineering and an M.S. in engineering science. Assignments at MSFC since 1961 have centered on heat transfer, fluid mechanics, and thermodynamics, and he has over 15 years of specialized experience in low-gravity fluid management and heat transfer. He has often served on agency-level committees to assist in formulating plans/policies for low-gravity propellant management research and technology.

Cryogenic Fluid Management for the Aerospace Industry Technology Program

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The solar thermal propulsion concept requires that a number of technologies be matured prior to undertaking full-scale development including the subcritical liquid hydrogen (LH_2) storage/feed system. MSFC is participating with an Aerospace Industry Technology Program (AITP) consortium in the design and performance testing of a 2 m^3 LH_2 storage/feed system for the solar thermal upper stage demonstrator (STUSTD) program. Elements included are: Zero gravity venting, capillary screen liquid acquisition device (LAD), pressurization/expulsion, and multilayer insulation. Basically, the propellant management subsystem concept consists of utilizing the LAD and thermodynamic vent system (TVS) to flow 100 percent vapor to the thruster during burn cycles, i.e., the insulation is configured to match the LH_2 boiloff with the thruster flowrate and mission burn cycle (typically 100 to 200 burns).

The multilayer insulation (MLI) consists of 100 layers of double-aluminized Kapton with B4A Dacron net spacers to achieve a predicted total heat leak of (20.5 Btu/hr). The TVS includes an active mixer to assure a homogenous distribution of the thermal energy within the propellant and a Joule-Thompson (J-T) expansion valve. The cold fluid from the J-T valve flows through tubing brazed into the apex of the LAD, thereby assuring subcooling both the LAD liquid and bulk liquid. The LAD consists of four channels spaced at 90 degrees around the tank, with each leg about 1.6 m in length. The LAD/TVS subsystem is designed to feed 0.9 kg/hr (2 lb/hr) to the thruster at 172 kPa (25 psia). Testing will first be conducted to establish the baseline thermal performance (heat leak/LH_2 boiloff) for the MLI system. The LH_2 feed system will then be operated to simulate a 30-day mission with 140 burns (vent cycles). The test article assembly is complete and ambient leak checking has been conducted in preparation for installation and testing in the 66 m (20 ft) vacuum chamber at test position 301. Testing is expected to be conducted late 1996 through early 1997.

Sponsor: Office of Aeronautics

Biographical Sketch: Leon Hastings, currently assigned to the MSFC Propulsion Laboratory, received his B.S. in mechanical engineering and an M.S. in engineering science. Assignments at MSFC since 1961 have centered on heat transfer, fluid mechanics, and thermodynamics, and he has over 15 years of specialized experience in low-gravity fluid management and heat transfer. He has often served on Agency-level committees to assist in formulating plans/policies for low-gravity propellant management research and technology.

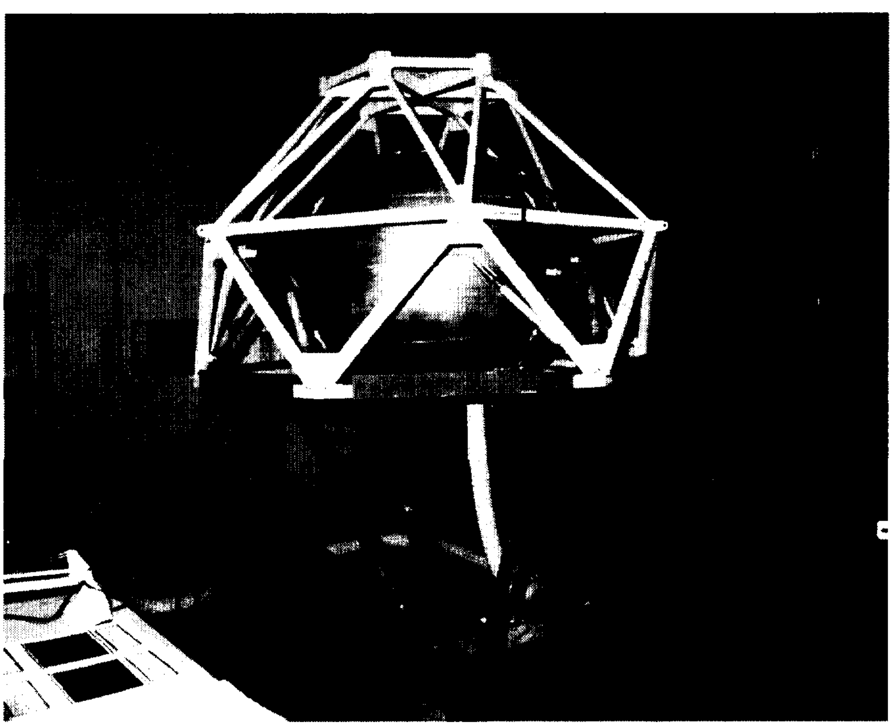

FIGURE 38.—AITP cryogenic fluid management subsystem tank.

Tridyne Gas Reactor Sizing

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Tridyne is a stable mixture of hydrogen, oxygen, and an inert gas such as helium or nitrogen. In this mixture, the inert gas is the primary constituent, usually 90 to 95 percent by volume. Tridyne's usefulness stems from the ability of hydrogen and oxygen to react in the presence of a catalyst to form water. As this reaction proceeds, it releases thermal energy causing the Tridyne mixture to warm and expand. Tridyne shows promise for two potential spacecraft propulsion applications:

- As a pressurant gas for pressurizing propellant tanks; and
- As a propellant for attitude control thrusters.

Tridyne offers the advantages of reducing spacecraft weight by eliminating heat exchangers and/or reducing the storage volume required for pressurant gases. To investigate these potential uses, NASA and the U.S. Army are conducting a joint research program to study the chemical reaction characteristics and potential uses of Tridyne gas.

Tridyne research began in the mid-1960's when Rocketdyne performed a series of experiments designed to reduce the weight of a propulsion system's pressurization subsystem.[1] The approach was to reduce the required pressurant mass by increasing its temperature. The reduction in mass also led to reductions in storage volume of gas and hence mass of the storage tank. Later experiments addressed the use of Tridyne as a monopropellant for attitude control thrusters.[2,3] Catalyst beds were sized empirically rather than analytically—an approach which makes it difficult to scale bed sizes for other applications.

The purpose of NASA's ongoing research is to bring the Tridyne concept to a higher level of technology readiness by determining reaction rate coefficients for use in reactor sizing.

The Tridyne study is organized into four phases. Using the apparatus shown in figure 39, Phase I will compare the activity of candidate catalysts by measuring temperature increase across the catalyst bed as a function of flow rate and inlet temperature. The selected catalyst will then become the subject of Phase II, which will evaluate the reaction rate coefficient as a function of temperature for a range of mass flow rates. Phase III will seek to estimate the expulsion efficiency for a pressurization system using Tridyne as a pressurant. Finally, Phase IV will examine thruster performance using a truncated nozzle installed immediately downstream of the catalyst bed.

At the time of this writing, the test article is 98 percent complete. Testing is currently projected to begin and conclude in the summer of 1997.

As described above, the primary benefits of Tridyne are expected to be mass reductions for spacecraft pressurization systems and decreased risks associated with handling storable monopropellants. The decreased

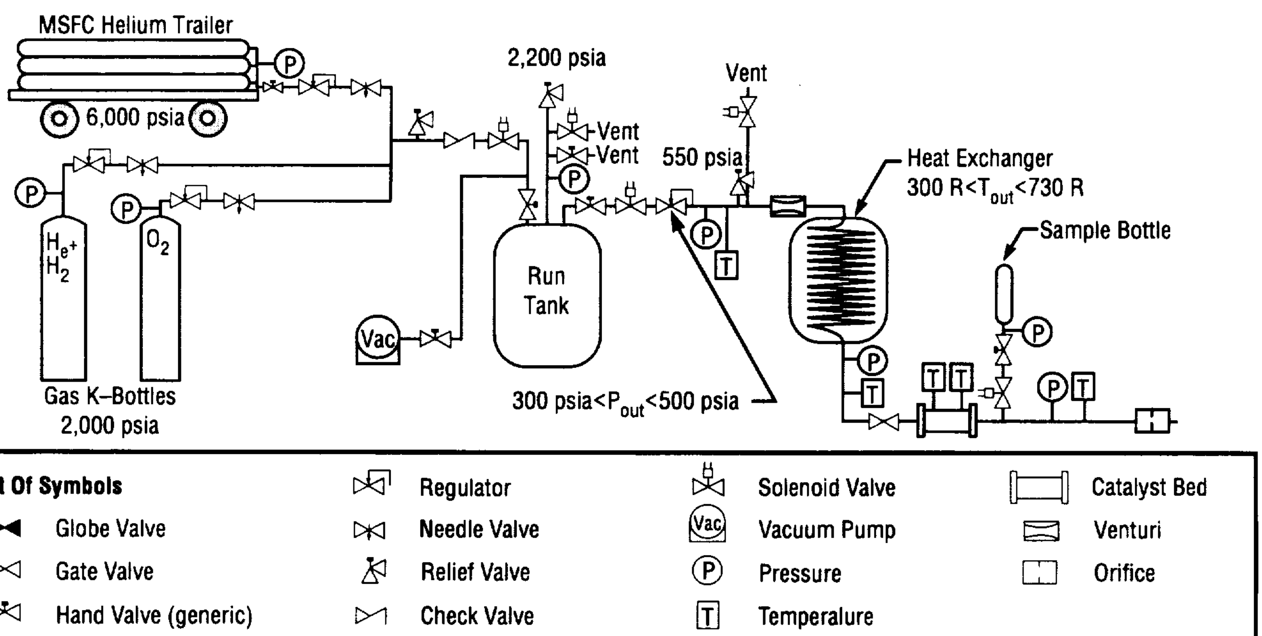

Figure 39.—Tridyne gas characterization fluid schematic for Test Phases I and II.

handling risk comes from the fact that Tridyne is a stable mixture and does not require some of the precautions required for hydrazine and its derivatives, which are toxic and carcinogenic.

The primary commercial application for Tridyne technology is expected to be propulsion systems for commercial launch vehicles and spacecraft, with the same mass reductions and risk mitigation described previously.

Through the test program described above, the MSFC Propulsion Laboratory is seeking to determine the Tridyne reaction rate constants to enable spacecraft designers to size Tridyne catalyst beds analytically. As this capability is developed, Tridyne should become a more readily available technology, offering the benefits of mass reductions and risk mitigation for future spacecraft propulsion systems.

[1]Barber, H.E.: "Advanced Pressurization Systems Technology Program Final Report." AFRPL–TR–66–278, 1966.

[2]Anonymous (Rocketdyne): "Lightweight Advance Post-Boost Vehicle Propulsion Feed System." AFRPL, F04611–77–C–0068, 1977.

[3]Barber, H.E., et al: "Microthrusters Employing Catalytically Reacted Gas Mixtures, Tridyne." AIAA Paper no. 70–614, 1970.

Sponsor: Center Director's Discretionary Fund.

Biographical Sketch: Patrick McRight works as a liquid propulsion systems engineer in the MSFC Propulsion Laboratory. He routinely analyzes and models subsystems within main propulsion systems, troubleshoots propulsion test articles, serves as principal investigator of the Tridyne gas characterization study, and coordinates other MPS test programs. He holds a bachelor of science degree in engineering (chemical) from the University of Alabama in Huntsville (1987).

A Complex-Shaped Composite Feedline for Liquid Hydrogen

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One of the many technological needs in making a single-stage-to-orbit (SSTO) vehicle a reality is being able to reduce component weight. Making components lightweight can lead to an increase in mass fraction and vehicle performance. One area with potential for substantial SSTO weight savings is the use of composite feedlines for the vehicle propulsion system. Typical feedlines for vehicles are made from aluminum or stainless steel materials. It is estimated that a substantial weight savings over conventional metallics could be achieved by using composite feedlines. The potential weight savings makes the use of composite materials a very attractive feature for future SSTO vehicles.

In 1995 under a cooperative agreement contract (NRA8–11) between MSFC and McDonnell Douglas Aerospace, the first composite feedline for liquid hydrogen service was developed. This feedline successfully demonstrated five key technology features that are fundamental in being able to use this material for a feedline application. These five features were the use of graphite/epoxy material, the manufacture and use of composite elbows, the manufacture and use of composite flanges, the ability to join a composite tube to a composite tube, and finally the ability to join a composite tube to a metallic tube. The feedline was designed by McDonnell Douglas and manufactured and tested here at MSFC. The feedline is a part of the auxillary propulsion system on the DC–XA Reusable Launch Vehicle and has been successfully flown on the vehicle. Details on this composite feedline can be found in the *1995 MSFC Research and Technology Annual Report.*

The work performed in 1995 formed the first building block in a whole new area of using composite materials. The next logical step is to expand and improve upon the previous DC–XA vehicle composite feedline work. In October of 1995 a small team of engineers from the Propulsion Laboratory and Materials and Processes Laboratory proposed to the Advanced Propulsion Technology Office here at MSFC a plan for enhancing the prior composite feedline work. This plan was accepted and funded by the MSFC Advanced Propulsion Technology Office. In this plan the MSFC team will design, analyze, manufacture, and test in-house a composite feedline that will demonstrate three more key technology features:

- The ability to manufacture a composite feedline that has a more complex geometry and do it in one piece with composite flanges on both ends.

  The prior composite feedline work for the DC–XA vehicle contained several individual composite components (elbows and flanges) that were joined together using a composite splice joint. Although demonstrating the ability to make joints in a composite feedline was one of the program objectives for the DC–XA vehicle feedline, it is not the ideal way to make a composite feedline. Every bonded joint in a composite feedline is another potential structural failure point and leak point. The MSFC team will build a feedline with no bonded joints, thus eliminating those potential failure points.

  The prior composite feedline work also demonstrated a complex geometry; however, it was only in one plane. On current engines and launch vehicles, the packaging volume is so tight that feedlines are sometimes required to be routed in all three geometric planes, thus taking on a very complex geometry. This MSFC team will build a feedline with a much more complicated geometry than the DC-XA composite feedline and do it in two geometric planes. The geometry proposed will be more typical of those used in feedsystems on launch vehicles. An isometric drawing of the feedline to be built is shown in figure 40.

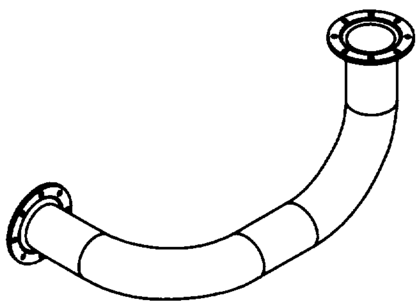

FIGURE 40.—Liquid hydrogen composite feedline.

- The ability to manufacture large diameter composite feedlines.

The prior composite feedline work for the DC–XA vehicle was for a 2-in-diameter feedline. Although the feedline demonstrated the potential for using composites and saving weight, it did it on a somewhat small scale (2-in-diameter line size). If maximum advantage of using composites to save weight is to be taken, then using this material for the large diameter feedlines found on launch vehicles should be looked at as well. These large diameter feedlines are typically found in the feedsystem located between the propellant tank and engine turbopump interface. On the Space Shuttle these line sizes range from 6 to 17 in in diameter. With these larger diameter feedlines there is significant potential weight savings. The MSFC team will build an 8-in-diameter composite feedline to investigate any potential scale-up problems in going from the previous 2-in-diameter composite feedline.

- The ability to seal composite flanges.

Since the use of composite flanges for LH_2 service is new technology, there has been very little work performed in the area of how best to seal the composite flanges against LH_2. The MSFC team will evaluate the best flange face design to use along with the best comercially available seal for a composite feedline.

In summary, this technology program will build a composite feedline for LH_2 service. The feedline will have composite flanges on both ends. The feedline design will have a complex geometry by bending in two planes and will have a large diameter of 8 in. It will be manufactured in one piece with no bonded joints and will also incorporate the best seal system for the composite flanges. Performance requirements for the design include:

- Operating pressure: 100 lb/in^2
- Temperature range: –423 degrees Fahrenheit to +150 degress Fahrenheit
- Service life: 20 temperature and pressure cycles
- Leakage rate: Less than $1.0 \times 10E^{-07}$ standard cm^3/sec of gaseous helium at room temperature. Less than 0.14 standard cm^3/sec of hydrogen at cryogenic temperatures.
- Material: IM7/977–3 graphite/epoxy material or an equivalent.

Currently the MSFC team is completing the detail design of the composite feedline. A detail structural analysis of the design is being performed. This analysis will optimize the number of plies and angles in order to meet the performance requirements while minimizing weight. On the manufacturing side, the team is evaluating simple and low-cost methods for manufacturing the tooling necessary to hand-layup the feedline. Several proof-of-concept composite elbows have already been made using a foam mandrel.

Once the best tooling methods have been selected, several development articles will be manufactured. These articles will be subjected to a rigorous test program at MSFC to gain confidence in the design and manufacturing process. Planned tests include: Pressure tests, thermal cycle tests, hydrogen leakage measurement, strength tests, and vibration tests. Once the test articles pass these tests, the full-scale line will be manufactured and it also will go through a series of similar tests.

It is anticipated this program will be complete by August 1997. The success of this program will again advance the technology of using composite materials for launch vehicle feedline applications. This program will not only address the technological aspects but also the issue of making it cost effective.

Tygielski, P.: "A Lightweight, Composite, Liquid Hydrogen Feedline." *1995 MSFC Research and Technology Report.*

Sponsor: Office of Space Access and Technology

Biographical Sketch: Philip Tygielski graduated from the University of Alabama in Huntsville in 1982 with a bachelor of science degree in mechanical engineering. He currently works in the Mechanical Systems Design Branch of the Propulsion Laboratory at MSFC. Tygielski has been involved in several different vehicle and engine propulsion feedsystem designs for many years. He most recently managed the composite feedline technology program for the DC–XA vehicle.

Soft Umbilical Test-Bed

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The Space Station Furnace Facility (SSFF) is a centerpiece for the material science to be conducted on the *International Space Station*. This facility will accommodate several different types of furnaces used for semi-conductor crystal growth in space. In order to maintain the proper environment for optimal crystal growth, these furnaces are mounted in isolation systems to protect them from unwanted vibrations and motion generated by the Space Station. The current generation of furnace isolation systems performs well, and maintains the proper environment for crystal growth. The drawback to these systems is that they cannot tolerate excessive loads during operation. The main source of excessive loads is the set of umbilicals used to supply station resources to the furnaces. These umbilicals consist of electrical power cables, data cables, gas and cooling water hoses, and vacuum lines. Each furnace requires a unique set of umbilicals that must be designed and tested to ensure proper isolation capability. The soft umbilical test-bed will be used to measure the forces produced by these umbilical sets in order to verify that proper isolation will be possible during on-orbit operation.

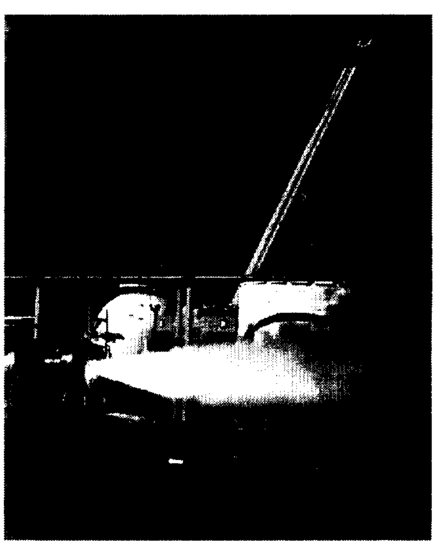

FIGURE 41.—Large subscale solid rocket combustion simulator.

The soft umbilical test-bed consists of a 6-degrees-of-freedom load cell mounted on a three-axis motion system operated by computer control. This assembly is mounted on a large optical table which can accommodate any foreseeable size of umbilical member. One end of the umbilical is held fixed, and the other end is attached to the load cell. The load cell is moved throughout the operating range of the isolation system while force and moment data are continuously collected. These data can be displayed visually, as well as saved to disk for later retrieval. The control program is written in Labview, which is a graphically oriented data acquisition language, along with Motion Toolbox, which is used to operate the motion control system. The motion control and data acquisition occur simultaneously, and act as a standard computer application requiring minimal operator training.

Utilizing the soft umbilical test-bed will allow Space Station engineers to test all required configurations of furnace umbilicals. Future additions to this system will allow the testing of the entire umbilical set in one operation, saving considerable development time.

Sponsor: Space Station Furnace Facility

Biographical Sketch: Rodney Krienke is currently a cooperative education student in his senior year of mechanical engineering at the University of Alabama in Huntsville. He is in his third work term here at NASA working in the Mechanical Systems Design Group of the Propulsion Laboratory. As an avionics technician in the United States Marine Corps for over 4 years, Rodney has extensive experience with electronic systems especially including computer-controlled, automated test equipment.

Advanced Docking Mechanism

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Docking technology began with the development of the Gemini and Apollo docking systems by the United States, and the successful probe and drogue series of docking systems by the Soviet Union. These early systems laid the groundwork for the development of the Apollo-Soyuz docking system from which the current manned spacecraft docking hardware is derived, the U.S. Space Station Phase B docking/berthing system and the Russian automated payload attach system (APAS). Both U.S. and Russian docking experts have recognized a new approach, termed capture-berthing, as a leading candidate for the next generation of spacecraft mating hardware. Traditionally, docking systems rely on the loads generated by contact of the two mating spacecraft to enable the docking process. This leads to potentially high loads in the spacecraft being mated. Capture-berthing, however, is a process by which one spacecraft "reaches out," attaches to, and mates with the other spacecraft after the two spacecraft are station-keeping within close proximity of each other. This process greatly reduces the potential loads which could be generated in both spacecraft.

The proposed effort seeks to take one of the current docking system designs, the Space Station Phase B docking/berthing system, and modifying it to develop a capture-berthing system and then characterize the systems performance. The present design of the space station Phase B docking/berthing system lends itself well to the application of capture-berthing. The system was developed in a joint program between MSFC and McDonnell Douglas Aerospace during the Phase B phase of the *Space Station Freedom* program.

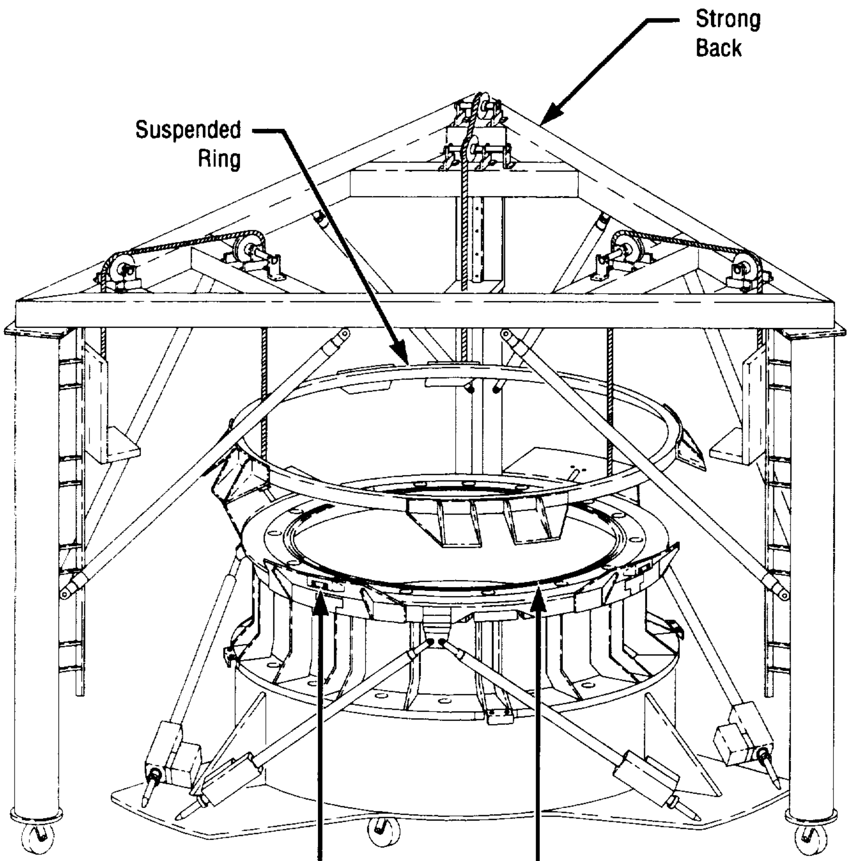

FIGURE 42.—Active docking mechanism.

Work has begun on the project. Figure 42 shows the hardware setup. The active mechanism represents the chase spacecraft and the suspended ring represents the target spacecraft. The active mechanism has an extendible ring which is attached by six linear actuators. These actuators, through the use of a control program, position the centroid of the extendible ring on the centroid of the suspended ring, thus enabling the capture-berth. The actuators then damp the motion of the suspended ring and pull the captured ring down to be mated with the active mechanism. The target centroid location is obtained through the use of a video guidance sensor which has been developed by MSFC and this 6-degrees-of-freedom target data is used by the control program to determine the positioning of the extendible ring. The control program was developed utilizing Labview, an icon driven, graphical, data acquisition and control program in conjunction with Motion Toolbox, an application used to control the actuators. The control program uses the target location and the geometry of the active mechanism to determine the required lengths of the six actuators to bring the two centroids together. The test stand provides 5-degrees-of-freedom motion, excluding roll, to the suspended ring to simulate the relative motion of two spacecraft in close proximity.

In developing and proving the new technology, the proposed activity seeks to lay the groundwork for the next generation of spacecraft mating hardware. The new approach, capture-berthing, combines many of the strengths of previous systems while avoiding many of their problems and thereby enabling many different spacecraft to be mated on orbit.

Sponsor: Center Director's Discretionary Fund

Biographical Sketch: Alan Bean has worked with mechanism design since April 1990 in the MSFC Propulsion Laboratory. Bean obtained his spacecraft mating expertise during his work as a design engineer for the *Space Station Freedom* common berthing mechanism. Bean has also been involved in the development of advanced proximity sensors which are used for spacecraft mating.

Automated Fluid Interface System

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The automated fluid interface system (AFIS) is an advanced development program aimed at providing a standard interface for on-orbit consumable transfer. The AFIS is capable of transferring propellants, fluids, gases, power and cryogens from a tanker craft to other spacecraft. This technology could be utilized for any on-orbit systems requiring resupply, including the *International Space Station*, satellites, and spacecraft. This technology could greatly increase the life and flexibility of future satellites.

An engineering unit has been designed and built as a joint venture with MOOG, Inc. This design is lightweight, reliable and flexible. This can be attributed to an innovative design in which all required operations are accomplished by one actuator. This actuator rotates protective covers, locks the two spacecraft sides together, and engages couplings for transfer of consumables. The actuator accomplishes this by providing two motions. The actuator extends a shaft linearly out and then at the end of stroke, rotates 45 degrees and linearly retracts again.

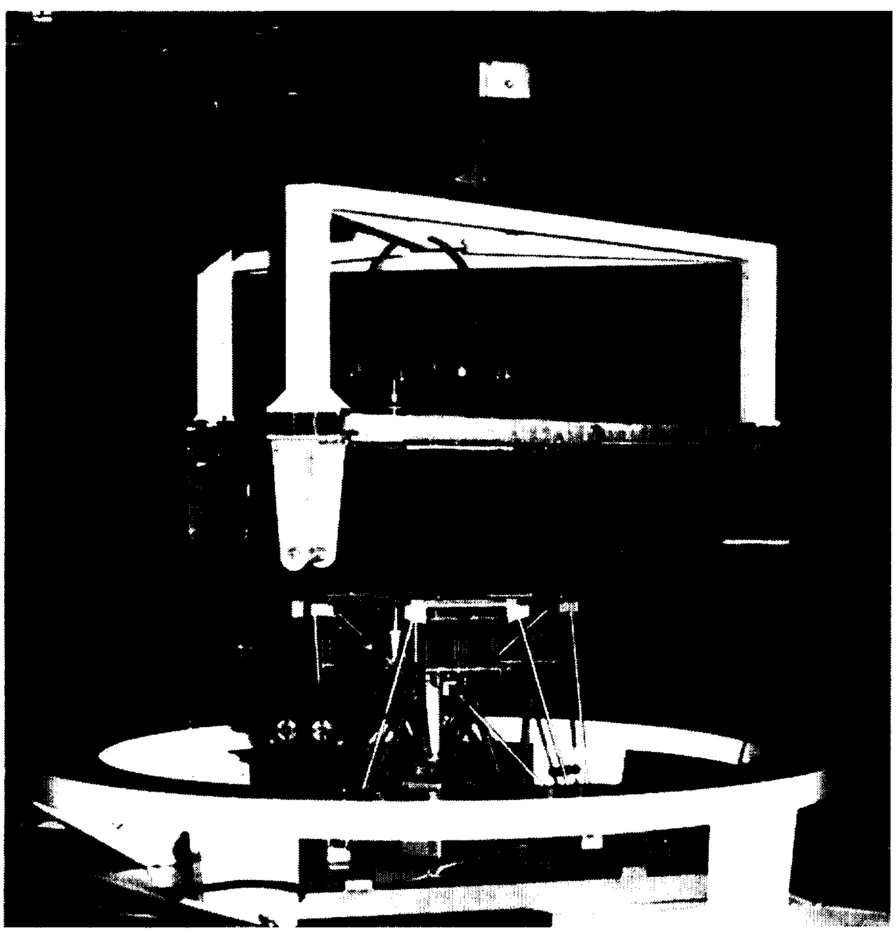

FIGURE 43.—Automated fluid interface system/three-point docking mechanism (AFIS/TPDM). Flat floor test autodocking of AFIS/TPDM before capture.

The engineering unit is currently undergoing testing at MSFC. The purpose of the testing is to determine the acceptability of the design and determine additional improvements required. This testing consists of functional, load, simulated docking and engagement, thermal vacuum, and vibration. Most of the testing is complete. The design has been proven to satisfy requirements well. However, some improvements and changes have been determined and will be implemented in the next generation design.

This program has laid the groundwork for a flight qualified system which can be easily adapted by future users requiring on-orbit consumable resupply. The future for this program is to build, qualify, and fly a flight experiment based on this technology.

Sponsor: Advanced Projects Office, NASA Headquarters

Biographical Sketch: Tony Tyler has worked in mechanism design since May 1989 in the MSFC Propulsion Lab.

Nick Johnston has worked as an electrical engineer in the robotics group since 1989 in the MSFC Astrionics Laboratory.

Structures and Dynamics

TREETOPS Structural Dynamics and Controls Simulation System Upgrade

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The objective is to provide current and complete upgrade for the TREETOPS suite of analysis tools. TREETOPS is a time history simulation of the motion of a complex multibody flexible structure in a tree topology with active control elements. TREETOPS refers to the simulation program, TREETOPS plus two interactive preprocessors, TREESET and TREEFLX, an interactive postprocessor, TREEPLOT and an adjunct program, TREESEL.

The simulation provides an advanced capability for analyzing the dynamics and control-related issues of complex flexible structures. The code has been used to analyze and design controllers for a number of large space systems including the Hubble Space Telescope. TREETOPS is capable of simulating the dynamics and control of flexible systems as complex as the Space Station mission, the rendezvous and docking of spacecraft and the robot tasks and manipulations.

TREETOPS, a multibody dynamics and controls analysis tool, has undergone various upgrades to improve its applicability as well as modeling fidelity. These upgrades have included basic formulation enhancements as unrestricted boundary conditions for flexible bodies, accommodation of effects due to geometric nonlinearities, additions of sensor and actuator math models and revisions to increase computational performance. TREETOPS development efforts have been performed largely in a research and development environment, where the emphasis has been on adding analysis features to obtain numerical results. In a simulation development environment, emphasis has been placed on documentation and design details.

This upgrade will provide a format for maintaining the current tools as well as accommodations for future enhancements.

As part of the upgrades and enhancements, geometric nonlinearity was implemented. This implementation is of the general form of nonlinear foreshortening effects in TREETOPS. It gives rise to the theoretical background on nonlinear differential stiffness, motion stiffness and the generalized active force due to the foreshortening effects.

Test were done on beam-buckling and plate-buckling type problems to address the foreshortening effects. This enhancement offers a tremendous improvement to the analytical results.

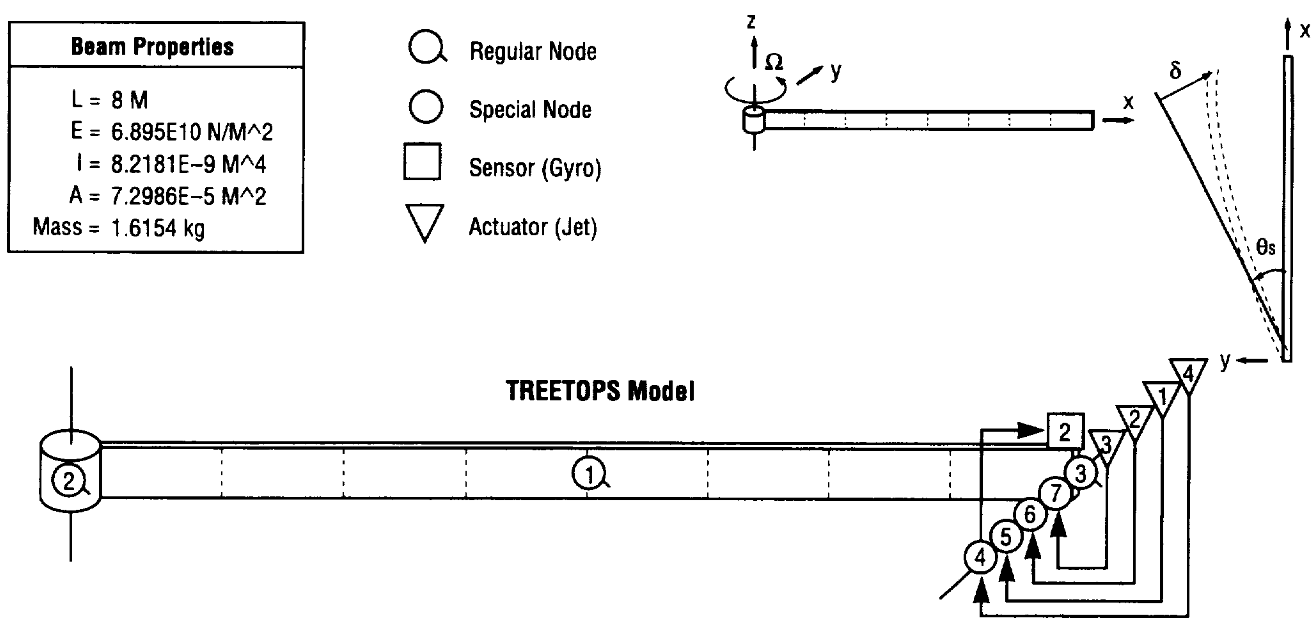

Figure 44.—TREETOPS model of spin-up beam.

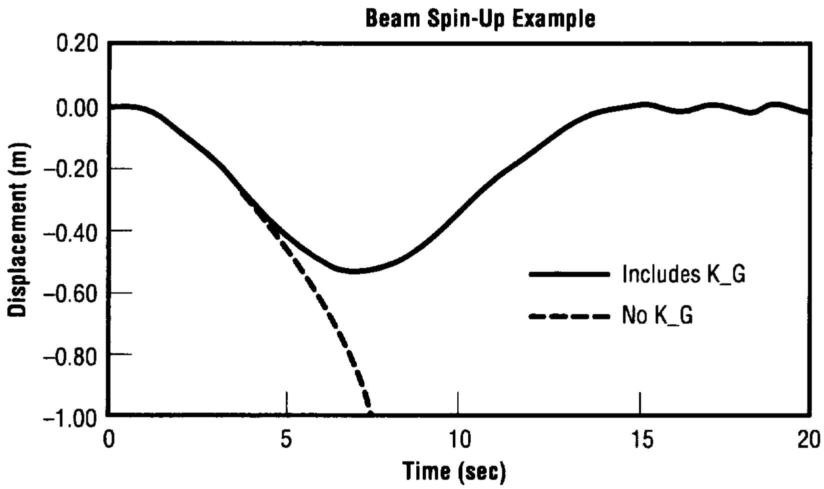

FIGURE 45.—Effect of geometric stiffening (K_G) on tip response.

Sponsor: NASA Headquarters, Office of Equal Employment Opportunity, Historically Black Colleges and Universities Program

Industry Involvement: Boeing Aerospace, McDonnell Douglas, Martin Marietta, Rockwell International Space Division, General Motors Company

University Involvement: Stanford University, Massachusetts Institute of Technology, Georgia Institute of Technology, University of Iowa, University of Toronto, University of Alabama, Auburn University, University of Alabama in Huntsville, Howard University, University of Maryland, and University of Colorado.

Other Involvement: Johnson Space Center, Goddard Space Flight Center, Langley Research Center, Stark Draper Laboratory, Sandia National Laboratory, Oak Ridge National Laboratory

Biographical Sketch: George Myers has a B.S. and M.S. in applied mathematics with 16 years of experience in control systems. He has experience in structural dynamics, control system design and attitude control of multibody systems. He has over 10 years of experience in multibody modeling for large space structures. He has coordinated activities related to TREETOPS with universities and the aerospace industry, in the field of multibody modeling. He has served as the focal point for TREETOPS multibody modeling activities for over 10 years.

Experimental Determination of Preswirl Effects on Damping Seal Performance

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The destabilizing forces generated by the seals, turbines, splines, and impellers of a turbopump increase with pump speed. These whirl drivers are opposed by the stabilizing damping forces associated with the seals and bearings of the pump. At high speeds the destabilizing forces exceed the stabilizing forces and the rotor will whirl at frequencies near the lowest critical frequency of the rotor. This self-excited vibration is potentially destructive and imposes limits on turbomachinery performance. For example, a high-pressure oxidizer turbopump was destroyed early in the development program by subsynchronous vibration and a speed limit had to be imposed on the turbopump. The whirl problem was eliminated by adding two shaft pilots and replacing two labyrinth seals with damping seals.

Computer codes developed at MSFC have shown that damping seals inhibit subsynchronous whirl by providing more damping than whirl forces. These codes indicate seal roughness and fluid preswirl have important effects on the seal's stabilizing capacity. The objective of this program is to experimentally assess the effect of roughness and fluid preswirl on damping seal performance. The effect of roughness will be established using an existing test rig to compare the performance of a smooth seal and a seal with an isogrid roughness pattern. Tests will be performed at 5,000-, 10,000-, and 15,000-r/min and 1,000-, 1,500-, and 2,000-lb/in^2 delta pressure. The effect of fluid preswirl will then be established by repeating this test series with a new shaft that will greatly increase the tangential velocity of the fluid.

Resulting data will be compared to computer program predictions, and anchored programs will then be used to design new turbomachinery.

Sponsor: Center Director's Discretionary Fund

Industry Involvement: Wyle Laboratories

Biographical Sketch: Eric Earhart holds a B.S. degree in mechanical engineering from the University of Wisconsin. He has been with the Marshall Space Flight Center for 7 years and specializes in rotordynamics.

Measurement of Damping of Advanced Composite Materials for Turbomachinery Applications

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The previous phases of this task have shown that advanced composite materials in general, and specifically fiber reinforced ceramic matrix composites (CMC's), do indeed possess higher damping properties than the baseline metal sample, Inconel 718. Currently, nickel-based super alloys, like Inconel 718, are used in rocket engine turbomachinery applications. Fiber-reinforced ceramic matrix composites can be used to replace the current selection of metal alloys due to their high-strength, low-weight, high-temperature capability and increased damping capacity. With the increased material damping in CMC's, additional and often complex mechanical dampers will not be needed to allow the component to withstand higher dynamic loading.

This damping study is in its final phase and is tentatively scheduled for completion by June 1997. The study was approved in October 1993. Phases 1, 2 and 2a were completed by the summer of 1996 and consisted of damping tests on many beam specimens.

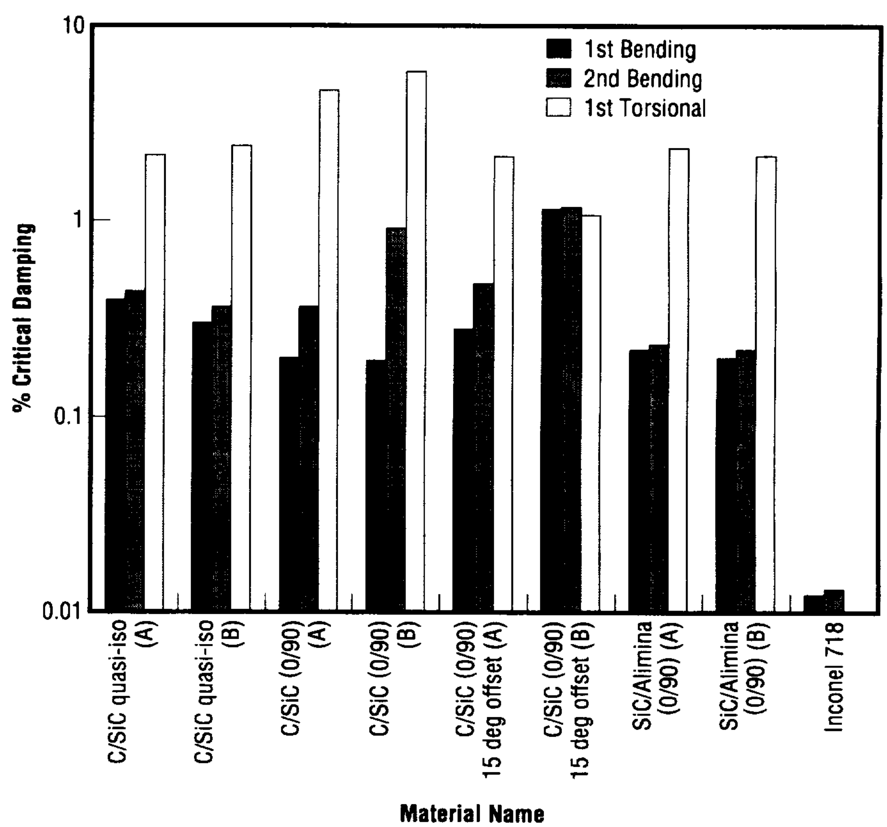

FIGURE 46.—CDDF/CBLISK beam samples damping results (FY96).

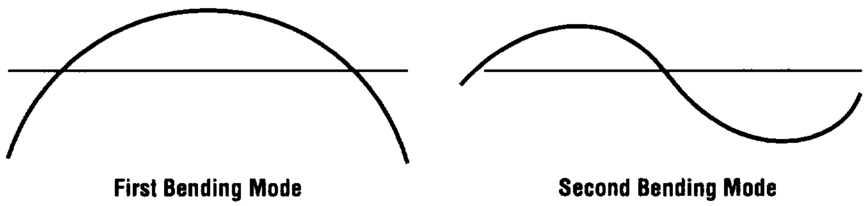

FIGURE 47.—Beam mode shapes in free-free boundary condition.

This task was developed to measure the inherent material damping capacity of composite materials that have promise for use in rocket engine turbine applications. This information can be used in dynamic analysis to predict the dynamic stress of a component under loading.

During this phase of testing, the damping capacities of eight beam samples and two disks of the size used in rocket engine turbines were determined. The beam samples were composed of carbon/silicon carbide (C/SiC) and silicon carbide/alumina (SiC/alumina), where the first term is the fiber and the second is the matrix material. Three fiber architecture's were evaluated, (0/90), (0/90) with 15-degree offset and quasi-isotropic. All three architecture's were represented for the C/SiC material while for the SiC/alumina, only the (0/90) was tested. The two disks, 22.86-cm in diameter, were purchased from Oak Ridge National Laboratory (ORNL) Oak Ridge, Tennessee. The disk samples were composed of silicon carbide/silicon carbide (SiC/SiC) and only differed in fiber architecture, polar woven and cloth lay-up. The polar woven preform was provided by ORNL free of charge. That preform was surplus from an Air Force CMC Disk/Blisk task. The cloth preform was provided at cost as well as the densification and additional handling. The damping capacities for these samples were determined through impact tests conducted at MSFC.

The data obtained from this task can aide in the selection of materials for turbomachinery applications. Turbopump components produced from composite materials will allow the engine to be lighter, thus providing an improved thrust-to-weight ratio. Composites in the turbine area could allow the engine to run at higher temperatures which would increase performance. With the addition of higher inherent material damping, additional external mechanical dampers would not be needed, allowing the component to withstand higher dynamic loading and reduce the possibility of failure through high-cycle fatigue. This increased performance equates to larger payloads or the delivery of smaller payloads to higher orbits.

With the commercialization of space, this data can be utilized by private companies in the development of space vehicles. These vehicles will be lighter, able to perform better and do so at lower development and operations cost.

Composite materials can offer lighter weight, and less costly components to rocket engine applications. The test data from this task has shown that fiber-reinforced composites provide higher material damping than the selected baseline advanced metal alloy. Additionally, with higher damping, composites may increase the life of components subjected to high-vibration environments. The study of the damping properties of advanced composites can aide the engine component designer in the selection of materials for high-vibration environments.

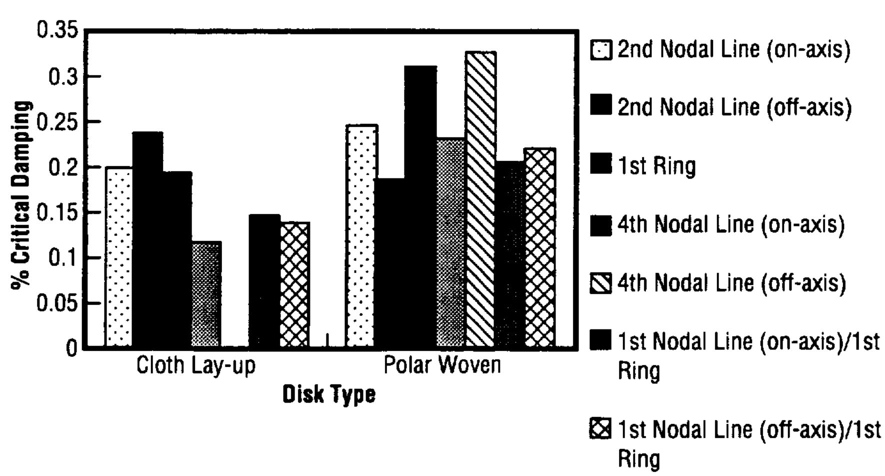

FIGURE 48.—Disk damping results.

Sponsor: Center Director's Discretionary Fund

Biographical Sketch: Donald L. Harris started his career with NASA as a cooperative education student from Tuskegee University in 1986. Harris, upon graduation from Tuskegee in 1990 with a bachelor's degree in aerospace science engineering, accepted a permanent position with NASA/MSFC. He is an aerospace technologist (AST), Structural Dynamics, performing structural dynamic analysis on liquid rocket engine components.

Analytical Model Improvement Using Singular Value Decomposition With a One-Dimensional Line Searching Technique

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The goal of analytical model improvement is to systematically improve a finite element model so that predicted responses such as mode shapes and natural frequencies closely match those measured by actual experimental tests. The updated finite element model can then be used to more accurately predict transient response loads and displacements. In general, both the experimental data and the analytical model may contain errors, and the improvement process should detect and minimize these differences.

The software code AMI (analytical model improvement) used in this study, was developed for both structural optimization applications and for analytical model improvement applications. AMI consists of a UNIX script file which calls NASTRAN to provide structural data and also calls several FORTRAN codes that calculate improved or optimized design parameters.

The methodology developed for AMI uses several advanced mathematical techniques. A search direction is first calculated with a linear least-squares solution, using singular value decomposition (SVD). Second order information is then utilized, in a one-dimensional line search, to determine a step size which yields the optimal match between experimental and analytical data. Two approximation functions are considered for use in the one-dimensional line search.

The analytical model improvement analysis, in its simplest form, is essentially a linear least-squares problem. That is because the number of Eigenvector degrees-of-freedom and Eigenvalues, measured during the modal test, usually greatly exceed the number of design variables that are to be solved for. In matrix notation, this can be expressed by a linear equation as,

$$\Delta = J\,\delta$$

where Δ is a vector containing the differences between experimental measured and analytical quantities such as eigenvalues and eigenvectors. The vector δ contains the design parameter changes to be solved for in order that the experimental and analytical quantities are in agreement. The Jacobian matrix J contains the sensitivities of the analytical modal quantities with respect to the design parameters.

Using SVD the Jacobian matrix J can be written as the product of three matrices,

$$J = U\,W\,V^T$$

And the above linear equation can be solved as,

$$\delta = V\,W^{-1}\,U^T\,\Delta$$

The solution that this SVD method yields, is the so-called minimal p-2 norm residual error solution. It basically represents the best fit of the analytical model to the experimental data possible. Any ill conditioning present in the system of equations becomes readily apparent when examining the singular values or the resulting condition number which is the ratio of the largest singular value divided by the smallest singular value. Singular values less than a given tolerance level are discarded, thus removing any ill conditioning, and insuring the accuracy of the solution.

In practice, the relationship between experimental and analytical eigenquantities is often not well approximated by the above linear equation. Significant nonlinearities may exist. The problem then becomes one of nonlinear data fitting which can generally only be solved by iteration. For this reason, the analytical model improvement problem is best approximated as a series of sequential linear least-squares problems. With this method, the FEM is updated during each analytical model improvement cycle, and if convergence is not achieved, the process of calculating sensitivities and solving the resulting linear least-squares equations is repeated.

Sometimes the linear least-squares incremental solution, δ will produce a more accurate parametric model than existed originally. Often times, however it may be wildly divergent. It can be shown that there exists a step-size parameter α, such that α times the vector δ will yield an incremental solution for the design variables,

$$\delta_{\text{incremental}} = \alpha\,\delta$$

with a residual error that is guaranteed to be less than the previous residual. If the residual error can be sequentially minimized, the final resulting solution should be the best solution possible.

In this mathematical scheme, the linear solution δ is used as the search direction and the step size parameter α represents what portion of the linear solution is to be used. The trick then, is to determine what value of the step-size parameter α to use. With a constant search direction δ, the estimated design variable values are solely a function of the parameter α,

$$\delta(\alpha)_{\text{estimated}} = \alpha\,\delta + \delta_{\text{initial}}$$

Approximations for Eigenvalues and Eigenvector degrees-of-freedom, which are a function of the estimated design variables, $\delta(\alpha)_{\text{estimated}}$ are also required. Two methods for the approximations were evaluated. The first method uses a special version of the method of moving asymptotes (MMA) to approximate the eigenquantities. The second method uses a generalized quadratic equation (GQE) for the approximations. The approximate eigenquantity functions are such that they exactly match the eigenquantities and their first and second derivatives at the initial design parameters.

Using the approximation functions (MMA or GQE), the p-2 norm residual error between the estimated and the test measured eigenquantities is next determined. This estimated p-2 norm residual error is now only a function of the parameter α.

A one-dimensional line search optimization routine in the International Math and Statistics Library (IMSL) is next used to find the value of α, which minimizes the estimated residual error. This value of the parameter, say α^*, is then used to get an improved estimate of the design variables.

Both approximation functions, MMA and GQE, use second order eigenquantity information, namely primary second derivatives, determined through a forward finite difference technique. Whenever a second derivative term is zero or is negative, a small positive number is substituted. This provides for a so-called convex approximation which provides for a unique solution.

A fixed-base modal survey was conducted at Marshall Space Flight Center on December 11, 1991, which experimentally determined the lower-frequency dynamic characteristics of the Small Expendable Deployer System (SEDS). Figure 49 shows the finite element model for the SEDS test article including several of the major structural components. This analytical finite element model contains approximately 6,600 degrees-of-freedom. The first two natural frequencies and mode shapes were used for this correlation study; the corresponding frequency range of interest was 50 Hz and less. The first test and analysis mode shape was a pitch mode of the canister about the x-axis. The second was a lateral canister translation in the x direction.

Table 3 shows the design variables that were chosen to be updated in this study. Design variable number one is the canister delta mass moment of inertia about the x- or z-axis. This variable augments the finite element model prediction of the mass moment of inertia of the tether which is inside of the canister. It tends to compensate for modeling the tether with using only two lumped masses connected by very stiff bar

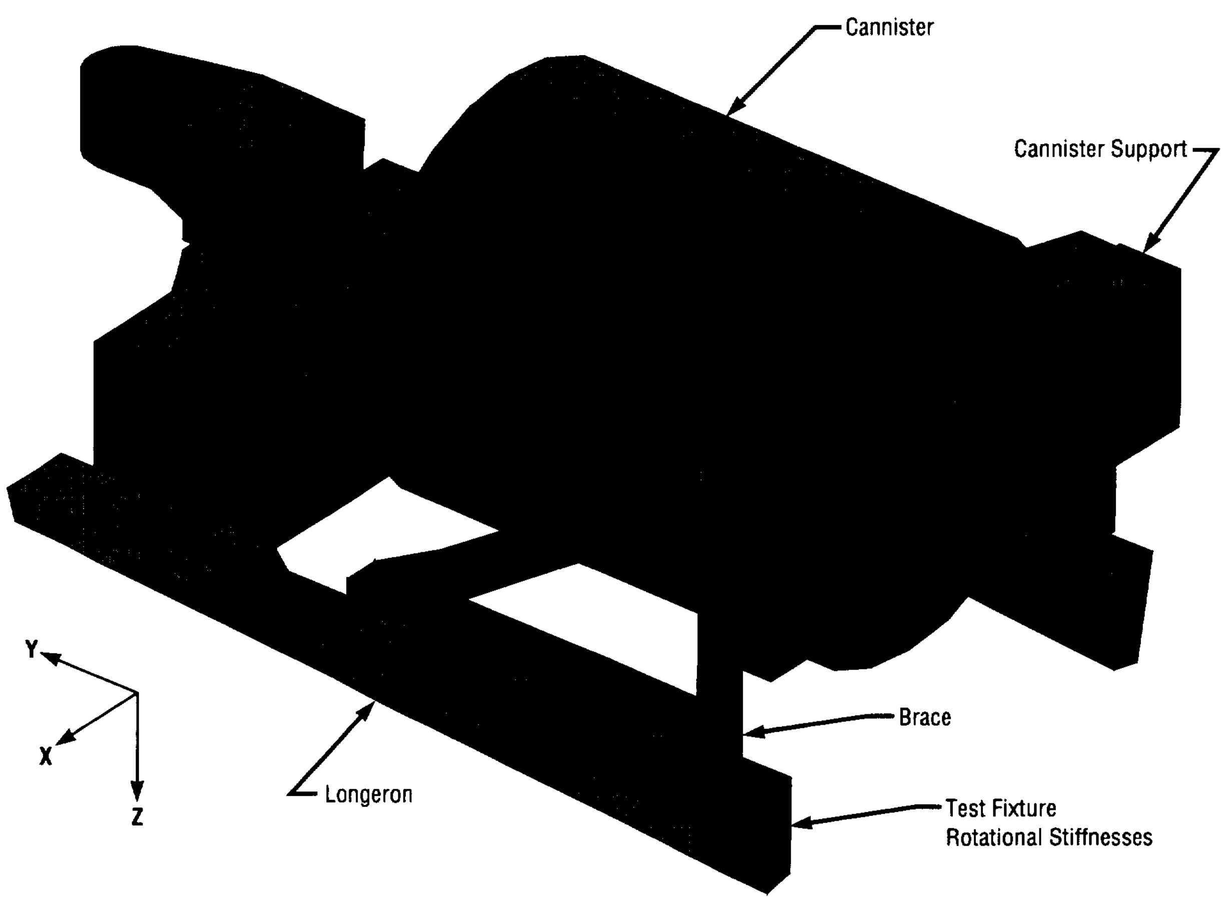

Figure 49.—Small Expendable Deployer System (SEDS) finite element model

Table 3.—*Design parameter definitions.*

Design Parameter	Description
1	Cannister Delta Moment of Inertia
2	Aft Test Fixture Rotational Stiffness $K_{\theta y}$
3	Brace to Torquebox to Cannister Stiffness K
4	Aft Test Fixture Rotational Stiffness $K_{\theta x}$
5	Longeron Stiffness E (modulus of elasticity)
6	Aft Test Fixture Rotational Stiffness $K_{\theta z}$
7	Brace Stiffness E (modulus of elasticity)
8	Cannister Support Stiffness E (modulus of elasticity)

elements; the mass moments of the tether's inertia had not been determined exactly. The modulus of elasticity of the longeron, of the canister support or torque tube, and of the brace were also chosen as design variables. Three rotational stiffnesses design variables, at the aft ends of the longerons, represent test fixture effects. Another design parameter is a bearing stiffness between the brace and canister support and canister.

With the eight design parameters chosen, the unbounded linear solution was prone to fairly large excursions. This is partly due to combining mass or inertia design variables with stiffness variables during the analysis. Using physically realistic design parameters is an important requirement for this type of analysis, however, if the results produced are to be meaningful. Figure 50 shows several analyses using four different options for selecting the step-length parameter α. A constant move-limit assumption indirectly specifies the parameter α since the largest design variable is limited to a given fraction

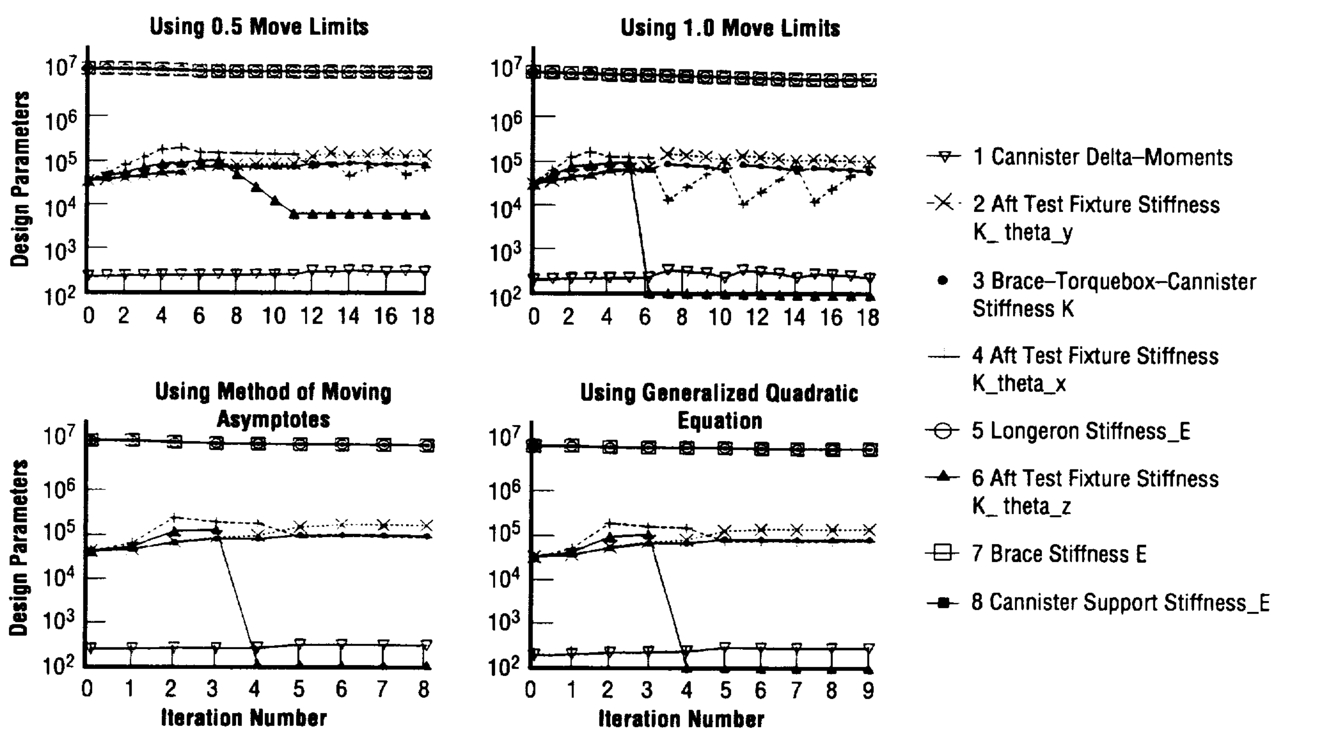

Figure 50.—Analytical model improvement analysis—design parameters versus iteration number for various methods of computing a.

Table 4.—*SEDS simulated data test cases.*

Test Case Number	Test Case Description: Design Variable	Test Case Description: Changes From Nominal Case	Iterations Required to Converge	Maximum % Error in Predicted Design Variables
1	1–	+100%	4	0.0
2	3–	+100%	4	0.0
3	5–	+13.3%	3	0.1
4	8–	+13.3%	3	0.1
5	1– 3– 5–	+100% +100% +13.3%	6	0.1
6	1– 2– 3– 4– 5– 6– 7– 8–	+100% +100% +100% +100% +100% +66.7% –44.4% –66.7%	7	0.2

of its previous value and other design parameters are ratioed accordingly. This move limit option is often used in structural optimization problems. The move-limit options using move-limits of 0.5 and of 1.0, however, did fail to converge even after 18 iterations.

The processes using the method of moving asymptotes and generalized quadratic equation converge in eight and nine iterations respectively. These results show the advantage of using approximation functions with second order information.

The AMI software also includes a FORTRAN code that monitors various test-related parameters such as modal assurance criteria numbers (MAC) and cross-orthogonality numbers. The final MAC numbers predicted were 0.994 and 0.993 for the first two modes. The diagonal cross orthogonality numbers between analysis and test were 0.999 for both sets of modes; the off-diagonal values were only 0.004 and 0.003. And frequency errors were minimized to 0.05 percent for both modes. Acceptable values for frequency errors are usually three to five percent, and diagonal cross-orthogonality numbers are usually required to be 0.900 or greater; off diagonals should be less than 0.1. The above results predicted by AMI are significantly better than these requirements.

The second order approximation functions were very effective for reaching a converged solution in a reasonable number of iterations. The accuracy of the solution was still somewhat in question, however. For this reason, six simulated test cases were designed where the target solution was known before the AMI analysis was begun. Table 4 gives results of this study. The MMA determination of the step size α was used for this study since it seemed to yield somewhat better results than the GQE method.

For test case number one, the first design variable was increased by 100 percent from its nominal value, i.e., increased from 268.7 to 537.4 lb/in^2, as given in weight units. Modal data were calculated for this configuration and used as experimental test data. The analytical model improvement analysis matched the design parameters for this test case in four iterations with negligible errors.

For every one of the six test cases in fact, each of the design parameters was predicted to the correct value with negligible errors. The most difficult test case considered, number six, took more iterations (seven) to converge—as would be expected—since this configuration had been substantially modified from the nominal configuration.

The AMI software is a useful tool that can be used by the analyst for the sometimes difficult task of analytical model improvement. The approximation functions, using second order information, converge to an accurate solution in a reasonable number of iterations. Improved design variables calculated by AMI are both physically realizable and also very realisitic.

Orr, M.F., Jr.: "Analytical Model Updating Using Singular Value Decomposition With a One-Dimensional Line Searching Technique." AIAA/ASME/AHS Adaptive Structures Forum, Salt Lake City, UT, 1996.

Sponsor: *International Space Station*

Biographical Sketch: Matthew F. Orr, Jr. has worked in the aerospace engineering field as a structural dynamicist for approximately 23 years after serving a 3-year tour in the U.S. Army. He received a B.S. in aerospace engineering from University of Kansas in 1973 and received a master's of mechanical engineering with a perfect straight-A average from the University of Utah in 1978. He has worked at Beech Aircraft, Thiokol, Martin Marietta, McDonald Douglas, and has been with NASA/MSFC for over 5 years. He recently was awarded the Professional Engineering License from the State of Alabama.

Automated Signal Processing System of High-Frequency Dynamic Measurements for Engine Diagnostics

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NASA's advanced propulsion systems have been undergoing extensive flight certification and development testing. This process involves large volumes of health monitoring measurements. Under the severe temperature, pressure, and dynamic environments sustained during operation, numerous major component failures have occurred resulting in extensive engine hardware damage and schedule impact. To enhance engine safety and reliability, detailed analysis and evaluation of the high-frequency measurement signals are mandatory to assess the propulsion system dynamic characteristics and operational conditions. An efficient and reliable automated signal processing system that can analyze large amounts of high-frequency dynamic measurements can provide timely assessment of engine performance and diagnosis. Such a system will reduce catastrophic system failure risks and expedite the evaluation of both flight and ground test data, thereby reducing launch turnaround time.

During the development of the Space Shuttle Main Engine (SSME), a hierarchy of advanced signal analysis techniques for mechanical signature analysis has been developed by NASA and ASRI for the improvement of safety and reliability for Space Shuttle operations. These techniques can process and identify intelligent information hidden in a measurement signal which is often unidentifiable using conventional signal analysis methods. By providing additional insight into the system response, the techniques can better identify well-hidden defect symptoms as well as false alarm signatures. As a result, use of signal analysis techniques reduces false alarm/misinterpretation rates and greatly improves system reliability. These techniques have been tested using SSME static test and flight data and appear to be extremely promising for failure analysis and detection in other complex machinery. These advanced mechanical signature analysis techniques as shown in table 5 have been integrated into an advanced signal analysis library (ASAL) for use at MSFC's Structural Dynamics and Loads Branch on the operator interactive signal processing system (OISPS).

The mechanical signature analysis techniques in the ASAL library have been used extensively in supporting critical, day-to-day MSFC SSME project flight and test program operations. The detection and understanding of anomalous signatures and their physical implications is the most important function of the ASAL techniques. However, due to the highly interactive processing requirements and the volume of dynamic data involved, such detailed diagnostic analysis is currently being performed manually which requires immense man-hours with extensive human interface. The advanced nonlinear signal analysis topographical mapping system (ATMS) utilizes a rule-based expert system to supervise a sequence of diagnostic signature analysis techniques in the ASAL library in performing automatic signal processing and anomaly detection/identification tasks in order to provide an intelligent and fully automated engine diagnostic capability.

Figure 51 shows the logic flow of the overall ATMS system. Typical input to the system for SSME ground tests contains 60 to 80 channels of dynamic data at a sample frequency of 10,240 Hz for a test duration of approximately 550 sec. SSME flight data inputs range from 24 to 36 dynamic channels sampled at 10,240 Hz for approximately 520 sec. The interfaces between the CLIPS expert system and the ASAL programs were developed first. A set of ASAL execution rules of how to perform

TABLE 5.—*ATMS Advanced Signal Analysis Library (ATMS–ASAL).*

- Auto/Cross Bi-Spectral Analysis for quadratic nonlinear correlation identification
- Auto/Cross Tri-Spectral Analysis for cubic nonlinear correlation identification
- Hyper-Coherence Analysis for harmonic correlation identification
- Hyper-Coherence Filtering for waveform enhancement
- Instantaneous Frequency Correlation for frequency synchronous correlation analysis
- Micro-Frequency Cross Correlation technique for time delay estimation
- Composite-Modulation Analysis for higher order nonlinear correlation identification
- Phase Synchronous Enhancement Method for spectral resolution enhancement
- Coherent Phase Wideband Demodulation for cavitation detection
- Synchronous Time Averaging for waveform enhancement with keyphasor data
- Synchronous Phase Averaging for waveform enhancement without keyphasor data
- Rotary Spectral Analysis for dynamic orbit analysis
- Adaptive Comb/Notch Filter for dynamic orbit enhancement
- Recursive Least Square adaptive filter for adaptive noise cancellation
- Phase Domain Average technique for signal discreteness determination
- Topographical Algorithm for signal mapping and compression
- High-frequency Envelope Analysis for bearing fault detection
- Modified Wigner Distribution for high-resolution spectral analysis without cross-coupling

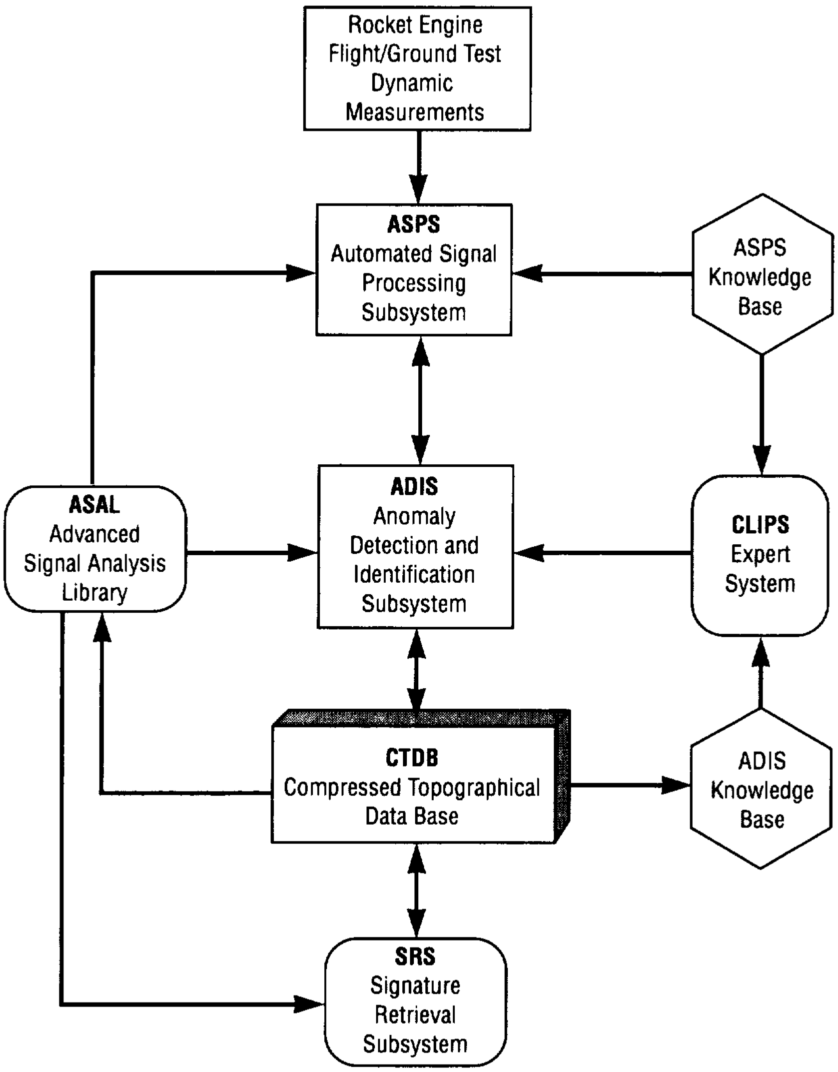

Figure 51.—ATM system logic flow.

the analysis of each ASAL program with correct parameter settings were established in the automated signal processing subsystem (ASPS) knowledge base (ASPS-KB). Based on this knowledge base, the ASPS then utilizes the CLIPS expert system to supervise the ASAL in performing a sequence of standard analysis tasks for engine postflight/test evaluation. The ASPS will automatically convert high-frequency dynamic signals from the engine operational run into a bank of succinct image-like patterns in a compressed topographical format and other various special formats to be stored in the compressed topographical data base (CTDB). The results of the ASPS operations thus provides the basic fact data base and key statistic information for more detailed analysis in the subsequent anomaly detection and identification subsystem (ADIS). In addtion, the signature retrieval subsystem (SRS) can be enacted to provide fast signature retrieval, trending, and fault-pattern comparison/identification capabilities which allows the entire engine test history to be readily accessible.

The ADIS is the most intelligent element of the ATMS. Its major function is to first detect the existence of any anomaly in the CTDB data base created by ASPS. Anomaly identification will then be performed in order to determine the physical underlying cause of the anomaly. The signature analysis techniques in ASAL can often provide valuable insight about the source of an anomaly and identify its underlying causes. Table 6 lists the typical anomaly detection and identification capabilities offered by ASAL for engine diagnostic evaluation. This anomaly detection and identification task requires interactive processing of various signal analysis techniques in ASAL. An ADIS knowledge base (ADIS-KB) was designed and established by extracting the knowledge and thought logic of experienced human experts in performing such anomaly detection/identification, and reducing them into a set of rules for expert system execution. The ADIS then utilizes the CLIPS expert system to automate an intelligent ADIS analysis task by performing an extensive and highly interactive analysis for anomaly detection and identification.

A typical example of the ADIS logic flow will now be given. If a strong anomaly is detected at some frequency in the accelerometer data from the SSME high-pressure fuel turbopump (HPFTP), the ADIS will perform a sequence of appropriate signal analyses in order to identify the potential sources of this anomaly as:

- A high vibration level at the HPFTP synchronous and/or harmonic frequency due to rubbing, imbalance, misalignment, or instability;
- A bearing defect (inner race defect, outer race defect, rolling element defect) characteristic frequencies of various ball/roller bearings (pump-end ball (PEBB), turbine-end ball (TEBB), turbine-end roller ball (TERB));
- A modulation/sideband spectral component of a bearing fault pattern;

Table 6.—*ATMS–ADIS anomaly detection/identification capabilities.*

- Detect nonlinear modulation/sideband phenomenon associated with bearing fault mechanisms
- Detect wideband modulation phenomenon associated with cavitation-induced vibration
- Identify feed-through or resonance from neighboring equipment
- Identify RPM/harmonics interference/overlap within a multi-rotor system
- Discriminate rotor-related vibration from independent nonrotor-driven source/noise
- Identify syncronous (RPM) modulated spectral component associated various nonlinear vibration mechanisms (including mechanical-driven) such as deadband interaction, and fluid-driven such as cavitation-induced asynchronous vibration, etc.
- Identify pure-tone electric line noise
- Identify structural/acoustical resonant mode
- Detect Frequency Modulation (FM) phenomenon associated with various FM vibration mechanisms such as shaft torsional vibration or gearbox transmission error
- Identify signal source through time-delay estimation
- Improve the signal-to-noise ratio in the vibration measurement data corrupted by noise
- Enhance spectral resolution for all RPM-related vibration components

- A synchronous/harmonic frequency feed-through from other engine turbopumps;
- Aliasing;
- An electrical line noise;
- A cavitation-induced vibration; or
- A structural mode, etc.

If the anomaly cannot be absolutely identified, ADIS will then try to identify certain dynamic characteristics associated with the anomaly such as:
- Whether it is synchronous frequency related or synchronous-independent;
- The anomaly modulation relationship with synchronous;
- The discreteness of the anomaly; or
- The instantaneous frequency/amplitude characteristics (periodic or random) of the anomaly, etc.

Preliminary testing of ATMS using actual SSME test data has demonstrated that the ATMS can perform detailed dynamic data analyses of large volumes of dynamic data without human interface thereby reducing the analysis man-hours. ATMS has also been used to support anomaly/incident investigations for the advanced turbopump (AT) HPFTP program and the information obtained was instrumental in the redesign of the AT/HPFTP hardware.

ATMS will significantly reduce manpower requirements for processing and analyzing large volumes of rocket engine flight/test dynamic data for diagnostic and performance evaluation. ATMS will allow NASA engineers to quickly evaluate rocket engine operational conditions of flight/test data, thereby reducing launch turnaround time and enhancing flight safety and reliability. ATMS will provide timely assessments of the engine performance, identify probable causes of malfunction/anomalies, and indicate feasible engineering solutions to enhance engine performance. In addition, failure history, fault symptoms, and anomalous signatures created in the CTDB will provide a foundation for future propulsion development programs.

An intelligent and fully automated rocket engine diagnostic system has considerable commercial application potential outside the NASA's propulsion area. Such a system would greatly increase the performance of monitoring and providing diagnostic data for critical mechanical/drive-train components of many industrial systems used by power plants, transportation, and manufacturing sectors.

[1]Jong J.; Fiorucci T.; McBride J.: "Phase Synchronized Enhancement Method for Machinery Diagnostics." *1994 MSFC Research and Technology Report*, 1994.

[2]Jong J.; Jones J.; McBride J.; and Coffin T.: "Correlation Identification Between Spectral Components in Turbomachinery Measurements by Generalized Hyper-Coherence." Third International Machinery Monitoring And Diagnostic Conference, December, 1991.

[3]Jong J.; Jones J.; McBride J.; Fiorucci T.; Zoladz, T.: "Phase Synchronized Enhancement Method for Space Shuttle Main Engine Diagnostics." NASA Conference on Advanced Earth-to-Orbit Propulsion Technology, 1994

Sponsor: Space Shuttle Main Engine Project, Reusable Launch Vehicle—Long Term/High Payoff

Industry Involvement: Dr. Jen-Yi Jong, AI Signal Research, Inc.

Biographical Sketch: Tony Fiorucci is an aerospace engineer with the Structural Dynamics and Loads Branch of the Structures and Dynamics Laboratory at Marshall Space Flight Center. He specializes in evaluation and characterization of vibration environments for both flight and ground test propulsion systems supervised by MSFC. His current and primary tasks include assessment/qualification of all vibration data acquired in support of the development, certification, and flight programs for the SSME project. Fiorucci graduated with a B.S. in engineering mechanics from the University of Tennessee in 1988.

Design of a Ceramic Matrix Composite Integrally Bladed Turbine Disk

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This program is in its second year and will enter shortly into Phase II which consists of the actual hardware fabrication and testing. Primary members of the multiple discipline Science and Engineering MSFC/LeRC team are: LeRC: Andy Eckel, Dr. Tom Herbel, Ali Sayir; MSFC: G. Genge, EP32; Dr. Corky Clinton, EH34; Michael Effinger, EH34; Don Harris, ED23; Dr. James Min, ED27; Dr. Roy Sullivan, ED28; Jose Roman, ED64; R. Beshears, EH13; and the author. Subscale tests have been completed to either address simplex turbopump test requirements or to generate gaseous oxygen (gox) or thermal-based data for upcoming programs. The following presents limited results from the subscale tests and analyses that have been performed. Because of ITAR (International Traffic in Arms Regulations) restrictions on export of technologies and the fact that data represents a technology unique to the United States, requests for detailed data may be made through the Technology Transfer Office.

Telecons with DoD and industry participants produced historical design data that enabled the team to quickly identify the key design parameters for composite blisks: shear strength limitation of composites, higher compressive strength of C/SiC composites, the biconic attachment coupling design, and the potential for tailoring blade strength properties through the implementation of ceramic polar weaves.

A preliminary analysis was performed to help determine differences in stress levels experienced with ceramics versus the traditional metallic blisk. In order to be consistent with previous simplex results, the ANSYS simplex turbine blisk model was modified with composite properties for a simple comparative case study and the calculations for maximum stress and blade hub values were presented to the team. While stress values were lower for the ceramic case, only centrifugal loading was considered at this time for this particular phase of the design. Examination also was made of three attachment designs, based on earlier work performed by Garrett Aircraft in the early 1980's. In the future, a blisk model with a bionic attachment definition will be used for structural assessment. The blisk geometry will be finalized when subscale torque test results are available for incorporation into the hub attachment design. Additional work was performed to provide recommendations for high cycle fatigue and low cycle fatigue test parameters.

With key composite integrally bladed disk (CBLISK) design parameters identified from the industry-government telecons, and guidance in use of the design of experiments approach, a test matrix for the torque testing was generated for optimizing the blisk hub attachment design. Due to funding limitations, however, the test matrix will be reduced to reflect evaluation of two designs rather than three.

Several subscale tests were performed to resolve materials performance questions for blisk concepts in general; a few tests address simplex-specific turbopump test requirements for turbines operating in a gox environment.

Damping tests were performed on eight beam samples, two of which were provided by the CDDF (Center Director's Discretionary Funds) damping study entitled "Measurement of Damping of Advanced Composite Materials for Turbomachinery Applications." The tested materials included two samples each of:

- C/SiC Quasi-Isotropic
- C/SiC (0/90)
- C/SiC (0/90) 15-degree offset
- SiC/Alumina

Figure 52 shows the results of the testing compared with an Inconel 718 beam sample. The results indicate a significant increase in damping over the metal sample. The C/SiC (0/90) 15-degree offset sample was dropped before testing which probably caused more matrix cracking, which in turn allowed more slip and produced more damping for all modes tested. Additionally, the two disks procured from Oak Ridge National Laboratory for damping tests in the CDDF task were provided to the CBLISK team for torque requirements testing.

Three thermal testing tasks were conducted at NASA/LeRC on the C/SiC composites. These were thermal shock, stressed

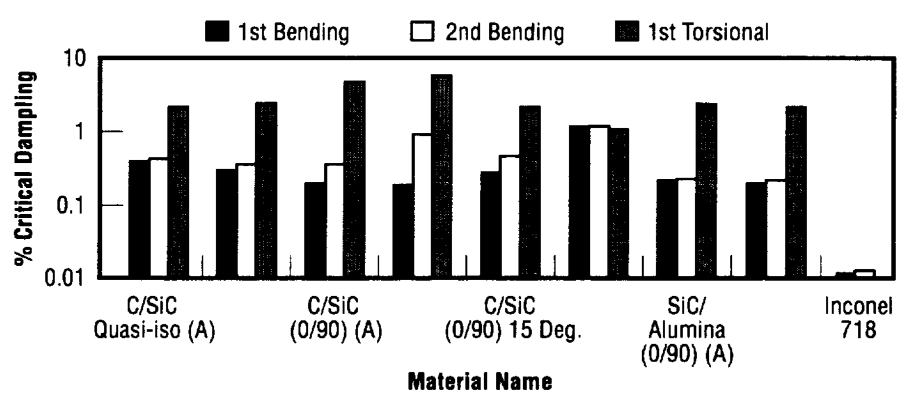

Figure 52.—CDDF/CBLISK beam samples damping results (FY96).

oxidation and thermogravimetric (TGA) testing. Due to funding limitations, it was decided by the team to divide the testing into two phases; Phase II is planned for FY97.

The first set of stressed oxidation testing was completed and analysis of the results was reported. TGA testing was also partially completed and results are available. TGA testing was performed on both fiber architectures and at three temperatures. This testing is meant to assess how rapidly the materials oxidize (without stress) in a flowing oxidizing gas at elevated temperatures. Weight loss data is recorded in real time as the sample is suspended unstressed in a laboratory furnace. Each test runs for a maximum of 24 hr. So far, the TGA data are consistent with results from the stressed oxidation testing. These data and plots are available upon request.

Results for the particle impact test of coated C/SiC targets indicated that the samples do not burn at temperatures up to 700 °F. In most impacts, the material appeared fragmented and de-layered rather than burned. More tests will be run to generate additional data. Remaining samples will be reserved until the injector is redesigned (beginning in 1997) to handle 1,000 °F. Particle impact test data from LeRC exist on SiC/SiC samples; it is reported that the SiC/SiC samples fared well.

Promoted combustion and frictional ignition tests were performed to satisfy pump test requirements. Materials characterization (fatigue, tensile, shear, modulus, specific heat, etc.) tests were also conducted using C/SiC specimens. These properties will be used in the structural assessment.

Many components can be subjected to a spectrum of loading frequencies ranging from a few hertz to several thousand hertz. During its design sessions, the team established the influence of high-cyclic loading frequency on the tensile fatigue life of a woven-carbon-fiber/SiC-matrix composite turbine blisk. Published literature identified frequencies affecting the properties of the ceramic composites. Recent fatigue studies, conducted at University of Michigan, have shown that the tension-tension fatigue life of fiber-reinforced ceramics decreases as the fatigue loading frequency is increased. A limited number of samples were used in load-unload tests for predetermined stress levels and frequency of cycling parameters identified for the high-cycle fatigue testing. Fatigue data on tensile specimens were generated. An attempt was made to begin to characterize the composites under various loading conditions while operating at 10 and 50 Hz. See figure 53 for a plot of the data. Test failures were discovered at a high number of cycles (i.e, 1×10^7) for high loads. Previous testing for other materials (i.e., metals) would have assumed run out at a lower number of cycles (i.e., 1×10^6). More samples are required to better define this finding. Due to limitations of the test machine, high load and high frequencies could not be obtained. While the low number of samples prohibit a statistical characterization, it does suggest a general trend of the current C/SiC material specimens for the specified test conditions. It is important to note that the frequency dependency of composites is a design factor that will impact structural response and should be characterized as close to operating frequency as practical for planned applications.

In addition to the wrap-up of the FY96 subscale tests, preliminary analysis and developing requirements for the critical design parameters, the team completed a benchmark evaluation of Oak Ridge National Lab (ORNL) rapid densification process through acquisition and nondestructive evaluation (NDE) of polar woven disks. Improved MSFC NDE in-process inspection procedures were established for composites. The actual CMC test blisks will, however, be produced by DuPont through the traditional densification

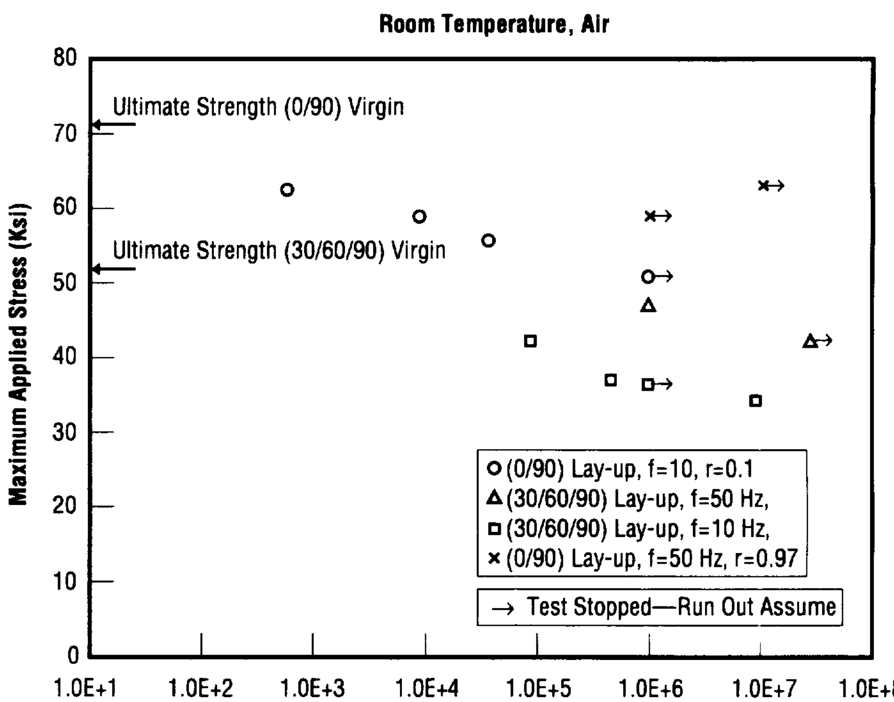

FIGURE 53.—Fatigue of C/SiC ceramic matrix composite.

process. One disk from each type (quasi-isotropic and polar weave) will be used in the turbopump tests.

Fewer parts count and the lighter weight parts will result in reduced operational costs. Acquisition of CBLISK technology is desired to realize cost savings from two areas. Use of a single-piece turbine construction (integrally bladed) damped lightweight composite materials will reduce weight and cost of labor intensive operations of assembly and disassembly, as well as for inspection of complex blades/damper systems. In addition, use of composites is expected to impart needed internal damping to the configuration to address the vibratory stresses encountered due to unsteady flow loads through the bladed turbine regions. However, the structural response of these single-piece structures (blisks) to high-vibration environments must be considered. This task will aid in characterizing the extent to which composites can damp these vibrations and will help benchmark the ceramic blisk technology for application in high-temperature environments. In addition, unique gox-rich environments data will be generated which will broaden the application of composites.

During the progress of this year, this program has produced data which will enable the ceramic matrix composite integrally turbine to be tested in the Simplex turbopump environment. Biconic attachment design parameters were identified and a design of experiments for determining torque test friction factors was formulated. In addition, a limited set of unique frequency/fatigue data base reveals the dependency of composites under high frequency cyclic loading to stress levels which will aid in the characterization of future composites applications.

[1]Turbine Rotor Development Program, DuPont Lanxide, October 1994. Sponsor: Aero Propulsion and Power Laboratory, Wright Research and Development Center, Wright Patterson Air Force Base, Ohio.

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[3]Clinton, R.G.: "Selection and Characterization of Ceramic Matrix Composite Materials for Rocket Engine Integrally Bladed Turbine Disks (Blisks)." Presented at the annual conference of Advanced Composites sponsored by American Ceramics Society, January 1996.

Sponsor: Office of Space Access and Technology

University/Industry Involvement: DuPont Lanxide; Southern Research Institute, Foster Miller

Biographical Sketch: Katherine Mims is a senior structural dynamics analyst at the MSFC Structures and Dynamics Laboratory, Structural Analysis Division, Structures and Loads Branch. She is a mechanical engineering graduate of Auburn University and has been interested in blisk dynamics since she became affiliated with the Government through DoD/MICOM, Redstone Arsenal in 1983 and then, at MSFC, NASA in 1985.

Testing of Low-Profile Composite Dome Under Internal Pressure

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Low-profile domes are becoming more and more important in aerospace design as a means of reducing overall vehicle weight and increasing the volume of a tank for a given length. Most low-profile dome designs considered thus far have been metallic. Since composite materials offer significant performance and weight advantages over metals, a Center Director's Discretionary Fund (CDDF) project was initiated to apply composites to the low-profile dome concept.

The purpose of this project was to design, manufacture and test a low-profile composite dome with a radius-to-height ratio of three using graphite-epoxy material. Design and analysis was performed using several computer programs for determining ply layups and finite element analysis to verify the design and generate test predictions. Computational methods and spreadsheets were also used to determine the ply layup sequence and to give technicians the proper geometries of each ply. The dome was successfully manufactured in the MSFC Productivity Enhancement Complex (PEC) via hand layup using a toughened resin graphite-epoxy material.

The test will consist of a sequence of internal pressure loadings that will measure the strain and displacement response of the dome as a function of pressure. At least three potential failure modes exist: Circumferential buckling, biaxial tension and biaxial tension-compression. Valuable data as to which of these modes causes first failure will be obtained, along with data from modern inspection methods such as acoustic emission, video image correlation and laser shearography.

The data obtained from this effort will provide a valuable technology that will greatly assist designers of future aerospace vehicles such as the Reusable Launch Vehicle, future expendable launch vehicles, upper stages, reusable orbital transfer vehicles and future exploration vehicles. Data from this study will also be of use in other applications since it characterizes the behavior of composites under a variety of stress states.

Sponsor: Center Director's Discretionary Fund

University/Industry Involvement: NASA Academy Summer Intern Program

Biographical Sketch: Rafiq Ahmed is a structural analyst and has performed stress analysis on space shuttle and advanced technology hardware.

A Combined Micromechanics, Fracture Mechanics, and Statistical Approach for Life Prediction of CMC/MMC

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In order to save weight and increase performance, advanced rocket systems will continue to make use of ceramic matrix composites (CMC's) and metal matrix composites (MMC's). In order to qualify space flight systems, the useful life of the rocket components must be determined. The analysis tool being developed will determine the useful life of rocket components made with CMC's and MMC's.

The technical objectives of this project include the development of a new analysis technique that combines micromechanics, fracture mechanics and statistical principles to model and predict the mechanical response and failure mechanisms of CMC's and MMC's. The proposed technique uses the coefficient of friction at the fiber-matrix

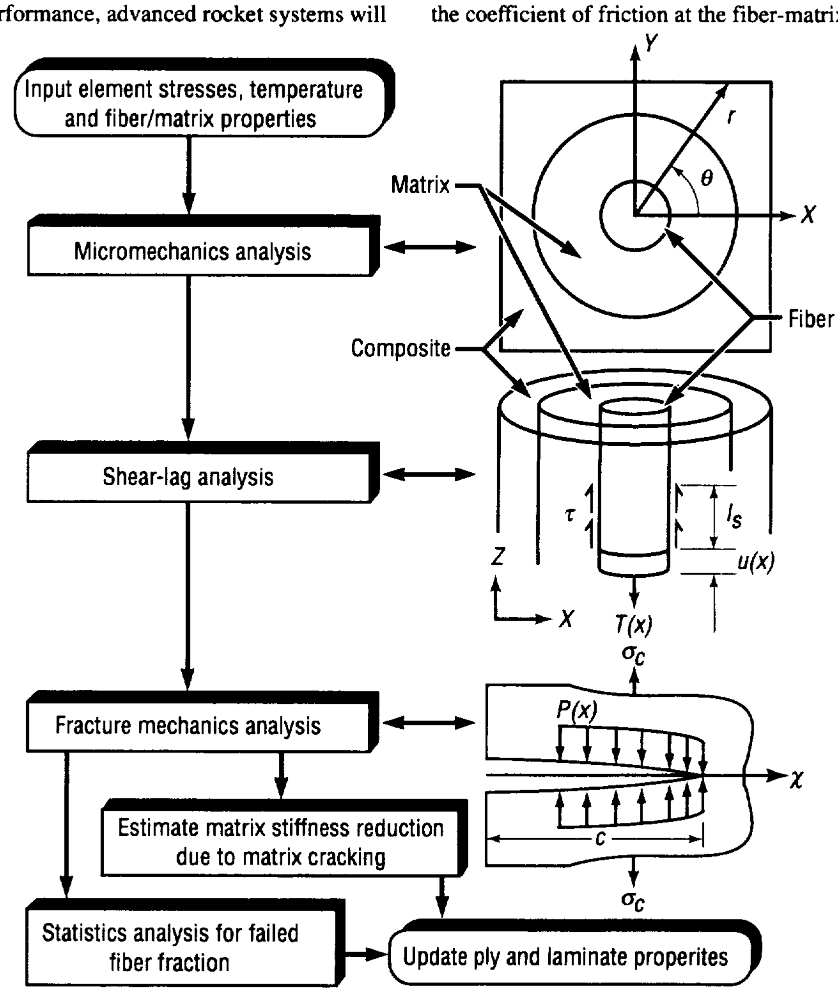

Figure 54.—Flow chart of combined micromechanics, fracture mechanics and statistical approach of composite damage prediction.

interface as the interface parameter which, unlike the interfacial shear stress parameter in the earlier models, can account for the effects of fiber diameter, fiber volume fraction, loading, transverse stress and thermal effects. Thus, a single parameter can now be used to correlate data for different temperatures, fiber volume fractions and loadings, which was not possible with the earlier models.

Phase I result of this project has established an analytical tool for composite damage and life prediction using the techniques described above. Phase I analyses were classical closed-form solutions. Only the material degradation in the fiber direction was considered. A flow chart of Phase I analysis is displayed in figure 54.

The goal of Phase II is for the practical application of the theory. The analytical tool developed in Phase I is applied in the analyses of general structures with multilayer laminates. Finite element analysis has to be applied to the entire structure for obtaining stress and strain information of each element. To predict the failure of a laminate element, the stresses in each ply are estimated by using engineering approaches. The theory developed in Phase I then can be applied to each ply to predict the fiber-failure fraction of each ply. To complete this kind of analysis, one major task is how to estimate the material damage in the off-fiber direction since transverse matrix cracking is the initial damage occurring in the composite ply. In Phase II studies, the volume element damage mechanics (VEDM) model is planned to be used to predict the matrix cracking in the off-axis plies. Figure 55 shows the flow chart of the failure prediction of a laminate element.

The successful completion of this project will result in the development of a new, general purpose analytical tool called CMLife, for the fatigue life prediction of laminated and textile ceramic matrix and metal matrix composites and will, thereby, fulfill a critical need in the design of high-temperature components at NASA and in industry. It will have a menu-driven, point-and-click user interface which will enhance its appeal to engineers and designers at NASA and in industry. Also, it will be seamlessly integrated with a commercial finite element code ABAQUS for life prediction of CMC's and MMC's.

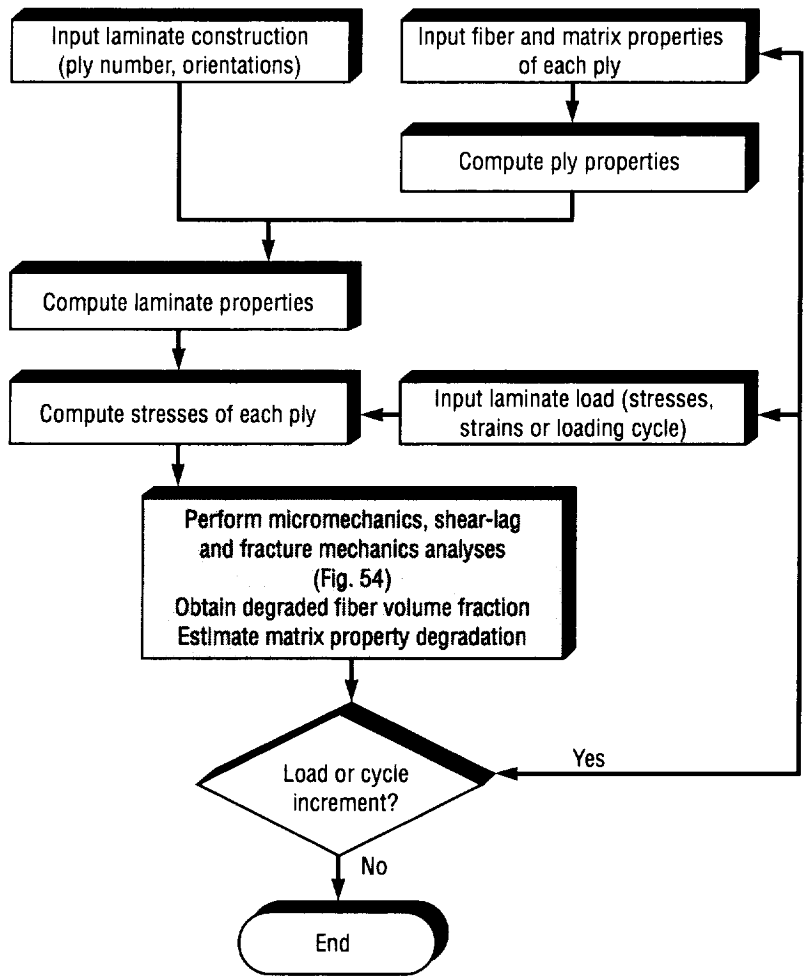

Figure 55.—Flow chart for failure prediction of a laminate element.

Sponsor: Office of Advanced Concepts and Technology; Small Business Innovation Research

Industry Involvement: Analytical Services and Materials, Inc.

Biographical Sketch: Dr. James Min is a member of the Structural Integrity Branch in the Structural Analysis Division of the Structures and Dynamics Laboratory at MSFC. Min joined the Marshall Center in 1989. His current activities include stress, fracture/fatigue, durability and damage tolerance analysis of metallic and composite structures. Min received a B.S. in mechanical engineering from Han Yang University, Seoul, Korea. He also holds a M.S. in engineering mechanics, civil engineering, and materials science and a Ph.D. in mechanical engineering from University of Illinois, Chicago.

Life Prediction Methodology for Ceramic Matrix Composites

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MSFC along with the expertise of LeRC personnel began a program in FY95 with the overall goal of developing, codifying and validating a life prediction methodology for ceramic matrix composite (CMC) engine components. The critical damage mechanisms are being investigated through a large number of interrupted high-temperature cyclic and monotonic tests. The test coupons are being evaluated through both nondestructive and vibratory dampening testing to ascertain the degree of damage. Also, sequential through-the-thickness polishing and microscopical evaluation is performed to determine the ongoing damage mechanisms, measure the crack density and crack size distribution. The effect of time at temperature (i.e environmental stability) is considered by pre-exposing selected specimens to high temperature for an appropriate time prior to testing. The evolving cyclic or time-dependent flaw population and distribution will be quantified, correlated to the nondestructive evaluation (NDE) and used in the analytical modeling. Further cyclic and monotonic data and other material properties of the selected CMC will be obtained by testing and supplemented by literature search where possible. The life prediction code will be validated through subcomponent cyclic and monotonic testing of complex geometries such as bolt holes or notches at appropriate test conditions.

Over the past year LeRC personnel have tested DuPont Lanxide C/SiC 0/90 plain-weave laminate coupon specimens. The tests conducted were elevated temperature tensile, creep, and fatigue tests. Test temperatures were 842 °F, 1,022 °F, and 1,200 °F. Stiffness data was monitored and stored throughout the tests. NDE inspections were performed on selected specimens which were subjected to interrupted testing and repeated inspection. Also, the fractography of failed specimens was initiated. Initial findings show that failure appears to be driven by environmental degradation of carbon fibers for this material. Strength of this CMC degrades rapidly at both 1,022 °F and 1,200 °F. Very little strength degradation was shown at 842 °F which verifies the hypothesis that the ongoing material damage is primarily governed by the failure of the carbon fibers since it is known that the environmental degradation of these fibers becomes negligible below approximately 900 °F. Tests done under cyclic loading showed longer time to failure than creep specimens when tested under similar temperatures and stresses.

One NDE technique being used for these specimens consists of the determination of the specimen's natural frequency as a function of creep exposure. A 1,200 °F stress rupture test was periodically interrupted and the natural frequency of the specimen was measured in a specially designed rig. The test conditions duplicated a previously tested specimen so that the approximate stress rupture life of the specimen was known. The natural frequency measurements were obtained in the as-machined condition prior to the test, 10-, 25-, 50-, 90-, and 100-percent of the estimated life. The actual failure occurred at approximately 125 percent of the estimated life. A decrease in the natural frequency was observed in the early stages of the test. The decrease of the measured natural frequency continued throughout the test. This technique is currently considered cumbersome and time consuming, but it is highly sensitive in detecting the evolution of damage even in its early stages. Natural frequency measurements can be translated into a measurement of the dynamic modulus of the specimen. The degradation of the modulus, which appears to occur in the early stages of testing, can then be used in the analytical life prediction models.

Sponsor: NASA Headquarters, Office of Aeronautics

Biographical Sketch: Rene Ortega has been employed with MSFC's Structural Integrity Branch for 9 years as a structural analyst (AST, Structural Mechanics) where his primary responsibility has been fracture analysis, stress, and fatigue of liquid rocket engine components. Ortega received a B.S. degree in civil engineering and a B.S. degree in architectural engineering from the University of Miami. He also received a M.S. degree in mechanical engineering from the University of Alabama in Huntsville.

Elastic-Plastic and Fully Plastic Fatigue Crack Growth

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The objectives of the elastic-plastic and fully plastic fatigue crack growth (EPFCG) research effort are to develop analytical solutions and computer programs for predicting the fracture life of flawed metallic structures which experience appreciable plastic crack tip stresses. In order to achieve these objectives, work is being focused on research to develop the analytical solutions and crack growth algorithms, as well as software development to extend the capabilities of the NASA/FLAGRO fracture mechanics program.

The research effort for analytical solutions in previous years has resulted in a list of over 20 flaw geometries for which J Integral solutions exist. These elastic-plastic solutions include collected works from the Electric Power Research Institute (EPRI), newly developed solutions combining finite element results and the reference stress method (RSM), and derived solutions using the reference stress method for existing elastic solutions in NASA/FLAGRO. This year, a modified J-integral estimation scheme for cracks at notches has been developed and validated against finite element results. This technique combines the EPRI and RSM estimation schemes to allow computation of J from the linear elastic limit through to the fully plastic limit (net section yielding) for all crack depths.

Research efforts have also concentrated on crack growth algorithms which use the J solutions to assess flaw instability, fatigue crack growth, crack closure, and multiple loading conditions. Most of the research work in the past year has been on algorithms for crack instability of ductile materials. Analytical models were developed which account for the possibility of the combined effects of fatigue crack growth and ductile tearing during cyclic loading. Crack tip zones that experience consistent loading and environmental conditions are assessed with the memory model, while those which experience overload or material changes (toughness) are assessed with the loss-of-memory model. For load cycles that create crack driving forces in excess of the elastic-plastic fracture toughness (material capability), the memory model includes the effects of ductile tearing for a given load cycle (n) only if there is an increase in crack driving force over the previous load cycle (n–1). Otherwise, if there is no increase in crack driving force, then only fatigue crack growth is accounted for in total crack extension during a given load cycle (n). On the other hand, the loss-of-memory model includes ductile tearing for every load cycle which creates crack driving forces in excess of the material capability. These two models significantly extend the capability of flaw growth prediction beyond the brittle fracture assumptions of the past.

In addition to research, a practical tool for assessing real elastic-plastic fracture problems is being created through the extension of the NASA/FLAGRO computer program. Considerable progress has been made in programming the elastic-plastic capabilities for the following NASA/FLAGRO geometries:

- TC01: Through center crack subjected to tension.
- TC02: Through edge crack subjected to tension or bending.
- EC01: Embedded elliptical crack subjected to tension.
- CC01: Corner crack in a rectangular plate subjected to tension or through wall bending.
- SC01: Surface crack in a rectangular plate subjected to tension or bending.

Both through flaw geometries, TC01 and TC02 are complete and have been verified for the plane stress and plane strain RSM solutions. A failure algorithm for calculating critical loads and crack sizes, along with software modules for the other three flaw configuration solutions, is currently in work.

Chell, G.G.: "Fatigue Crack Growth Laws for Brittle and Ductile Materials Including the Effects of Static Modes and Elastic-Plastic Deformation." Fatigue Engineering Material and Structures, vol.7, 1984, pp. 237–250.

McClung, R.C.; Hudak, S.J., Jr.; Bartlett, M.L.; FitzGerald, J.H.: "Growth of Surface Cracks During Large Elastic-Plastic Loading Cycles." Fracture Mechanics: Twenty-Third Symposium, ASTM STP 1189, 1993, pp. 265–283.

NASA/FLAGRO: "Fatigue Crack Growth Computer Program 'NASA/FLAGRO' Version 2.0." NASA, Lyndon B. Johnson Space Flight Center, May, 1994.

Sponsor: Office of Aeronautics

Industry Involvement: Southwest Research Institute, Rocketdyne Division of Rockwell International

Biographical Sketch: Wayne Gregg has been employed with the Structural Integrity Branch for 9 years as a structural analyst (AST, Structural Mechanics) where his primary responsibility has been fracture analysis, stress, and fatigue of liquid rocket engine components. Gregg received a B.S. degree in mechanical engineering from Mississippi State University and an M.S. degree in mechanical engineering from Stanford University.

Base Heating Testing Improvements

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All multi-engine launch vehicles experience heating near the aft end (base) during ascent, induced by the hot exhaust plumes of the propulsion system. These heating environments are important to the vehicle design because they determine the weight, cost, and complexity of the thermal protection system (TPS) for the vehicle base region and engines. This effort developed innovative base heating test techniques and base heating model designs which will dramatically lower test cost, reduce test time, and significantly improve launch vehicle design. Emphasis was placed on using off-the-shelf hardware in designing rather than specialty items. These test improvements are generic and fully adaptable to the X–33 Reusable Launch Vehicle design concept currently selected for a flight demonstration program.

The effort produced a series of products leading to laboratory cold flow demonstration hardware to validate the proposed new testing innovations as illustrated in figures 56 and 57. The X–33 propulsion system and geometry data were reviewed to develop base heating testing requirements. Potential test facilities were evaluated and a cost benefit analysis was performed for each facility. A new test hardware design specification spread sheet analysis method was developed and utilized for a generic design application. A transient hot firing analysis PC-based code was implemented to verify the transient start-up behavior of the chosen generic design. An AutoCad solid model of the new selected design was produced based on the design specifications spread sheet. This solid model was used by the Alabama Industrial Development Training Center to produce a rapid prototype of the internal flow passages using stereolithography. Visual inspection and measurement of this solidified resin physical model verified the AutoCad solid model design. A new simpler nozzle gimbal mechanism was devised, designed and verified using the rapid prototyping method. A demonstration cold flow model was then

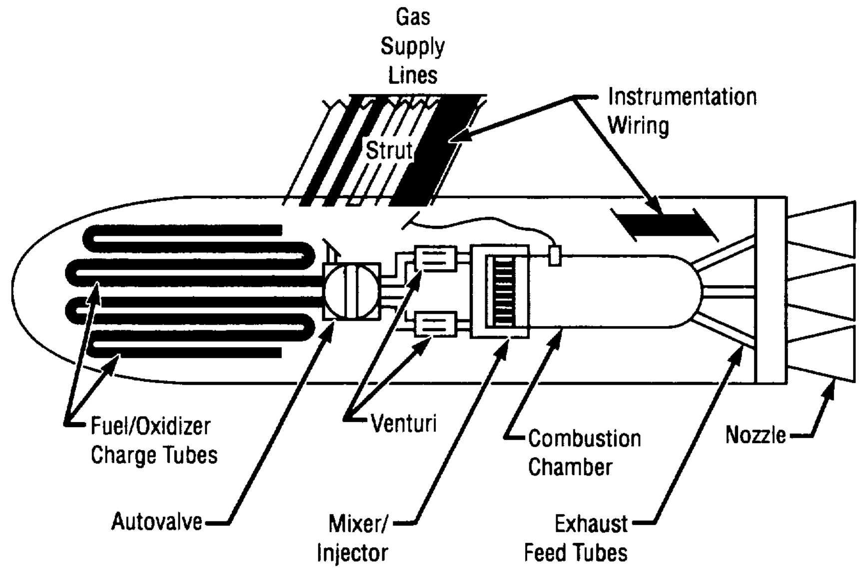

Figure 56.—Existing short duration hot flow propulsion simulation system.

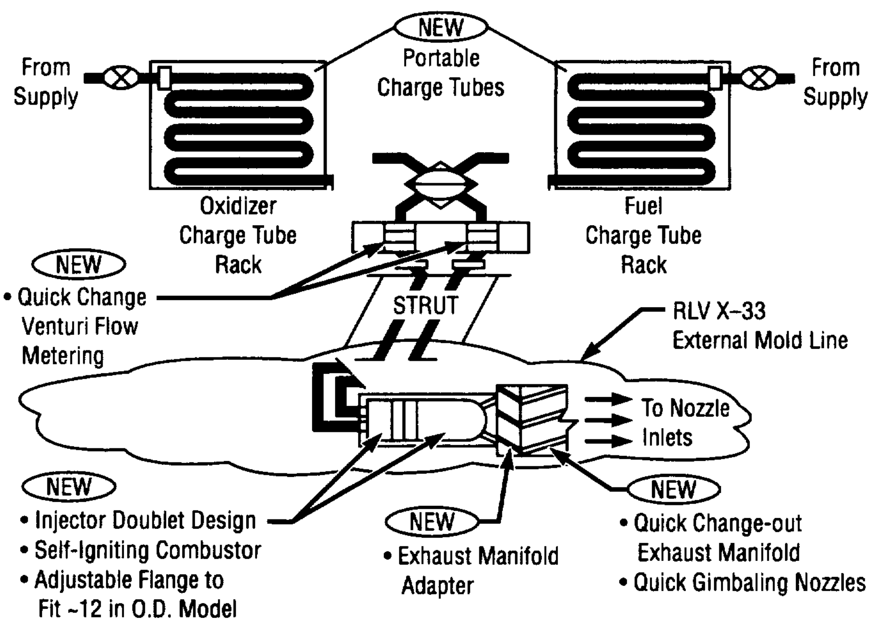

Figure 57.—Innovative Qualis short-duration hot flow propulsion simulation system.

designed, fabricated and tested. The test results provided the experience and evidence that hot flow tests could be accomplished quicker and much cheaper. Primary findings included:

- Flexible off-the-shelf tubing was found easy to work with and provided an excellent charge tube. Internal variations with the charge tube diameter had no effect on charge tube performance;
- A buffer gas can be used to shorten the hydrogen tube as demonstrated by the nitrogen buffer gas used with helium. External charge tubes reduce model complexity and cost;
- Long run times of 100 to 150 msec have been demonstrated with the current charge tubes compared with 30 to 60 msec in the past. The low cost and low volume of coiled charge tubes makes almost any run time feasible. Thus, increasing the reliability of base heating test data;
- A current off-the-shelf solenoid valve with an opening time of approximately 20 msec appeared to be quite adequate to control the charge tube flow. This eliminates the need for costly one-of-a-kind auto valve designs for new launch vehicle concepts;
- Experience showed that a simple six-bolt attachment method provided a quick and simple method for making model modifications; and
- The data obtained demonstrated that a two-dimensional flow aerospike geometry can be supplied from a central manifold even when fine geometric tolerances are involved. Multiple axisymmetric conventional nozzle firings had been demonstrated previously.

Short-duration hot flow testing can be the cost effective testing technique of the future for a variety of plume, base heating, plume impingement, combustion studies and computational fluid dynamics (CFD) verification work.

Sponsor: Small Business Innovative Research

Industry Involvement: Qualis Corporation

Biographical Sketch: Dr. Seaford is an engineer in the Fluid Dynamic Analysis Branch at MSFC's Structures and Dynamics Laboratory. He is currently responsible for generating launch vehicle base thermal design environments and developing improved plume flowfield and plume-induced environments methodology. He is currently responsible for defininining X–33 and X–34 thermal design environments. Seaford earned his Ph.D. in aerospace engineering from the North Carolina State University, Raleigh, NC, in 1983 and has been employed by NASA for the last 12 years.

Propulsion Chemistry for CFD Applications

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In order to perform combustion analyses for advanced propulsion systems, the thermodynamic properties of the fuel, oxidizer, and all significant combustion products must be available. Conventional hydrocarbon propellants, such as RP–1, pose a difficult challenge because of the many species which are involved. Even small amounts of soot which can be formed cause severe heating and surface deposition problems. Data for many species are already available in literature, but many are not. Most of the data are for low pressure only (ideal gases). SECA, Inc. has developed a real fluids model for generating thermal and caloric equations of state and predicting transport properties suitable for direct use in computational fluid dynamics (CFD) analyses of finite-rate combustion processes. Prior to the advent of CFD design methodology, experimental property values alone were used for design purposes.

SECA's real fluids model utilizes ideal gas properties as a basis upon which dense gas, liquid, and multi-phase effects are added to cover the entire range of propellant properties. The individual correction equations have been carefully selected to provide highly accurate predictions over a wide range of conditions while requiring a minimum of information for the individual species. The multitude of experimental data and previous estimation techniques available in the literature substantiate this procedure for producing accurate estimates of properties for well defined mixtures of pure species.

When applied to actual fuels, such as RP–1, additional complications must be considered. RP–1 is compromised of literally hundreds of species, which vary in quality from lot to lot of fuel. SECA has purchased chemical analyses of RP–1 samples (since such data were not found in the literature) to provide a representative set of species which comprise this fuel. These species were then represented by a surrogate which matched species type and molecular size with a modest number of neat hydrocarbons. The RP–1 surrogate was then simulated with the real fluids code. The results predicted with the thermal equation of state are presented in figure 58. This simulation provides not only accurate thermodynamic properties, but also realistic species for subsequent estimation of combustion kinetics, including soot formation and oxidation.

Applications of the real fluids model to the analyses of advanced launch systems are in progress. Future applications to JP and diesel type fuels and pulverized coal combustion are envisioned. The real fluids model may be used as a subroutine in a CFD code, as a stand-alone code to predict fluid properties, or as a means to provide tabulated thermodynamic and transport property data for convenient use.

The thermodynamic property routines developed in this investigation allow accurate prediction of combustion processes under a wide range of operating conditions and for the propellants expected to be used in the advanced launch vehicles now being designed. The use of these property routines with CFD design methodology will result in more economical and timely designs.

Sponsor: SECA, Inc., Huntsville, AL

Biographical Sketch: Kevin Tucker is currently a member of the computational analysis team in the Fluid Dynamics Analysis branch. He received his M.S. degree from the University of Alabama in Huntsville in 1992. His recent work is focused on application of CFD methods for rocket engine combustion devices.

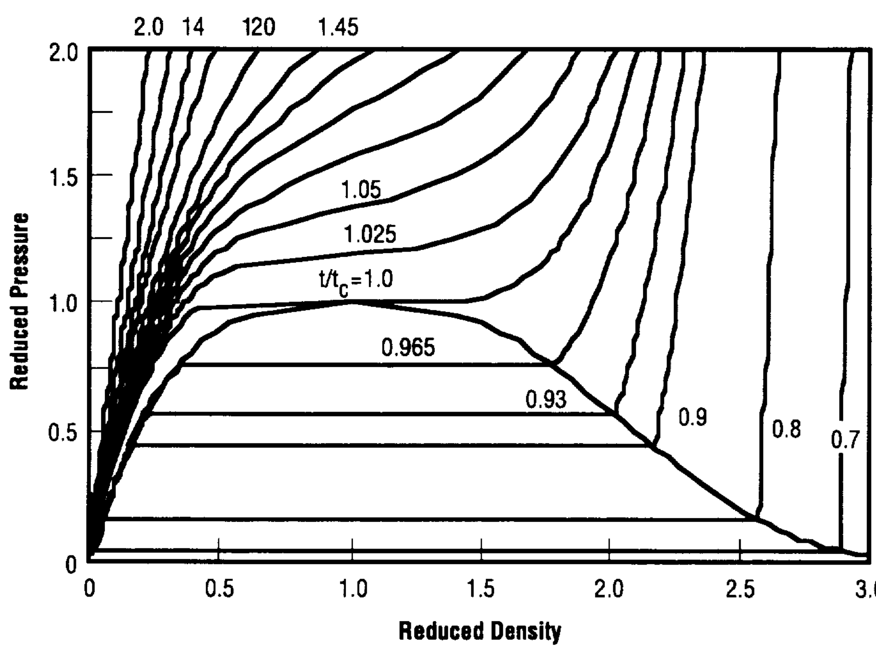

FIGURE 58.—RP–1 thermal equation of state predictions.

Analysis of Flowfields Over Four-Engine DC–X Rockets

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The objective of this study is to validate a computational fluid dynamics (CFD) methodology for the aerodynamic performance of an advanced conical launch vehicle configuration, the Delta Clipper-Experiment (DC–X) rocket, with emphasis on multiple-engine plume-on effects. Both wind tunnel and flight test data are used for validation. Computational base-drag characterization in the critical subsonic regime is the main goal since until recently, almost no multiple-engine data exists for a conical launch vehicle configuration.

For launch vehicles using clustered engines, it is well known that the base environment significantly affects the overall drag and integrity of these vehicles. Hence, it becomes very important to be able to predict the base drag during the vehicle design phase. While empirical equations, wind tunnel and historical flight test data are still an integral part of the design process, CFD-based methods have emerged as a new tool. The DC–X tests are unique in that the flight vehicle and the cold-flow model have satisfied the basics of the scaling law and can therefore complement each other's limitations in terms of the measurement. A systematic validation process of both tests is an opportunity to further prepare CFD as a powerful design tool to support future X–33 reusable launch vehicle aerodynamic performance characterization and vehicle design refinement and optimization.

A three-dimensional, viscous flow, CFD design code FDNS is used for this purpose. While previous benchmarks[1] covered a range of nozzle exit-to-ambient-pressure-ratio from 5 to 510, this work covers the critical lower spectrum of pressure-ratio

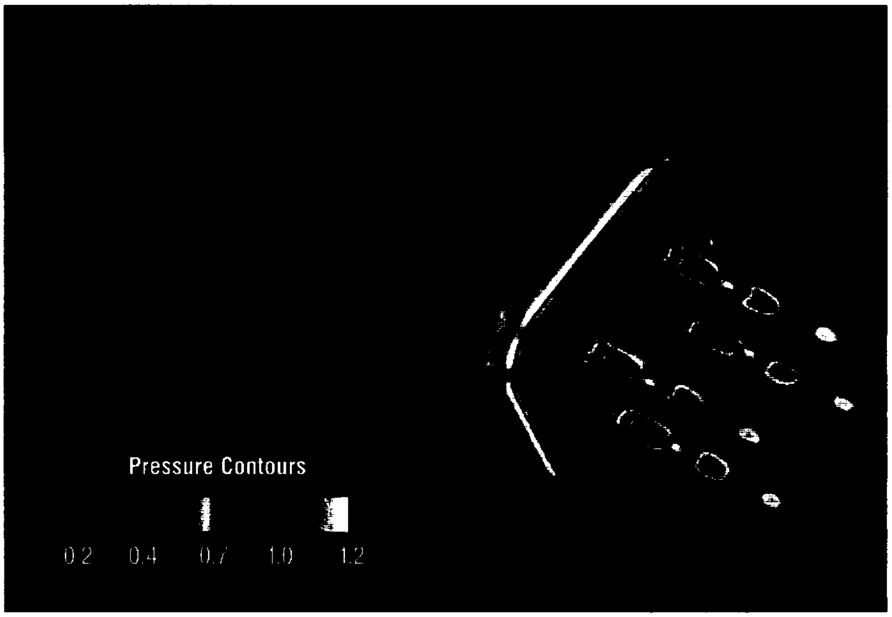

FIGURE 59.—The computed DC–X ascent flight test pressure contours.

from 1.2 to 1.7. Parametric studies using high-order difference schemes are performed for the cold-flow tests while finite-rate afterburning chemical kinetics are used for the flight tests. The computations are performed on MSFC's CRAY-YMP and CRAY-Trident machines.

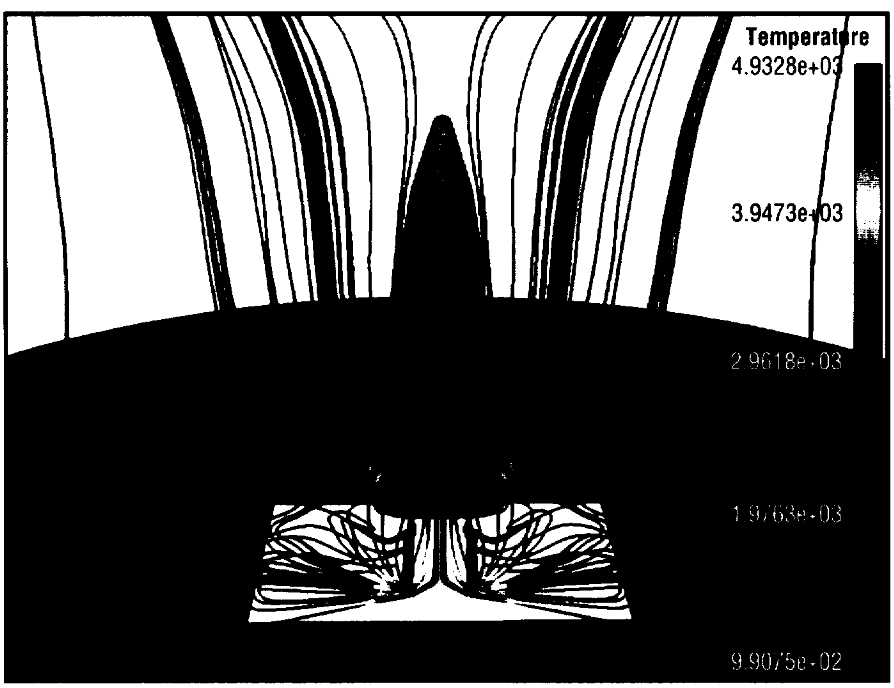

FIGURE 60.—The computed particle traces (colored by temperature) for DC–X landing on grate.

The computed DC–X ascent vehicle total drag, forbody and aftbody and base-surface pressure coefficients compared favorably with those of the test data. The result demonstrates that with adequate grid density distribution, high-order difference scheme, finite-rate afterburning kinetics to model the plume chemistry, and an appropriate turbulence model to describe separated flows, plume/air mixing, and boundary layers, the CFD methodology can be used to predict low-speed aerodynamic performance for reusable rocket designs. In addition, FDNS is also benchmarked for the DC–X in-ground effects. Reasonable base heat flux and aerodynamic force are predicted and compared to the flight tests. This validated computational methodology is later used to study the flow anomaly of DC–XA landing on grate.

[1]Wang, T.S.: "Grid-Resolved Analysis of Base Flowfield for Four-Engine Clustered Nozzle Configuration." *Journal of Spacecraft and Rockets*, vol. 33, no. 1, Jan.–Feb. 1996, pp. 22–29.

Sponsor: McDonnell Douglas—NASA Marshall Space Flight Center Cooperative Agreement for Reusable Launch Vehicle/ X–33 Technology Development Program

Biographical Sketch: Dr. Ten-See Wang is currently a team leader of the Computational Analysis Team in the Fluid Dynamics Branch. He received his Ph.D. degree from Louisiana State University in 1980. He had previously been affiliated with SAIC, Continuum, SRA, and SECA, Inc.. His recent work has been applying CFD methods for propulsion system and launch vehicle environment.

Thermokinetics Characterization of Kerosene/RP–1 Combustion

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Russian-built kerosene-fueled rocket engines such as RD–170 or its U.S.-proposed counterparts such as RD–704 or the Bantam engine series, have been identified as potential candidates to fly the single-stage-to-orbit reusable launch vehicles. In order to support the associated engineering issues, especially the preliminary conceptual design and evaluation of the propellant injectors and thrust chambers using computational fluid dynamics (CFD), accurate and computational efficient models that properly represent the fuel formula, thermodynamics, and combustion kinetics have to be used. Unfortunately, models pertaining to those aspects were underdeveloped.

In this study, based on reported physical-chemical property data, a one-formula surrogate fuel is proposed as a general representation for kerosene and its derived fuels, RP–1 in particular. Its heat capacity, enthalpy and entropy are generated based on available data base and the proposed surrogate fuel formula. The resultant surrogate fuel model and its thermochemical properties are verified by comparing a series of one-dimensional rocket thrust chamber theoretical performance calculations under Russian Engine RD–170 operating conditions. The computed chamber and nozzle exit temperatures and species compositions from the proposed model compared very well with those of using its elemental formula and those from literature. A kerosene/RP–1 combustion kinetics is also proposed based on a quasiglobal kinetics format. Following that format, two global steps are proposed: one for the paraffin portion and another for the naphthene part of the surrogate fuel. The rates of the two global steps are modified directly from those of the straight chain and cyclic global steps according to the paraffin and naphthene split of the proposed surrogate fuel model. A global step making soot directly from the surrogate fuel is also proposed, along with a soot oxidation step originated from a heterogeneous reaction model. The quasiglobal combustion kinetics is closed with a conventional CO-wet mechanism.

The proposed thermal-kinetics models are incorporated into a CFD code, FDNS, for computing the thermo-flowfields of an unielement coaxial-type tripropellant (liquid RP–1/gaseous hydrogen/ gaseous oxygen) injector test performed at the Cryogenic Combustion Laboratory located at Pennsylvania State University. The multiphase FDNS solves simultaneous liquid-droplet-gas dynamics by combining the volume-of-fluid and Eulerian/Lagrangian tracking methods into a unified algorithm for efficient calculations of multiphase free surface and droplet flows at all speeds. The computation predicted reasonable flame structure and combustion efficiency as observed and measured from the test. The thermokinetics model developed in this study is being used to support the Bantam engine development effort.

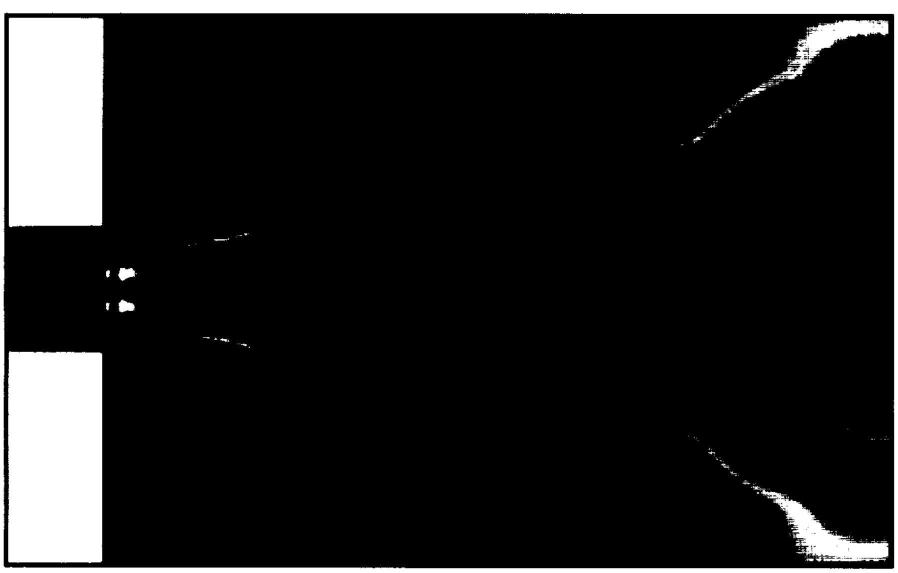

FIGURE 61.—The computed unielement tripropellant injector temperature contours.

Sponsor: Rocketdyne—NASA Marshall Space Flight Center Cooperative Agreement for Reusable Launch Vehicle/X–33 Technology Development Program

Biographical Sketch: Dr. Ten-See Wang is currently a team leader of the Computational Analysis Team in the Fluid Dynamics Branch. He received his Ph.D. from Louisiana State University in 1980. He had previously been affiliated with SAIC, Continuum, SRA, and SECA, Inc. His recent work has been applying CFD methods for propulsion system and launch vehicle environment.

Injector Spray Combustion Modeling

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Injector design and combustion chamber compatibility are among the key technologies in developing a new generation of cost effective high thrust-to-weight ratio propulsion systems for the reusable launch vehicles. A design analysis tool for predicting the complex combustion flowfield near the injector plate can be very useful for the engine design team in enhancing the engine performance leading to increased thrust-to-weight ratio.

The main objectives of this project is to synthesize relevant state-of-the-art physical sub-models into an advanced computational fluid dynamics (CFD) code for modeling spray combustion using proven methodologies and to validate the related numerical and physical models systematically against available experimental data from the open literature and other ongoing test programs. The physical models include turbulence/droplet interaction, dense spray atomization, interphase transport, chemical reaction, droplet sub/super-critical vaporization and combustion. A state-of-the-art volume-of-fluid (VOF) method for spray atomization and combustion is developed. Droplet atomization/breakup mechanism along the gas-liquid interfaces is modeled by empirical correlations applicable to coaxial injector elements. A robust point implicit finite-rate chemistry module is also employed to model the gas-phase chemical reactions.

Benchmark validation test cases for water spray and hot-flow spray combustion flows were investigated to validate the present numerical model. Good results were obtained in the validation processes. Applications of the present technology to the liquid rocket engine injection systems have also shown promising results. It is expected that the presented technology will be developed into a user-friendly design tool to be incorporated in the liquid rocket engine industry and many other commercial and government industrial applications.

In summary, a computational spray combustion technology has been developed for liquid rocket engine chamber flow analysis. An injector spray combustion design tool will be developed into a commercial product which will allow the present technology to be widely used by the industry.

Sponsor: Engineering Science, Inc., Huntsville, AL

Biographical Sketch: Dr. Ten-See Wang is currently a team leader of the Computational Analysis Team in the Fluid Dynamics Branch. He received his Ph.D. from Louisiana State University in 1980. He has previously been affiliated with SAIC, Continuum, SRA, and SECA, Inc. His recent work has been focusing on applying CFD methods for propulsion system and launch vehicle environments.

Real-Time Condition Monitoring of Propulsion Systems Through High-Performance Computing

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MSFC is responsible for the testing and diagnosis of both current and future NASA propulsion systems including the Space Shuttle Main Engine (SSME) and the Redesigned Solid Rocket Motor (RSRM). During the development of the SSME, significant progress has been made within NASA and across the aerospace community in improving the diagnostic evaluation of high-frequency dynamic data. Fast and reliable evaluation of such data is crucial to the Space Shuttle Operations Program since such study is invaluable in preventing catastrophic engine hardware failures. Moreover, reliable engine system diagnostic evaluations can extend the scheduled maintenance intervals for major engine components such as high-speed turbopumps. Such dynamic assessment is very challenging due to the computational and manpower intensive nature of the dynamic signatures taken from various engine locations. Current SSME dynamic data processing and evaluation is done post-flight or following ground test (at both engine and component level), with a typical diagnostic turnaround time of 1 or 2 days. This "diagnostic lag time" must be eliminated if real time diagnosis of engine systems is ever to become a reality. A true real-time condition monitoring system must be capable of acquiring great volumes of high-frequency data containing complex and frequently subtle dynamic attributes which then must be successfully analyzed for correct test article diagnosis. The health monitoring system must utilize conventional signal processing, recently developed dynamic signal classification technology (i.e. nonlinear signal analysis), dynamic data compression/extraction methods, and unsupervised statistical classification methods. Development of such a real-time condition health monitoring system which effectively integrates dynamic data attributes is very challenging due to data bandwidth requirements, algorithm computational intensity, and cross-channel communications. However, the expected savings and improvement in overall real-time diagnostic capabilities make the development effort well worthwhile.

Even with the significant improvements in propulsion system dynamic data evaluation methods achieved over the past decade within the NASA/contractor community, there exists a great potential for advancement in the performance of the health monitoring function. The dynamic data evaluation function must be improved upon by:

- Reducing overall propulsion system diagnostic turnaround time;
- Cutting analysis manpower requirements;
- Including complex (i.e. nonlinear) dynamic data attributes in every diagnostic assessment;
- Eliminating end-to-end data processing discrepancies/variances at remote end users;
- Implementing dynamic indicators from test articles as on-line test control "redlines"; and
- Ending reliance on analog tape data backup.

In brief, NASA/MSFC's next generation dynamic data analysis system must be faster, better, and cheaper than its predecessor in order to become an integral part of a total real-time health monitoring system.

In an effort to overcome the limitations of current dynamic data acquisition, reduction, and evaluation efforts within the NASA/MSFC community, both short- and long-term goals have been identified. In the short term, a real-time dynamic data system capable of simultaneously acquiring at least 100 channels of high-frequency data with an initial analysis bandwidth of 20 kHz must be developed. This baseline system must be capable of extracting conventional dynamic attributes (i.e. power spectral density (PSD) domain indicators) from the monitored signals. These recovered attributes from the input data channels, along with raw-time varying signals, must be available for real-time display, test control, and immediate post-test analysis. Moreover, all data must be immediately archived for further post-test processing and trend analysis efforts. With the successful implementation of the baseline large-scale digital signal processing (LDSP), system efforts will then focus on the integration of recently developed signal processing "tools" which draw pertinent, yet subtle dynamic attributes from the monitored high-frequency data channels. A majority of these "tools" involve nonlinear signal analysis, which has consistently proven invaluable in failure mode identification. The nonlinear "tools" effectively exploit hidden nonlinear phase relationships within the spectra of acquired high-frequency dynamic data. These relationships are key in determining signal structures indicative of propulsion system/system component fault modes. Finally, with the successful integration of all dynamic data signal processing "tools" (including both conventional and nonlinear analysis) into the real-time LDSP system, efforts will be focused on integrating generated test article dynamic performance parameters with traditional operational parameters (i.e. pressures, temperatures, flow rates) into one comprehensive health monitoring system. Such an effort will not only rely on the effective extraction of the complex dynamic data attributes in real-time but also their compression and statistical classification.

NASA/MSFC has been provided an exceptional opportunity in working with the Air Force community in the development of a real-time LDSP system for the monitoring and analysis of propulsion article high-frequency dynamic data. Through an intra-agency technology utilization agreement, Arnold Engineering and Development Center (AEDC) has agreed to share with NASA/MSFC the technology associated with its highly successful computer assisted dynamic data monitoring and analysis system (CADDMAS) used in the support of gas turbine engine testing. CADDMAS effectively utilizes high-performance computing technology in performing real-time dynamic data acquisition and reduction. In return, NASA has agreed to share all resulting system upgrades resulting from the integration of MSFC diagnostic code to the baseline CADDMAS. Hopefully, the AEDC community will find the updates useful in their diagnosis of flight hardware along with their plant support equipment. Moreover, the NASA/MSFC dynamic data analysis community is fortunate in having the opportunity to work with the enabling software technology behind the CADDMAS solution. This technology contained in the multigraph architecture (MGA) developed by the Measurement and Control Systems Laboratory of Vanderbilt University[1] has been of great value to MSFC in the integration of proven NASA/MSFC diagnostic "tools" into the baseline CADDMAS. Key aspects of MGA, such as the structural adaptivity of the execution environment, a necessity for a real-time health monitor, are very important to NASA/MSFC. Key features of the MGA which underlay CADDMAS are allowing for substantial cost savings in the conversion of NASA/MSFC diagnostic code to the already proven test support system.

As previously discussed, NASA/MSFC is integrating high-frequency dynamic data diagnostic code into CADDMAS. Digital signal processing code, including both conventional and recently developed nonlinear applications,[2,3] have been successfully executed in real-time. Complex high-frequency analysis tools such as synchronous tracking and bicoherence are currently being used online to support SSME advanced turbopump development efforts. Such tools are invaluable in determining specific hardware failure modes such as turbomachine rolling element bearing flaws or cavitation via induced oscillations in propellant pumps.

In summary, high-performance computing can open the "bottleneck" associated with the evaluation of propulsion system high-frequency diagnostic data. NASA/MSFC, AEDC, and Vanderbilt University are converging on a cost-effective solution for an online condition health monitoring system which combines high-performance/distributed processing computing technology and MSFC-developed diagnostic expertise. Currently, a prototype version is successfully supporting SSME alternate high-pressure fuel turbopump development efforts at both the full-scale engine hot-fire and component test level.

[1]Sztipanovits, J.; Wilkes, D.; Karsai, G.; Biegl, C.; Lynd, L.: "The Multigraph and Structural Adaptivity." IEEE Transactions on Signal Processing, vol. 41, no. 8, August 1993, pp. 2695–2716.

[2]Jong J.; Jones J.; Jones P.; Nesman T.; Zoladz T.; Coffin T.: "Nonlinear Correlation Analysis for Rocket Engine Turbomachinery Vibration Diagnostics." 48th Meeting of the Mechanical Failure Prevention Group (MFPG), April 1994.

[3]Jong, J.; Jones, J.; McBride, J.; Coffin, T.: "Some Recent Developments in Turbomachinery Fault Detection." NASA 1992 Conference on Advanced Earth-to-Orbit Propulsion Technology, May 1992.

Sponsor: Space Shuttle Main Engine Project Office

University/Other Involvement: Arnold Engineering and Development Center (USAF); Vanderbilt University (Measurement and Controls Systems Laboratory)

Biographical Sketch: Tom Zoladz is an engineer working in the Fluid Dynamics Analysis Branch of the Structures and Dynamics Laboratory of Marshall Space Flight Center. He supports the characterization of unsteady flow environments within several of the propulsion systems under supervision and development at MSFC. Some current tasks include the analysis of a cavitation induced oscillation in the SSME high-pressure fuel turbopump and characterization of combustion stability in advanced hybrid rocket motors. He graduated from the University of Tennessee in 1987 with a B.S. in mechanical engineering.

Tony Fiorucci is an aerospace engineer with the Structural Dynamics and Loads Branch of the Structures and Dynamics Laboratory at Marshall Space Flight Center. He specializes in evaluation and characterization of vibration environments for both flight- and ground-test propulsion systems supervised by MSFC. His current and primary tasks include assessment/qualification of all vibration data acquired in support of the development, certification, and flight programs for the Space Shuttle Main Engine Project. Fiorucci graduated with a B.S. in engineering mechanics from the University of Tennessee in 1988.

Application of Rapid Prototyping Methods to High-Speed Wind Tunnel Testing

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The aerodynamic characteristics of a vehicle are among the initial inputs in the design studies for future launch vehicles. These initial studies can be more accurate if high-fidelity aerodynamic information is available for the configurations under consideration. The quick turnaround normally required for these design studies along with cost precludes wind tunnel testing's availability for early design phases. Using rapid prototyping (RP) methods and materials to fabricate wind tunnel models has resulted in a quick turnaround capability via wind tunnel testing to provide higher-fidelity aerodynamic characteristics early in the initial design phases.

A study undertaken at MSFC's 14-in trisonic wind tunnel, funded as Center Director Discretionary Fund project 96–21, has shown that rapid prototyping methods and materials can be used to fabricate wind tunnel models of sufficient quality to produce satisfactory aerodynamic characteristics over the subsonic, transonic, and supersonic Mach ranges for limited configurations.

This study was undertaken to determine if rapid prototyping methods could be used in the design and manufacturing of high-speed wind tunnel models in direct testing applications. It was also done to determine if these methods would reduce model design/fabrication time and cost while providing models of high enough fidelity to provide adequate aerodynamic data and

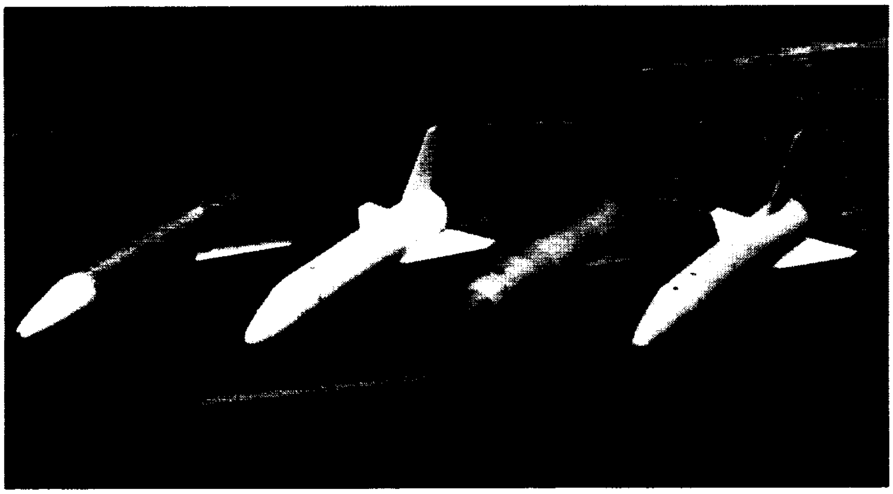

Figure 62.—Models used in rapid prototyping wind tunnel model study. Left to right: SLS, SLA, FDM-ABS, Al.

of sufficient strength to survive the test environment. Rapid prototyping methods utilized to construct wind tunnel models were fused deposition method (FDM) using both ABS plastic and polyetherether ketone (PEEK) as materials; stereolithography (SLA) using the photopolymar SL-5170 as a material; selective laser sintering (SLS) using glass reinforced nylon as a material; and laminated object manufacturing (LOM) using both plastic and wood as materials. The models produced that were of sufficient quality, FDM-ABS, SLA, and SLS were tested. These configurations were tested at subsonic, transonic and supersonic speeds, Mach 0.3 to Mach 5.0. A wing/body/tail configuration was chosen for this study. A comparison of results from models constructed using these rapid prototyping methods was made with results from a standard machine-tooled metal model constructed of aluminum. The plan was to determine if the aerodynamic characteristics of a generic vehicle would be effected by surface finish or other material properties. Also studied were the ease of manufacture and the wearability of the parts as compared to a standard metal wind tunnel model.

The results from this study showed relatively good agreement between the SLA model, the metal model with a replacement FDM-ABS nose and the metal model for the majority of operating conditions, while the FDM-ABS data diverged at higher loading conditions. Data from the initial SLS model showed poor agreement due to problems in post processing, which resulted in a different configuration than the other models. The data from the second SLS model tested showed good agreement with the other models. It can be concluded that rapid prototyping models show promise in preliminary aerodynamic development studies at subsonic, transonic, and supersonic speeds.

Springer, A.; Cooper, K.: "Application of Rapid Prototyping Methods to High Speed Wind Tunnel Testing." Proceedings of 86th Semi-annual Meeting Supersonic Tunnel Association, October 1996.

Springer, A.; Cooper, K.; Roberts, F.: "Application of Rapid Prototyping Models to Transonic Wind Tunnel Testing." AIAA 97–0988, 35th Aerospace Sciences Meeting, January 1997.

Springer, A.; Cooper K.: "Comparing the Aerodynamic Characteristics of Wind Tunnel Models Produced by Rapid Prototyping and Conventional Methods." AIAA 97–TBD, 15th AIAA Applied Aerodynamics Conference, June 1997.

Springer, A.; Cooper, K.: "Application of Rapid Prototyping Methods to High Speed Wind Tunnel Testing." NASA TP–TBD, January 1997.

Sponsor: Center Director's Discretionary Fund

Biographical Sketch: Anthony Springer is an aerospace engineer at NASA Marshall Space Flight Center responsible for launch vehicle aerodynamics and wind tunnel testing. He received his B.S. in aeronautical and astronautical engineering at the University of Illinois.

Ken Cooper is a materials engineering technician in the materials lab responsible for the operation and development of the FDM rapid prototyping process. He received an associate's degree in mechanical engineering from Wallace State College in Hanceville, AL.

Fault Tolerant Aerospace/ Commercial Heat Exchanger

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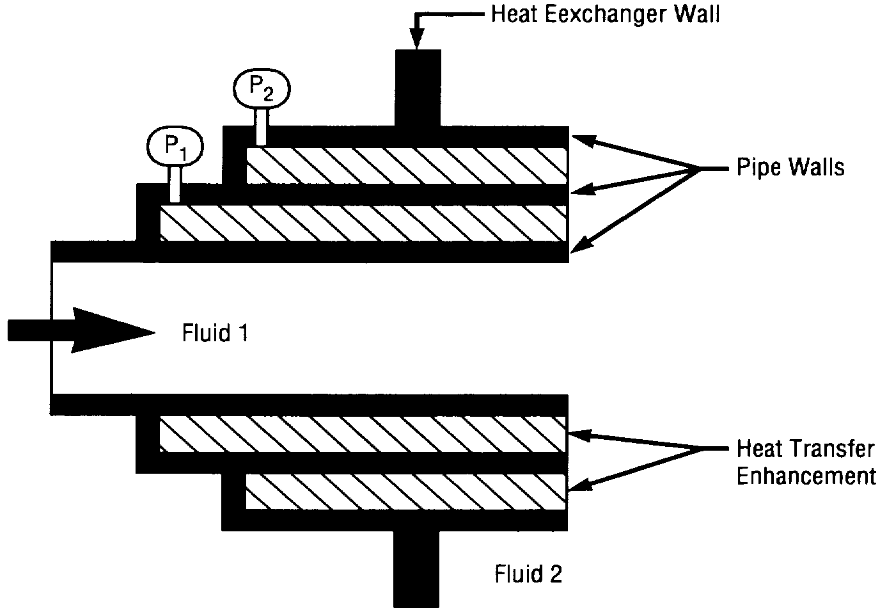
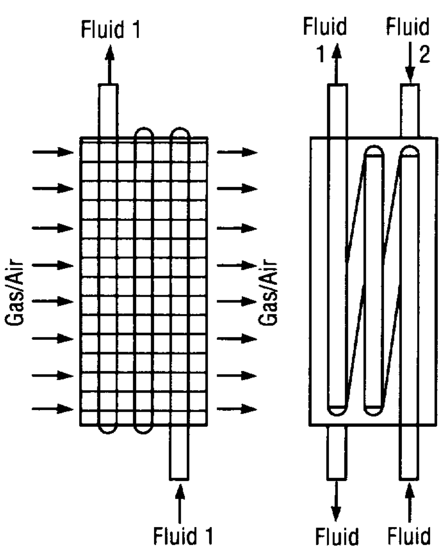


FIGURE 64.—Two fault-tolerant heat exchanger tube design.

In most all fluid heat transfer systems, a device, or heat exchanger, must be included which rejects heat from one portion of the system to another. The heat exchanger provides two functions. It is both a connection and barrier to the heat collection and heat rejection portions of the thermal control system (TCS). More often than not, multiple fluids, as shown in figure 63, are utilized in the system for reasons of efficiency which may cause safety and/or reliability problems.

Essentially two failure modes exist, a breach to the environment (i.e. a fluid may be toxic if released into the environment) or a system breach across the two heat transfer loops (i.e. two fluids are utilized which are hazardous when mixed). If the first failure mode is of concern, then often-added reliability must be incorporated to ensure that the second failure mode discussed does not also cause the first—release to the environment. This might be the case if materials were not compatible with both fluids or if large mismatches in design pressure were present. In order to accomplish isolation, strict attention must be given to these types of factors often resulting in high system costs. A rather simple solution to the aforedescribed problem is a fault-tolerant heat exchanger.



Fluid designation can be in liquid or gaseous form.

FIGURE 63.—Typical heat exchanger design.

The proposed device will allow TCS fluids to be utilized in different portions of the system which are neither chemically compatible nor have similar operating pressures. By increasing the number of barriers across the single device, required isolation is relieved at other sections of the loop, thereby increasing the reliability with minimal impact to cost, weight and efficiency.

By incorporating additional barriers in the heat exchanger only, additional failures can be tolerated at the interface allowing less attention to the system as a whole. An example design, shown in figure 64, allows for two failures with no operational impact to the system. At the fluid interface, multiple structural barriers are added, which in this case are pipes. The void between each pipe can then be filled with a variety of heat transfer enhancement materials to maintain the thermal efficiency of the device.

An additional benefit exists if the voids are also filled with a gas charged at a different pressure than either system operating pressure. By gas charging the voids instrumentation can also be applied which will allow failure monitoring to occur at the interface. This would be advantageous in systems which require a planned shutdown and heat exchanger failure is a concern. For these systems, monitoring for failures allows the system to continue operation (after one or more failures have occurred) until the system can be shut down by the required procedure.

The proposed design approach can be applied to essentially any heat exchanger design (shell and tube, thin wall, etc.) offering the possibility of increased system performance in a variety of areas where fluid release/mixing/design pressure is a concern. The multiple barriers allow less detailed attention to the total system design and may also decrease costs by improving reliability.

Sponsor: MSFC/Environmental Control Branch

Biographical Sketch: Jon Holladay is a thermal engineer in the Environmental Control and Life Support Branch. He earned his bachelor and master of science degrees at the University of Alabama.

Investigation of a Jet Pump-Based Two-Phase Thermal Control System

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A two-phase thermal cooling (TCS) system that has been under study recently (fig. 65) for use in aerospace (or commercial) applications incorporates a jet pump. This system offers several advantages over conventional two-phase pumped loops. Its most significant advantage is that electrical power is only needed to initiate the flow of coolant in the loop. Once flow is initiated, the waste heat is used to drive the flow around the loop.

The primary purpose of this Center Director's Discretionary Fund (CDDF) project is to investigate jet pump-based two-phase heat rejection systems. This investigation will demonstrate whether this type of system is practical for use in aerospace applications.

In order to investigate and quantify the performance attainable by a jet pumped system, design, fabrication and testing of a two-phase heat rejection flow loop apparatus is proposed (fig. 65). This apparatus will initially be used to verify previous research[1] and then modified to gain practical experience as well as design data for related hardware.

Over the last year a significant amount of research has been completed. The initial thrust of the project included gathering technical information on jet pumps and their applications. Over 100 articles were reviewed and a data base generated for reference purposes.

Three analytical methods were selected for simulating the jet pump. This approach provides many benefits including:

- Timely data required for design;
- Backup if the other methods stall;
- Analytical verification (independent analyses); and
- A better understanding of the physics of the flow than provided in previous papers.

The three analytical methods chosen were:

- Homogeneous equilibrium model (HEM): This model is based on the previously referenced Russian-sponsored work done by Fairuzov.[1] The model uses one-dimensional, two-phase flow initially assuming isentropic-homogeneous expansion with corrections for friction loss using velocity coefficients. This model can be easily integrated into a flow loop model for the iterative procedure necessary to solve the set of equations that characterize the overall two-phase system.
- Two-dimensional axisymetric computational fluid dynamic (CFD) models, fluid dynamic analyses package (FIDAP). The CFD model provides the capability to perform detailed performance evaluations of the pump including parametrics in two dimensions. It also allows the flow characteristics to be evaluated visually. Compressibility as well as two-phase mixing is included in the model. Several user adjustments had to be made in order to accurately simulate the flow due to the diffuser shock wave.
- One-dimensional compressible flow mixing model (CoFlo). One of the project goals is to develop a generalized formulation for jet pump compression ratio as well as the jet pump efficiency in terms of relevant flow and heat transfer parameters and examine the conditions under which both quantities can be maximized. This model splits the pump into several sections (primary nozzle, mixing throat, mixing tube, diffuser upstream, shock layer, downstream

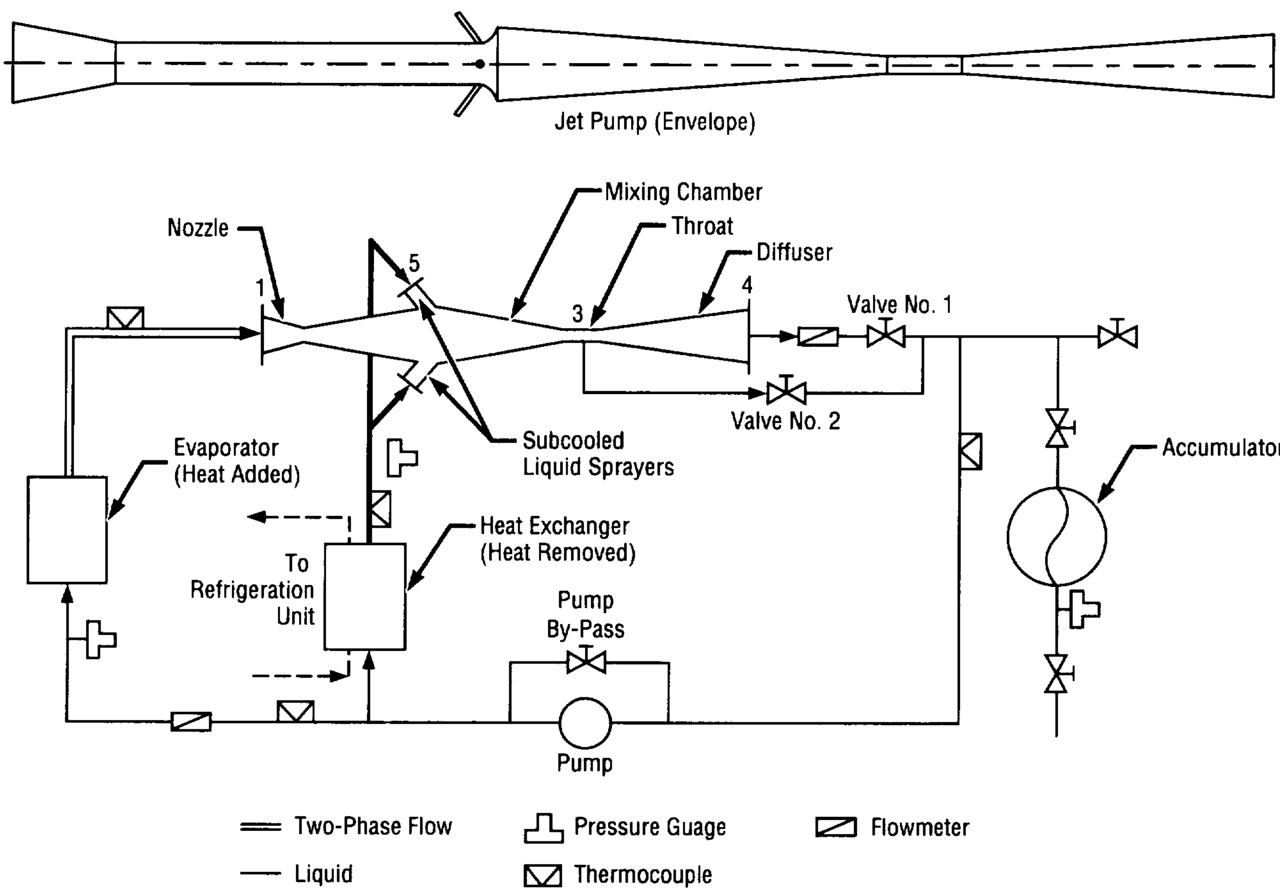

Figure 65.—Two-phase jet-pumped flow loop apparatus.

diffuser) employing appropriate solution techniques for each region to determine the pump "performance." This model will also have the capability for interface with the facility models to simulate the full-up system configuration.

If the results of the jet pump experiments prove promising, continued research including additional ground-based testing, proposed on-orbit testing, and additional analytical modeling is planned. Research from this study already appears to have potential for significant contributions to the area of two-phase jet pump research.

[1]Fairuzov, Y. Y.; and Bredikhin, V. V.: "Two-Phase Cooling System With a Jet Pump for Spacecraft." *Journal of Thermophysics and Heat Transfer*, vol. 9, no. 2, 1995.

Sponsor: Center Director's Discretionary Fund

University Involvement: University of Florida—Dr. S.A. Sherif and Mr. Justin Steadham

Biographical Sketch: Jon Holladay, Patrick Hunt, and Melissa Gard are members of MSFC's Thermal and Life Support Division team. They have over 30 years of experience in the thermal fluids area. Jon Holladay has bachelor and master of science degrees in mechanical engineering from the University of Alabama. Hunt earned bachelor and master's degrees in mechanical engineering from Auburn University, and Gard has a bachelor of science degree in engineering physics from Southwestern Oklahoma State University.

Fabrication, Testing, and Analysis of a Flow Boiling Test Facility With Enhanced Surface Characterization Capability

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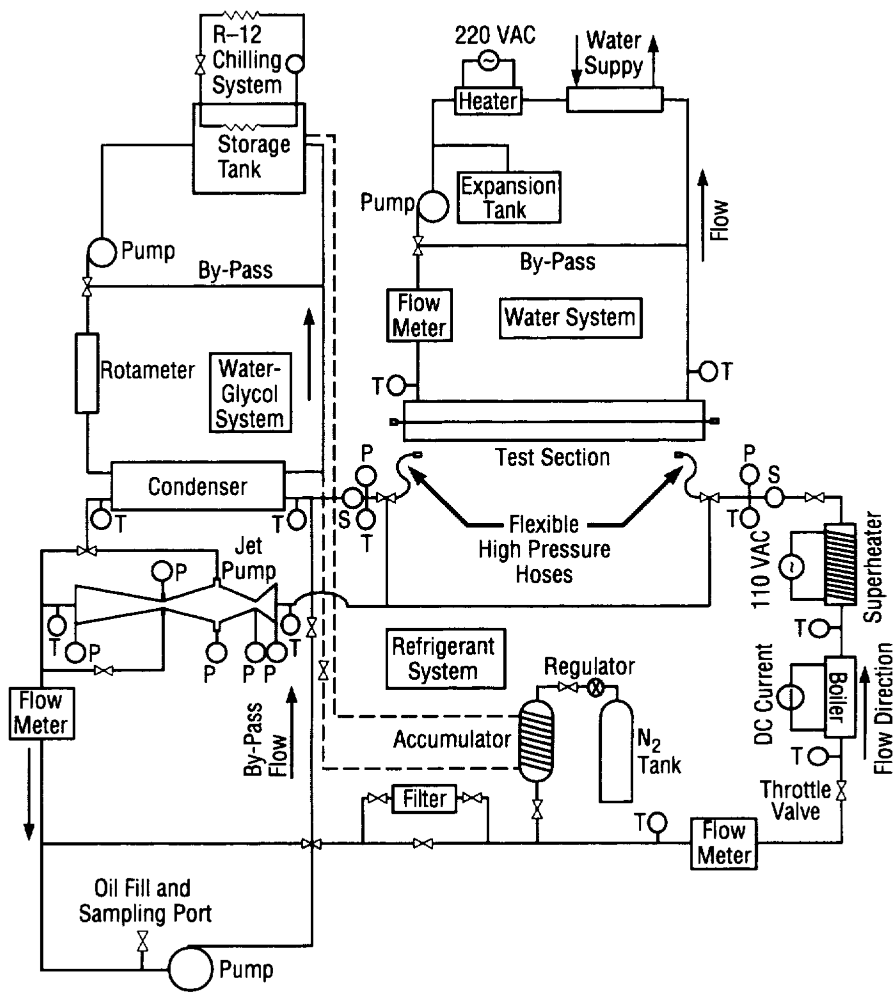

FIGURE 66.—Schematic for flow boiling apparatus using water heated/cooled test section.

The evolution of aerospace applications (spacecraft, satellites, platforms, probes, etc.) will place increasing demands on thermal control systems (TCS). These systems will require more efficient designs with higher heat rejection capabilities. An obvious solution to these challenges is the development of sophisticated two-phase flow systems that provide high heat transfer and reduced flow rates through the use of latent heat of vaporization.

Optimization of two-phase systems requires careful investigation of state-of-the-art heat transfer technology. This effort focuses on combining environmentally safe (non-CFC) refrigerants with enhanced surface technology. It will culminate in a data base of properties (corresponding to operating conditions unique to typical aerospace applications) for use in advanced TCS design.

This Center Director's Discretionary Fund (CDDF) will result in the development of a flow boiling facility (fig. 66) that will be made up primarily of components from previously completed small business contracts (SBIR's) and an experimental CDDF apparatus that is being used to investigate jet pump-based heat rejection. Typical test data are based on specific commercial applications (i.e., home and automobile air-conditioning systems, refrigeration units, etc.). Specialized aerospace applications will require information outside this range of data. A flow boiling test apparatus will not only provide data necessary to design highly efficient two-phase TCS's but can also be used to evaluate alternative (non-CFC) refrigerants and their performance using various heat exchangers with state-of-the-art heat transfer augmentation (enhanced surfaces).

Initially a survey of previously developed flow facilities was completed. An investigation into fluid property data bases was conducted. Investigation of several referenced fluid property computational methods (curve fits) yielded inadequate results leading to the decision to build a fluid property FORTRAN program in-house. The program, which has already been completed and verified, provides n-spline interpolation of ASHRAE data.

Two approaches were developed to provide fluid hydraulic analysis capability of the test loop(s): A systems improved numerical differencing analyzer (SINDA) '85 Fluint model, and a C (programming language) code which will allow timely evaluations of changes in test loop design parameters. In addition to the analytical work, a test area was set up and a chiller from a previous SBIR program was moved to the area with checkout and installation pending. A survey of existing hardware along with assessment of vendor hardware to be incorporated into the facility has been completed.

Sponsor: Center Director's Discretionary Fund

University Involvement: Douglas Nelson, University of Virginia

Biographical Sketch: Jon Holladay, Patrick Hunt, and Melissa Gard are members of MSFC's Thermal and Life Support Division team. They have over 30 years of experience in the thermal fluids area. Jon Holladay has bachelor and master of science degrees in mechanical engineering from the University of Alabama. Hunt earned bachelor and master degrees in mechanical engineering from Auburn University, and Gard has a bachelor of science degree in engineering physics from Southwestern Oklahoma State University.

Insulation System for Ultra-High Temperature Applications

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This investigation evaluated a new material system for concentrated solar energy applications. There are a few commercially available materials that could act as a thermal barrier at 4,500 °F for a short period of time. However the materials by themselves may not be suitable for the long-duration required by a storage-type solar energy engine. This study introduces a new concept of a material system to improve performance under these harsh conditions. This concept could be developed with a small budget, and experimentally proven for a high-temperature application.

In this study, thermal analysis was used to compare a conventional approach to the new concept. While insulating an engine operating at 4,500 °F, the new concept reduced the outside surface temperature 1,600 °F below the conventional approach over the same time period.

Conventional thermal protection system: zirconia-type FBD and type ZYF materials both have high-melting temperatures of 4,700 °F as used for this study. The zirconia FBD is used as inside insulation facing the absorber wall. The gap between the FBD and absorber wall is 1 in. Geometry models were generated consisting of the absorber and 1-in-thick layer of FBD surrounded by 4 in of ZYF felt insulation. It was assumed that the absorber temperature is 4,500 °F. With the intention to correlate the analytical results with ground test data without the effects of deep space radiation, the outside surface was considered adiabatic for the comparison of the insulation methods. The transient temperature distribution across the insulation walls is shown in figure 68. The temperature of the outside wall of the ZYF insulation was found to be 1,907 °F after the 4,500 °F was impressed at the absorber for 7,200 sec.

The proposed high temperature radiation shield system consists of high-strength and low thermal conductivity material overlaid with low emissivity and high melting temperature metal coatings on both surfaces as shown in figure 69. The core material could have physical and thermal properties similar to the ZIRCA type FBD. The overlaid surfaces could be made of a metal having physical and thermal optical properties that are similar to tungsten. Thickness of the metal surface could be made sufficient to serve as a part of the support structure. The high-temperature, high-strength and high-thermal-resistant material layers are located to insulate a hot body (i.e., an solar energy engine absorber). The clearance between the first FBD layer and absorber wall is 1 in. The gaps between five FBD layers and the 4 in of ZYF felt

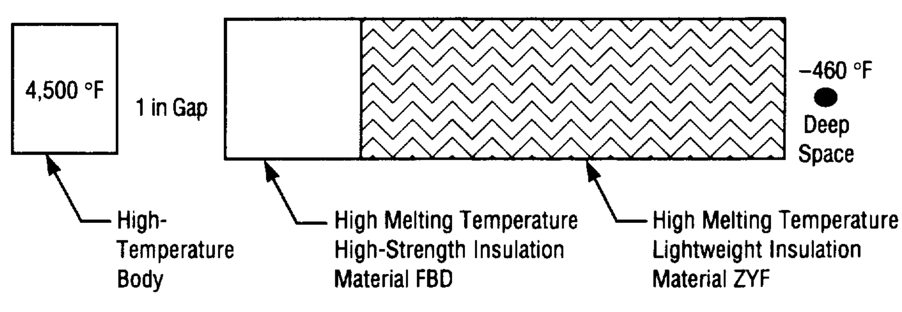

FIGURE 67.—Conventional thermal protection system.

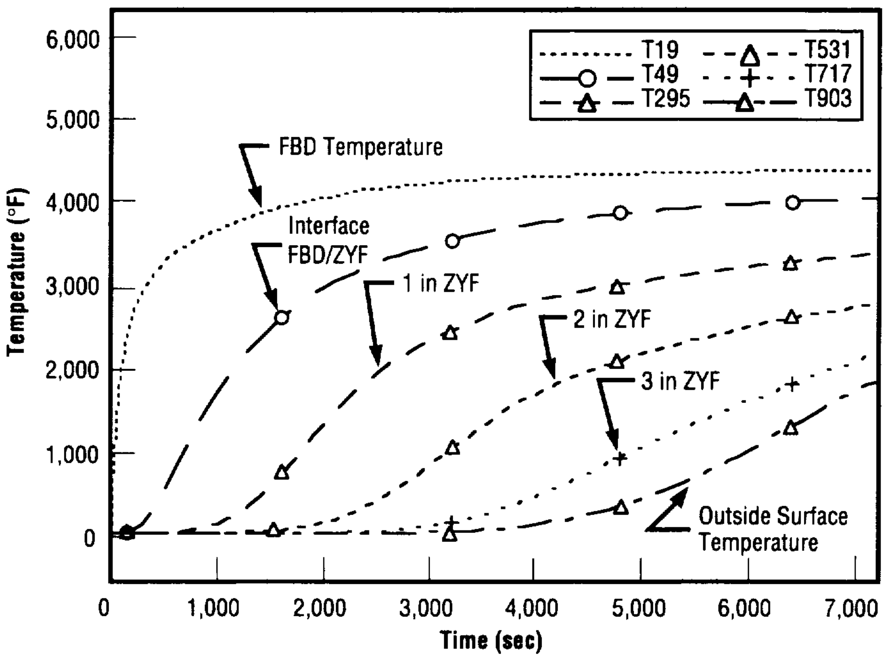

Figure 68.—Transient temperatures (°F) across insulation walls with 4-in ZYF (conventional TPS).

insulation are 0.3 in. It was assumed that the absorber temperature is 4,500 °F. With the intention to correlate the analytical results with ground test data without the effects of deep space radiation, the outside surface was considered adiabatic for the comparison of the insulation methods. The transient temperature distribution across the insulation walls is shown in figure 70. The temperature of the outside wall of the ZYF insulation was found to be 268 °F after the 4,500 °F was impressed at the absorber for 7,200 sec. The conventional TPS surface reached 1,907 °F under the same conditions. The same total thickness of insulation was used in both models to show the benefit of the radiation shield configuration. A new concept for combining radiation shields and high-temperature insulators shows promise for use in the extreme environments required for solar thermal propulsion. When the 1-in thickness of the insulation type

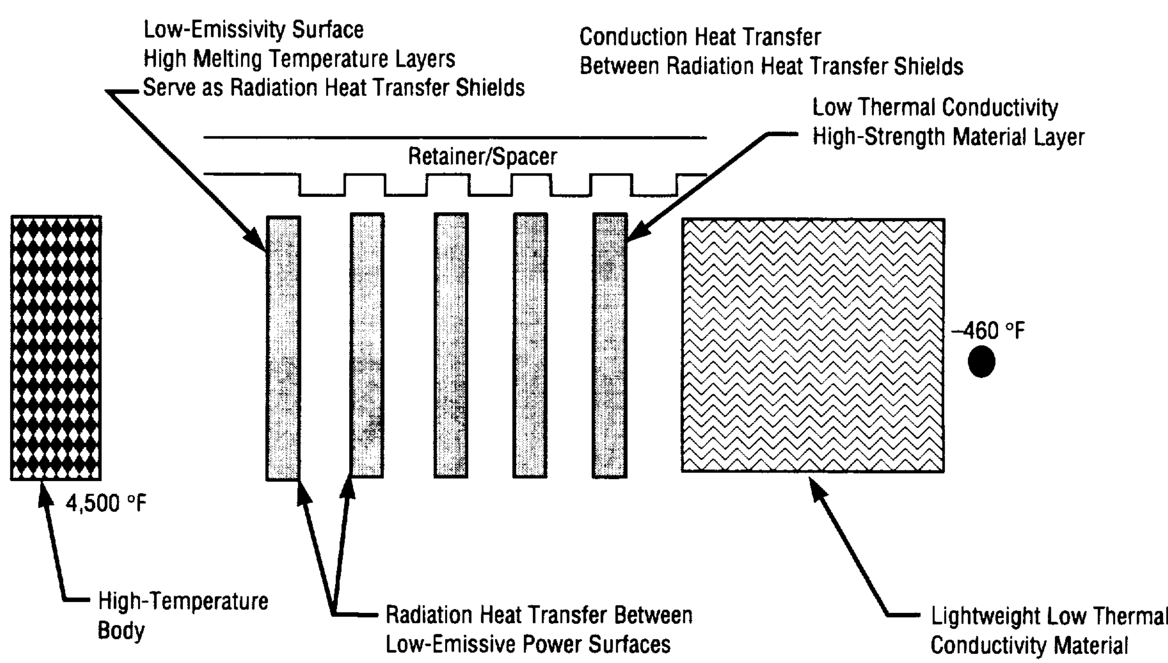

Figure 69.—Concept for a high-temperature radiation shield.

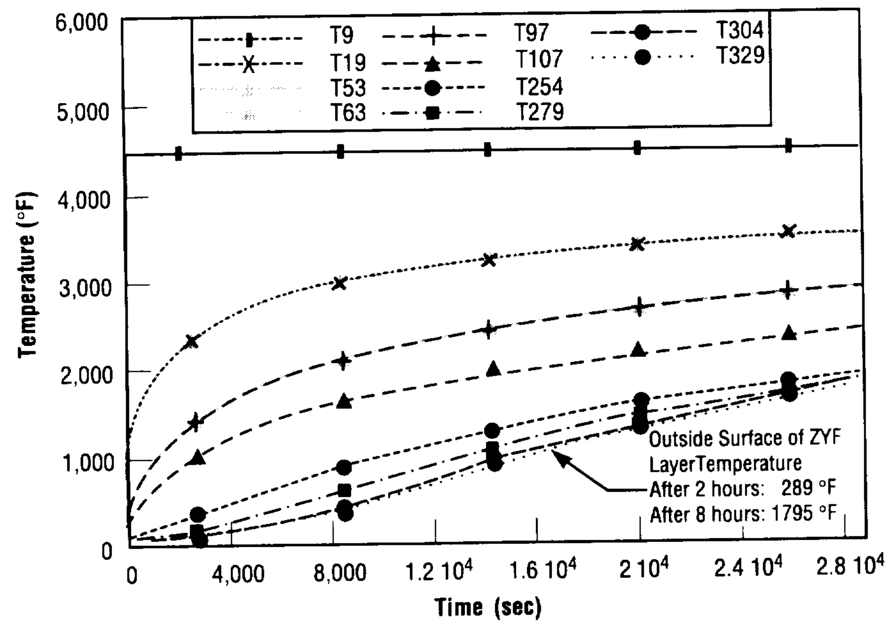

FIGURE 70.—Transient response of the high-temperature radiation shield system.

FBD was divided into five 0.2-in-thick layers and coated with low-emissivity material, the temperature of the outside surface was reduced considerably (1,600 °F) from the conventional application of these insulation materials over the same time period. Verification of these analytical results by testing is highly recommended.

This approach may improve performance for such high-temperature applications as the concentrated solar energy absorber/heat exchanger for the beyond LEO advanced space transportation (BLAST) engines. The new concept holds even greater potential for use in interplanetary travel vehicles. The insulation system concept should provide spacecraft a wider range of trajectories, mission profiles, and scientific objectives. Further potential industry applications include concentrated solar furnaces for material processing and synthesis, and high solar concentration devices for advanced medical research specially for the environment of the Space Station and the Moon surface.

Sponsor: MSFC's Preliminary Design Office

Biographical Sketch: Dalton Nguyen has a B.S. in mechanical engineering and works as a thermal engineer in the Structure and Dynamics Laboratory where he has been a member of the Engine and Propulsion Systems Team of the Thermal and Life Support Division since 1987. His contributions are in support of the Shuttle elements, Reusable Launch Vehicle programs including X-34 and X-33, new technologies such as the vacuum plasma spay processing, DC-XA liquid propulsion systems, and concentrated solar thermal energy propulsion programs.

Interdisciplinary Thermal/Stress Analysis

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A computer program was developed to convert NASA structural analyzer (NASTRAN) stress models to thermal radiation analysis system (TRASYS) and systems improved numerical differencing analyzer (SINDA) thermal models in support of the next generation space telescope (NGST) project. The NGST concept employed an exposed 8-m-diameter primary mirror that was subdivided into eight independently actuated petals. The primary mirror was blocked from the Sun on one side by an external light shade. Accurate determination of thermal deflections in the primary mirror induced by spacecraft attitude changes as well as by the difference between ground and on-orbit environments was essential to assess the feasibility of the project.

The computer program was used to convert the NASTRAN geometrical data (triangular and quadrilateral finite elements) to TRASYS polygons. The finite element mesh was converted to a mathematically equivalent thermal network that, along with the output from the radiation analyzer, was solved by SINDA. Internal structure, included as NASTRAN bar elements, was not modeled radiatively with TRASYS, but was included in the SINDA thermal network solution as conductors derived from effective cross-sectional area and length. The conversion process is illustrated in figure 71 as the NASTRAN nodal points become "arithmetic" nodes in the SINDA thermal network. A diffusion node is added corresponding to the centroid of the element, providing a convenient location to impose heat loads and thermal mass and to attach radiation conductors.

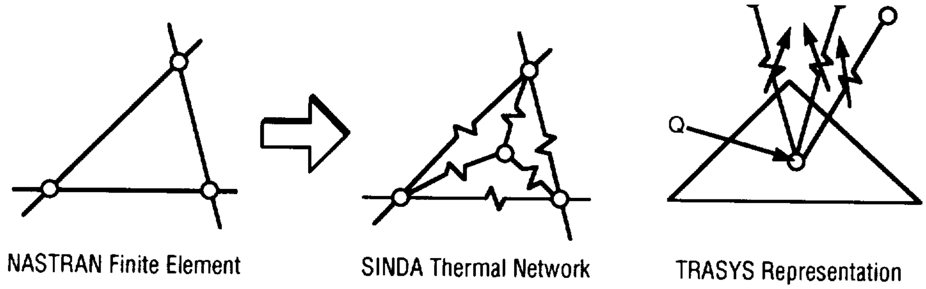

Figure 71.—NASTRAN to SINDA/TRASYS conversion.

The resulting thermal models were able to provide a one-to-one nodal correspondence between the thermal and stress models while accounting for the thermal conductance within the primary mirror and radiation exchange between all surfaces. Thermal analysis predictions from the correlated thermal/stress models are shown in figure 72.

Sponsor: MSFC Preliminary Design Office

Biographical Sketch: Greg Schunk received his bachelor's degree in mechanical engineering in 1983. He has worked at NASA's Marshall Space Flight Center for 13 years. His experience includes thermal analysis/heat transfer modeling for a number of projects including Spacelab, the *International Space Station*, and AXAF. He also supported the initial design and development of the *International Space Station* Environmental Control and Life Support System (ECLSS) test-bed.

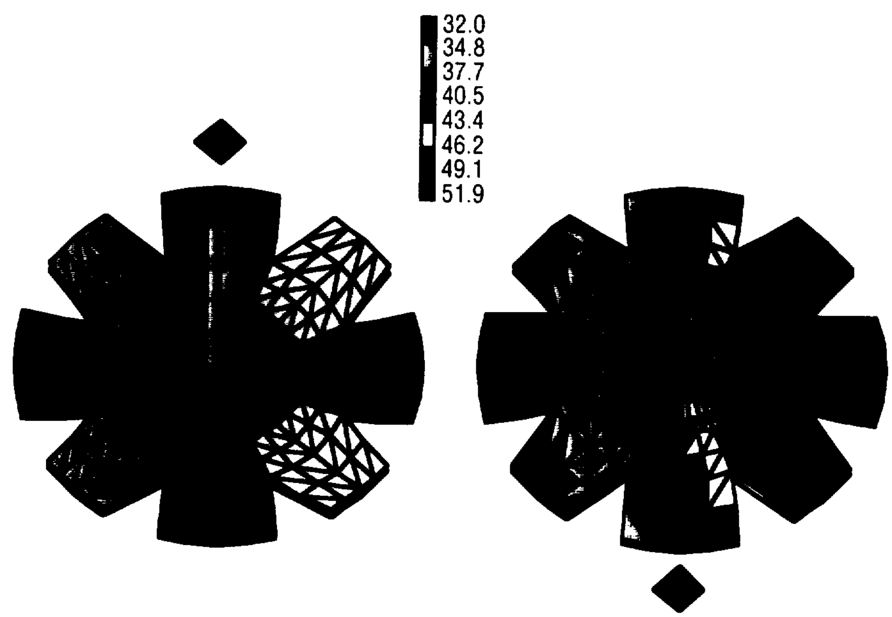

Figure 72.—NGST thermal analysis predictions (K).

Thermal Conditioning Module for Ultra-High Temperature Applications

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MSFC's Preliminary Design (PD) office, working in conjunction with personnel from its Science and Engineering (S&E) Directorate, completed an in-house feasibility study using solar thermal propulsion as an alternative means for transporting payloads from low-Earth orbit (LEO) to a geosynchronous orbit (GEO). The study found this concept to be technically feasible by the year 2000 and it could "reflect savings of 14 percent to 26 percent over current systems."[1] Due to these results, there has been a great deal of interest in pursuing this concept and several efforts have been funded to pursue the technology to make this concept feasible. The objective of a recent preliminary level one study requirement was to determine the feasibility of using a solar thermal upper stage for delivering payloads (up to 4,000 lb) from LEO to GEO in a reusable-type launch vehicle. The preliminary design configuration of the vehicle can be seen in figure 73. For the design effort, this report is written to identify one of the technology issues which needs to be addressed.

The thermal study[2] performed on the solar energy engine absorber for the beyond LEO advanced space transportation study (BLAST) revealed the following:

- Temperatures of the absorber were driven to the desired operating temperature of 4,500 °F by all four collector sizes. The rates at which an absorber can reach the operating temperature rely on a solar energy magnitude concentrated at the aperture.
- The steady-state temperatures exceeded the absorber tungsten housing melting temperature of 6,000 °F. In the case which simulates the actual expected operations, a thermal conditioning

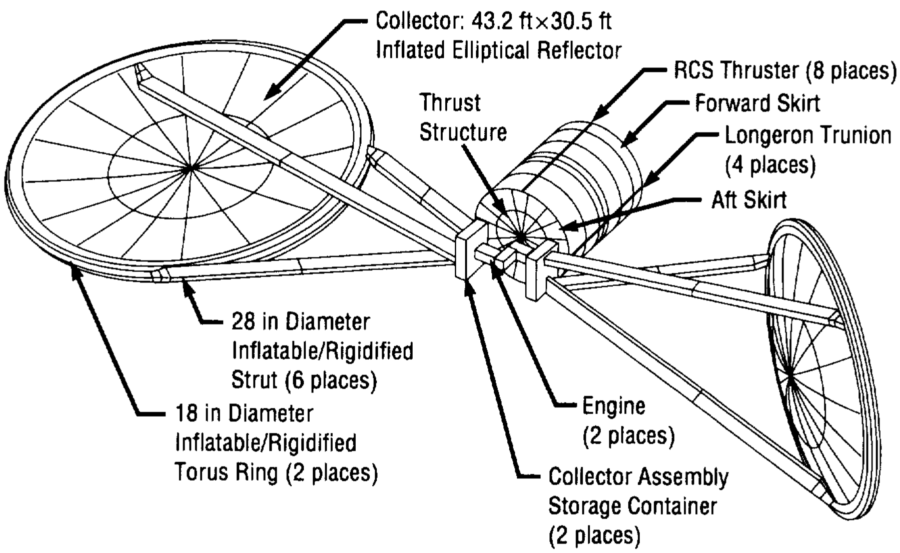


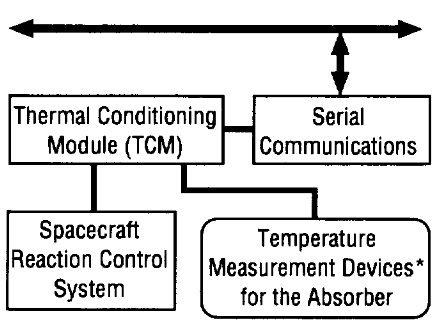
FIGURE 73.—A deployed configuration of a solar thermal upper stage vehicle.

module (TCM) is required to adjust the heating once the absorber reaches the operating temperature of 4,500 °F to achieve the rapid charge time of the larger concentrator, and to constantly keep the absorber at the operating temperature prior to an engine thrusting process.

The TCM is a unit that can process the temperature measurements from an ultra-high temperature measurement device. This device can measure the temperature of the absorber using a noncontact or contact method. Then the TCM (with a built-in ultra-high temperature data processor) can also command a device that adjusts the heat input to the absorber. This can be accomplished by several techniques (e.g., changing position of the concentrator relative to the Sun). The temperature measurement devices that can be used for this application are:

- The noncontact method: Optical pyrometer for high-temperature application (this type device is available for testing); or
- The contact method: Thermocouples which are made of metals having high melting temperatures and electrical conductive characteristics (these devices are not currently identified and need to be studied, developed, and tested.

The TCM can be made as a compact unit. A possible system configuration is sketched in figure 74. This approach should improve performance for such ultra-high-temperature applications as the concentrated solar energy absorber/heat exchanger for the BLAST solar thermal upper stage engines. The TCM holds even greater potential for use in interplanetary travel vehicles. The TCM should provide spacecraft a wider range of trajectories, mission profiles, and scientific objectives. Further potential industry applications include concentrated solar furnaces for material processing/synthesis, and high solar concentration devices for advanced medical research.



Noncontact Method: Optical Pyrometer
Contact Method: Thermocouples

FIGURE 74.—Thermal conditioning module system function schematic.

[1]Van Dyke, M.: "Beyond LEO Advanced Space Transportation Solar Thermal Upper Stage Report." PD21 (96–06), Marshall Space Flight Center, September 3, 1996.

[2]Nguyen, D.: "Thermal Analysis of the Solar Thermal Engine Absorber for the Beyond LEO Advanced Space Transportation (BLAST)." ED63 (22–96), Marshall Space Flight Center, July 5, 1996.

Sponsor: MSFC's Preliminary Design Office

Biographical Sketch: Dalton Nguyen has a B.S. in mechanical engineering and works as a thermal engineer in the Structures and Dynamics Laboratory where he has been a member of the Engine and Propulsion Systems Team of the Thermal and Life Support Division since 1987. His contributions are in support of the Shuttle elements, Reusable Launch Vehicle programs including X–34 and X–33, new technologies such as the vacuum plasma spay processing, DC–XA liquid propulsion systems, and concentrated solar thermal energy propulsion programs.

Materials and Manufacturing Processes

Endoscopic Shearography Nondestructive Evaluation of Lined Pressure Vessels

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Composite pressure vessels and fuel lines are being developed for use in advanced propulsion systems. To prevent leakage of fuel or oxidizer, composite tanks may be lined with a thin layer of metal or polymer. Several nondestructive evaluation (NDE) techniques have been developed which are highly capable of detecting damage in the outer composite structure. Among these are ultrasonics, thermography, and shearography. However, methods to detect an unbonded internal liner have not existed. Ultrasonic methods are a possibility, but remain limited if the liner is very thin or the case is thick or porous. Shearography detects slight changes in a surface shape when some stressing state is imposed and is very successful at detecting unbonds in paints, coatings and thin bonded layers. Shearography systems consist of specialized illumination and imaging optics as shown in figure 75. Due to space restrictions, insertion of the optical head or camera into the pressure vessel for inspection of the bond line integrity between the core or liner and the outer casing may be impossible. In some cases, personnel may be required to crawl inside the structure, which presents several safety risks. The need was thus identified for an endoscopic inspection system using borescopes or fiber optics to illuminate and view the inside of restricted spaces with shearography optics. Application examples are examining lined fuel tanks through access covers or drain ports and inside lined fuel or oxidizer lines. To this end a prototype borescope shearography system and method was developed to examine the inside of confined spaces with limited access.

Electronic shearography images a coherently illuminated object through an image shearing lens to produce an interference fringe pattern. The boundaries between light and dark fringes represent contours of constant change in surface slope due to some form of excitation. The MSFC NDE Branch electronic shearography (ES) system was modified for this study. This device utilizes a modified Michelson interferometer as an image shearing device, as shown in figure 75. A frequency doubled Nd:YAG-pumped diode laser ($\lambda = 532$ nm) is used as a source of coherent illumination, the beam of which passes through a beam expanding lens pair and a beam steering wedge to produce a laser speckle pattern on the surface of the test article. The light reflected from the object is collected by a telephoto lens, which provides a variable field of view, and is imaged onto the sensor

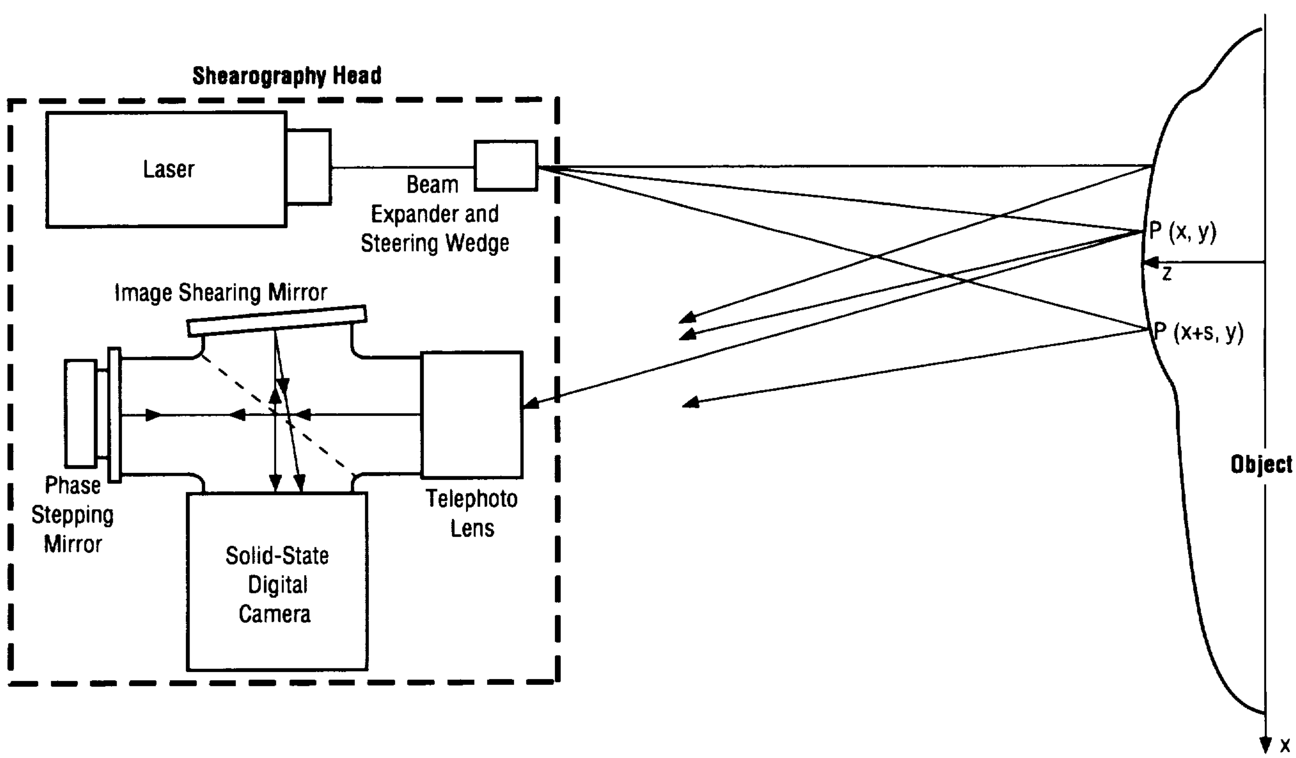

FIGURE 75.—Shearography optical system.

array of a CCD camera through the shearing interferometer.

Each ray passed through the telephoto lens is separated by the beam splitter into a reference beam and a sheared beam. The reference beam passes straight through the beam splitter, reflects from a phase stepping mirror back along its previous path, and is reflected from the back of the beam splitter toward the sensor array. The sheared beam is reflected from the front of the beam splitter toward the image shearing mirror, reflected back again at a tilted angle, then passed through the beam splitter toward the sensor array. The sheared beam is incident on the sensor array at a point which is shifted, or sheared, from the reference beam. Each point on the surface of the object is thus imaged to two separate pixels on the camera sensor array. A more complicated reverse ray trace shows that, similarly, a single pixel on the camera sensor array images two sheared points on the surface of the object. Assuming a planar object, all points in the image are sheared by the same lateral distance, referred to as the image shearing distance, s. The sensitivity of the device is proportional to s and thus related to the angle at which the image shearing mirror is tilted. By varying the tilt angle and direction of the image shearing mirror, the operator may adjust the sensitivity of the device to suit the structure being evaluated and the type of excitation being applied.

In the static test mode, sheared images are digitally acquired before and after some form of excitation is applied to the test article. The intensity recorded on each pixel is a function of the relative phase between the light rays reflected from the two corresponding points separated by in the direction of image shearing on the object surface, and thus a function of the relative slope across that interval of the image shearing distance. After the test object has been statically excited, typically by heating, cooling, or changing the pressure to which it is exposed, then a second sheared image is recorded. The digital frame subtraction of these two images results in a shearogram featuring a fringe pattern indicative of full-field values for the change in surface slope at each point on the object surface due to the excitation load.

Unlike electronic holography (EH), which produces fringe patterns indicative of object displacements toward the camera, ES senses changes in the slope of the surface of the object along intervals of the image shearing distance. That is, the fringes are produced by differences in motion toward (or away from) the camera between points separated by s. The ES technique is thus less sensitive overall than is EH. In addition, some EH techniques pass the reference beam directly from the laser to the sensor array inside an optical fiber and only the object beam reflects from the test article. Other EH techniques illuminate the test object with two coherent beams having almost entirely different optical paths in object space. The optical paths of the reference and sheared beam in ES differ only inside the interferometer. The ES technique is thus less sensitive to environmental effects (changes in vibration, temperature, etc.) than is EH. The ES apparatus does not require extensive environmental isolation, such as an vibration isolation optical table, and is regularly used for field evaluations.

A design was developed and tested for an endoscopic shearography method, as shown in figure 76. This design is a prototype which suggests the feasibility of a commercial apparatus and the supporting methodology. For this design, the shearing optics were removed from the ES system and a borescope was connected with the C-mount adapter to the shearography interferometer in place of the normal telephoto lens. This borescope will hereafter be referred to as the imaging borescope. A second borescope, the illumination borescope, was obtained and positioned parallel to the imaging borescope with the unexpanded laser beam entering the eyepiece. The beam expansion lens pair from the shearography head was positioned in front of the illumination borescope objective lens and adjusted such that the exiting laser beam was expanded to fill the imaging borescope field of view at a distance of 30 to 45 cm (12 to 18 in).

An experiment was conducted in which the endoscopic shearography design was positioned to image a flat test panel containing a programmed defect. This specimen was fabricated from graphite-epoxy with Teflon™ inserts of various sizes at various depths. For demonstration purposes a 4.45 cm (1.75 in) flaw was centered in the field of view at a distance of 30 cm (12 in) from the imaging borescope. The specimen was heated by a pair of 500 Watt quartz-halogen shop lamps from a distance of 20 cm (8 in) for 5 min causing the simulated defect to move differently

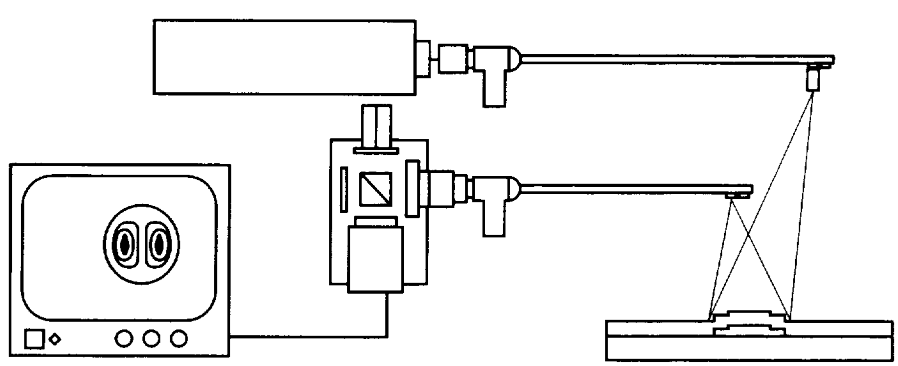

Figure 76.—Endoscopic shearography design with illumination and imaging borescopes.

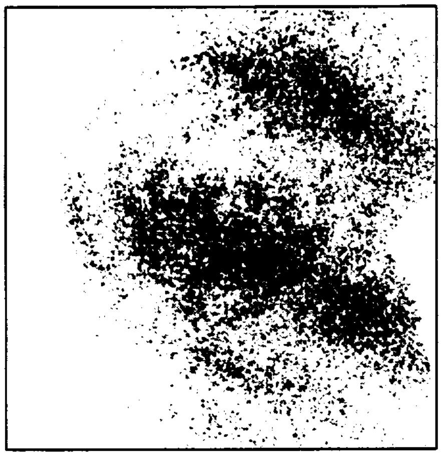

FIGURE 77.—Endoscopic shearography flaw indication.

than the surrounding area. Shearograms were recorded as the test article cooled after the lamps were turned off and moved away from the test setup. The flaw was successfully detected, as indicated by the circular fringe pattern in the shearogram of figure 77. The application of this device to inspect a lined fuel tank is shown as figure 78.

The feasibility and flaw detection capability of an endoscopic shearography apparatus has been demonstrated. This design utilizes commercially available borescopes for illumination and imaging. Endoscopic shearography allows the inspection of components such as lined fuel tanks which were previously difficult or impossible due to their closed structure. The method allows noncontact nondestructive evaluation without the need for personnel to enter the structure.

Sponsor: Office of Safety and Mission Assurance

University Involvement: Matthew Lansing/UAH Research Institute

Biographical Sketch: Dr. Samuel Russell is a materials engineer with NASA's Materials and Processes Laboratory at Marshall specializing in laser shearography and nondestructive evaluation. He holds a Ph.D. in engineering mechanics from Virginia Polytechnic Institute.

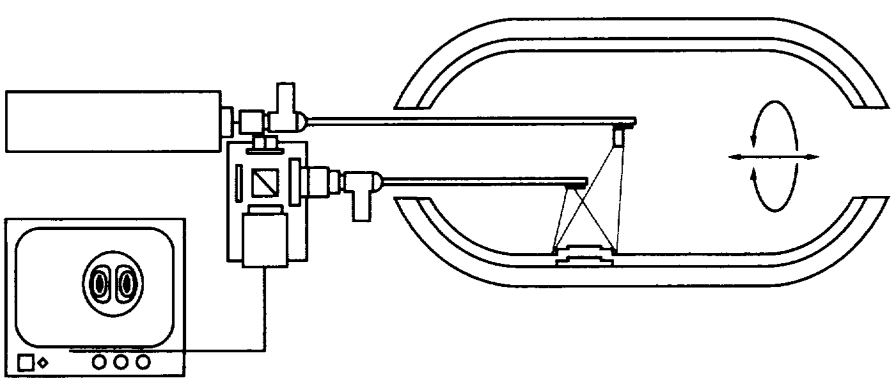

FIGURE 78.—Inspection of a lined fuel tank with final endoscopic shearography design.

LH_2 Bearing Test Program Started at Marshall Space Flight Center

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A bearing test rig capable of running liquid hydrogen as the coolant has been installed in the hazardous test area at the MSFC. This test rig expands the testing capabilities at MSFC to include cryogenic bearings running in fuel turbopumps. This tester is a follow-on to the successful liquid oxygen bearing test program known as the bearing seals and materials tester (BSMT) program.

This particular rig is a compact, easy to assemble and disassemble tester. Typical turnaround times are 3 to 5 days to change a configuration. No special tools are required for working on the test rig. This tester is very versatile; it can be built with rolling element (ball or roller) bearings or fluid film (hydrostatic, foil, hydrodynamic) bearings in its internal positions. Presently, the unit is being used to evaluate ball bearings for a NASA liquid hydrogen turbopump. Currently, there are two rolling element bearings mounted in the reaction and load positions, and a hydrostatic bearing in the 'slave' or lower position.

The test unit is approximately 2-ft high, 18-in in diameter, and weighs 850 lb. The tester housing and internal parts are made of Inconel for use in cryogenic applications. The housing is rated for 2,000-lb/in^2 internal pressures. The shaft is driven by a GN^2 gas turbine. The test rig is not limited to testing using liquid hydrogen, but has been designed to accommodate almost any process fluid including, liquid oxygen, liquid nitrogen, rocket propellant (kerosene), or jet engine fuel. The bearings are pressure-fed propellant by a 5,000-gal tank through a system of control valves. Flow rates are determined by calibrated orifices in the supply lines. Speeds over 60,000 r/min are possible. Condition

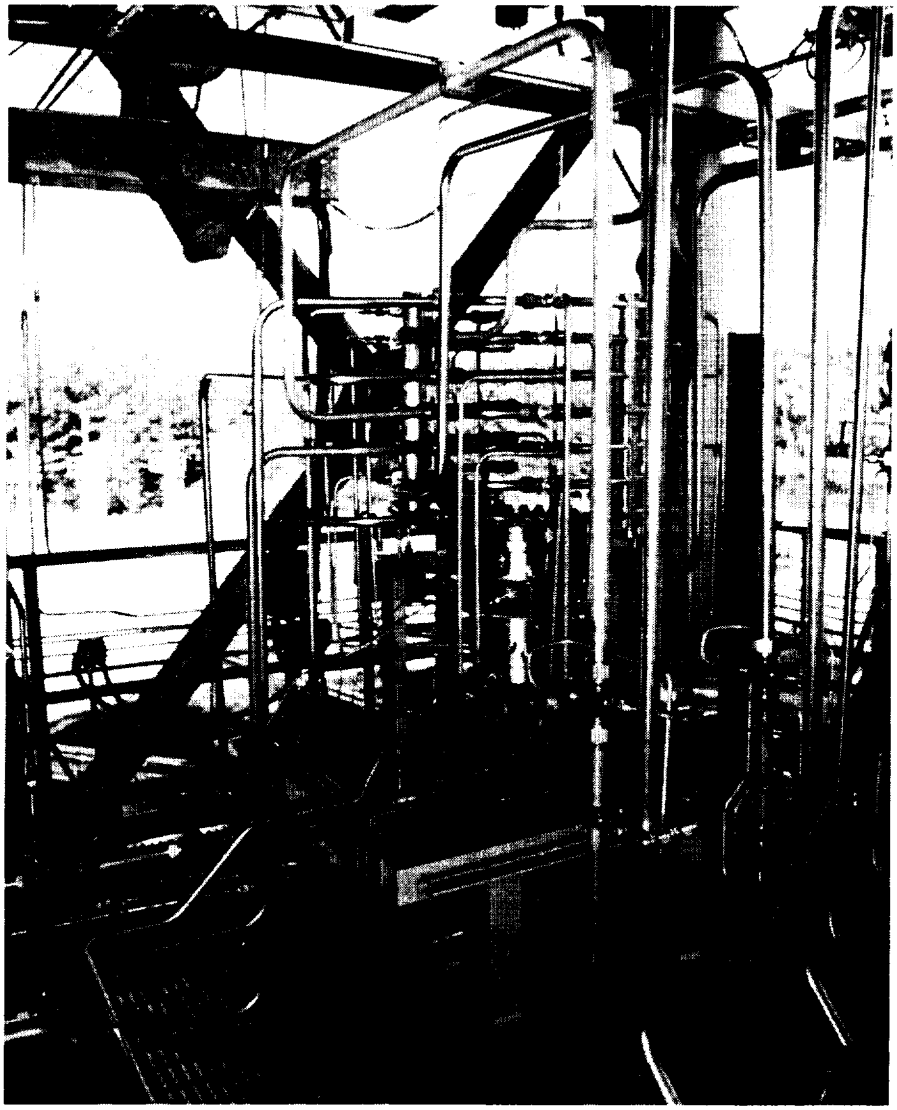

Figure 035a.—Bearing seal test facility located at Test Stand 500 second level.

Sponsor: Space Shuttle Main Engine Project Office

Biographical Sketch: Howard Gibson is a mechanical engineer with NASA's Materials and Processes Laboratory at Marshall Space Flight Center. His fields of expertise include mechanical design, hydraulics, pneumatics, industrial electrical controls, lubrication systems, and bearing design. He holds a degree in mechanical engineering from the University of Alabama.

monitoring is performed by pressure transducers and temperature sensors internal to the test rig. Facility measurements are used to control the inlet and outlet parameters.

The tester and control systems are fully operational. Currently, silicon nitride balls are being evaluated. Other bearing materials can be used such as 440C, 9310, and Cronidur 30. When built with hydrostatic bearings, design changes such as pocket size and shape, anti-wear coatings, and rotordynamic response can be studied.

With this test rig, MSFC has moved ahead into the area of evaluating advanced bearing technology for future space propulsion systems. This test rig is available for use by other Government agencies or industry through the use of NASA space act agreements.

Friction Stir Welding

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In conventional fusion welding the edges of a seam are joined as solidified metal left in the wake of a little weld pool melted by a powerful heat source and moved along the seam. As the metal at the rear of the weld pool solidifies, different temperature changes produce different amounts of shrinkage or expansion at different locations. Metal elements attached to other elements undergoing a greater expansion or a lesser shrinkage may be pulled apart and may crack. Certain metals have a strong tendency to crack and on this account are difficult to weld.

But metals need not be melted to weld them. Any time metal surfaces are brought into contact at the atomic level, whether by melting or by mechanical force, they stick together in a natural weld. A century or so ago the most common type of weld, the forge weld of the blacksmith, was a solid state weld. Hammer blows produced large forces that broke up the surface oxides and squeezed the metal surfaces into intimate contact. The metal was heated to make it flow more easily, but it was not melted. A flux, perhaps sand, was added to the joint to make the surface oxides melt so that they could be squeezed out of the joint more easily. The joint surfaces were humped so that the weld would spread from a single contact and oxide would not be trapped.

But the blacksmith's solid-state process was not terribly sensitive to surface contamination. The fusion welding process, on the contrary is often very sensitive to contaminants, which can cause serious porosity and cracking, accompanied by substantially reduced strength. The blacksmith hardly had recourse to inert gas shielding, solvent washes and scraping of joint surfaces, white glove handling, reverse polarity cleaning, etc. Fabricators of the Space Shuttle external tank use these techniques routinely.

As fusion welding techniques become more capable, more difficult welding challenges are being posed. The lighter-stronger 2195 aluminum-lithium alloy specified for the new Space Shuttle lightweight tank is more difficult to weld than the old 2219 aluminum alloy. As weldability constraints can be relaxed, stronger and lighter alloys can be specified.

On this account in 1994, MSFC began to consider solid state welding processes and became very interested in the friction stir welding (FSW) process invented by The Welding Institute (TWI) in the United Kingdom in 1991. In 1995, MSFC set up the nucleus of a laboratory to develop the FSW process to meet the needs of the next generation of space vehicle fabricators. MSFC FSW laboratory welds made in quarter-in-thick 2195 aluminum-lithium alloy plate already exhibit strengths a bit higher than comparable fusion welds, and the FSW process has yet to be optimized.

In FSW a rotating pin is inserted into the joint between pieces to be welded and moved along the seam, stirring the metal together as it goes. The plastic flow generates heat, the temperature rises near the pin, and the metal flow stress goes down so the forces are much smaller than they would be in cold metal. To keep the metal in place, a shoulder bears down on the metal surface above the pin and a backing bar supports the back of the seam. The shoulder contributes plastic flow and heating of its own.

A major drawback to the FSW process is the large forces that must be applied to the plate. A much simplified analysis of the FSW plastic flow process predicts forces inversely proportional to the rotational speed of the pin tool and suggests that by going to high rotational speeds the loads can be greatly reduced. Preliminary empirical studies at the University of Texas at El Paso seem to corroborate this idea; however, MSFC found a falling off of weld strength at higher rotational speeds.

Therefore in conjunction with a design effort directed towards the fabrication of FSW tooling capable of producing full-size space vehicle hardware, and an associated effort to develop nondestructive evaluation techniques appropriate for inspecting the unique structure of an FSW weld, an effort towards undertanding and characterizing the flow of metal in FSW welding is also underway at MSFC to be followed by tool geometry and process parameter optimization studies.

If the loads can be sufficiently lowered while maintaining weld strength, the minimal debris, electrical, and thermal hazards of the FSW process make it a candidate for an in-space as well as a terrestrial welding process.

Thomas, W.M., et al.: Friction Stir Butt Welding, December 6, 1991. International patent application number PCT/GB92/02203 and GB patent application number 9125978.8.

Sponsor: Office of Space Flight

Biographical Sketch: Robert Ding is principal investigator for the Friction Stir Welding development effort. He is an aerospace engineer with the Materials and Processes Laboratory at MSFC. Ding holds an M.S. in engineering from the University of Tennessee as well as bachelor's degrees in welding engineering (Ohio State University) and biology (Bowling Green State University, Ohio).

Dr. Arthur Nunes is an aerospace engineer with NASA's Materials and Processes Laboratory at Marshall, specializing in the theory of welding processes, basic engineering science, and materials science. He holds a Ph.D. in materials engineering from the University of California at Berkeley.

The Reaction of Nitrogen With 2195 Aluminum-Lithium Alloy: Continued

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In the *1994 MSFC Research and Technology Report*, attention was called to a detrimental reaction of nitrogen with 2195 aluminum-lithium alloy occurring at temperatures as low as 350 °C.

Optical hot-stage microscopy carried out at MSFC by Dr. J.E. Talia of Wichita State University and his student C.A. Widener, showed bubbling at grain boundaries during melting clearly indicating a gas reaction. Thermocouple measurements during the hot-stage microscopy showed this reaction to be exothermic, like the reaction of the 1994 differential thermal analysis (DTA) curves. The bubbling reaction, also like the DTA reaction, began in the neighborhood of 350 °C.

Followup gas chromatograph studies of 2195 alloy heated in an alumina tube to 620 °C for 15 min with pure nitrogen and with air revealed that for a mole of nitrogen lost approximately a mole of hydrogen appeared. Because hydrogen is so easily lost, for example by absorption in container walls, appreciably more hydrogen may have been generated than the measured quantity.

The appearance of hydrogen and the absence of grain boundary bubbling in lithium-lacking 2219 aluminum alloy points to a reaction of nitrogen with a lithium-hydrogen compound or compounds causing a release of hydrogen. The details of the reaction remain to be worked out although hydrogen containing lithium compounds in aluminum-lithium alloys are well known. Exposure to air containing a bit of moisture easily contaminates lithium containing alloys. Hot-stage microscopy shows that vacuum degassing can eliminate the reacting compounds, but this is not practical for shop practice. In practice a thin layer, for instance a quarter of a millimeter, of surface is machined off prior to welding to avoid the worst of the problem.

D. Huang, a student of Dr. J.C. McClure at the University of Texas at El Paso, measured the effect of contamination levels of nitrogen, oxygen, and hydrogen in the argon plasma gas and helium shield gas of a variable polarity plasma arc (VPPA) welding torch on a sample of 2195 aluminum. He ran gas compositions over a range from 10 to 500 p/m and from gas flow rate and weld speed computed a contamination volume per length of weld. He measured pore areas (up to 1.1 percent of the weld area; up to 0.16 mm^2) as a function of contamination volume per weld length.

All three gases caused porosity, but nitrogen always caused the highest porosity levels. A gray to black surface film of 1 to 2 µm irregularly shaped metallic aluminum particles sometimes appeared on the metal surface. The metallic particles might have been gas-driven ejecta from grain boundaries or surface pores.

A somewhat different film was observed by Talia in the vicinity of a crack: a loosely attached dark film of 10 µm diameter spherical particles. These spheres seemed to have a metallic interior with a sometimes cracked nonmetallic shell; EDAX analysis showed Al, Mg, Cu, O, N. (Li is not detectable by this technique.) The roundness of the particles suggests solidification while suspended in a gas.

It is noteworthy that hydrogen contamination appears to cause substantially less porosity in 2195 alloy than in 2219. This may be due to the formation of hydrogen compounds in the lithium-containing alloy.

The backside of a weld can easily exceed 350 °C below a weld pool of appreciable depth during a partial penetration cover pass. Hence even the backside of a partial penetration cover pass in an aluminum-lithium alloy should generally be shielded.

Talia, G.E. and Widener, C.A.: "High Temperature Analysis of Aluminum-Lithium 2195 Alloy to Aid in the Design of Improved Welding Techniques." Report: NASA/ASEE Summer Faculty Fellowship Program, MSFC, Summer 1996.

Huang, D.; McClure, J.C.; and Nunes, A.C.: "Gas Contamination During Plasma Welds in Aluminum Lithium Alloy 2195." Submitted to *Welding Journal*, 1996.

Sponsor: Office of Space Flight

Biographical Sketch: Dr. Arthur Nunes is an aerospace engineer with NASA's Materials and Processes Laboratory at Marshall, specializing in the theory of welding processes, basic engineering science, and materials science. He holds a Ph.D. in materials engineering from the University of California at Berkeley.

Environmentally Friendly Sprayable Ablator for the Solid Rocket Booster

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Progress has been made in the continuing effort to qualify and implement an environmentally friendly replacement for the ablator previously used on the Space Shuttle SRB's—Marshall sprayable ablator–2 (MSA–2). MSA–2 performed well, but has been phased out because of impending environmental regulation due to its chlorinated hydrocarbon solvent system. Marshall convergent coating–1 (MCC–1), which was selected to replace MSA–2, originated from a United Space Boosters, Inc. (USBI) independent research and development (IR&D) project. The process was transitioned to MSFC's sprayable ablator research cell at the Productivity Enhancement Complex (PEC), where it was scaled up to production size, and where the process was refined and optimized. MCC–1 was qualified for use on the SRB, with the first flight of the material occurring on STS–79, which lifted off on September 16, 1996. The flight performance was a success and compared favorably with that of MSA–2.

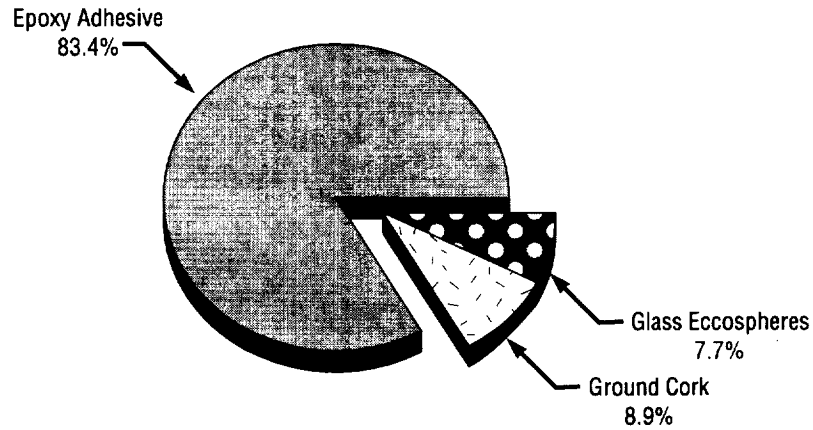

Figure 80.—Typical composition of MCC–1 in weight percentage.

MCC–1 is an innovative material that employs convergent spray technology (CST™), a solventless convergent spray process. MCC–1 utilizes an epoxy adhesive and ground cork and glass fillers (fig. 80), although various adhesives and fillers may be selected for other CST™ applications. It is robotically sprayed on a painted aluminum target located on a rotating turntable. A high-temperature cure provides the quickest processing timeline and provides optimum strength. After curing, the ablator is topcoated with a moisture-resistant paint to help maintain its strength and integrity while on the launch pad. Features of this process include on-demand availability and process robustness.

The Air Force was sufficiently impressed with this material to participate in a joint effort to qualify MCC–1 for the Titan IV rocket payload fairings. The schedule calls for the first Titan IV production hardware to be coated with MCC–1 in June 1997. Many industry spinoffs using CST™ are possible, due to the ability to change out adhesives and fillers as necessary to meet the desired end-use material properties. For example, pilot projects are currently underway to use CST™ to produce environmentally friendly anti-skid coatings for highway concrete bridge decks, as well as environmentally friendly roofing materials for industrial buildings.

In qualifying and implementing MCC–1, the PEC at MSFC is fulfilling its mission as one of the nation's preeminent research centers. Considering the impending environmental regulation, the implementation of a compliant replacement for MSA–2 has been of critical importance to the Space Shuttle Program. This environmentally friendly material and its core technology, CST™, will be available for other uses as well, as evidenced by the Air Force Titan IV application and the spinoff pilot projects, and will reaffirm NASA's commitment to the ecology of our planet.

Patel, S.V.: "Development of an Environmentally Friendly Convergent Spray Coating and Optimization of Its Application Process Parameters." Aerospace Hazardous Materials Management Conference, Cincinnati, OH, September 1995.

Sponsor: Solid Rocket Booster Project Office, Office of Space Flight

University/Industry Involvement: United Space Boosters, Inc. (USBI)

Biographical Sketch: Carl Lester is a materials engineer with NASA's Materials and Processes Laboratory at Marshall, specializing in the development and qualification of nonmetallic coatings and thermal protection systems. He holds a degree in chemical engineering from the Georgia Institute of Technology.

Material Robustness Testing and Nondestructive Evaluation Methodology Assessment for Liquid Rocket Engine Composite Nozzles

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Thrust-to-weight ratio requirements for Reusable Launch Vehicle (RLV) main propulsion systems are substantially increased relative to current high performance liquid rocket engines. One approach to achieve these requirements as described in the Access to Space Study is to develop lightweight components. High-temperature composite nozzles offer significant potential for weight reduction and cost savings relative to conventional regeneratively cooled metallic nozzles. The Materials and Processes Laboratory initiated a project to address critical technologies required for the development of high-temperature composite nozzle extensions. The effort is supported by the Long-Term/High-Payoff technologies project of the RLV program. Four technology areas were originally identified: Material systems, nondestructive evaluation (NDE), thermostructural analysis code development and verification, and nozzle attachment methodology. Discussions were held with Government and industry organizations to select areas in which up-front studies would benefit development of a composite nozzle extension supporting RLV concepts. Top priority was given to material systems screening and NDE methodology assessment and tasks were defined for each area. Attachment methodology was judged to be design-specific and not recommended for generic development. It was also determined that resources applied to analytical code development and verification would be most beneficial after final material system selection.

The objective of the materials screening task is to conduct a robustness evaluation of composite material systems, including substrates and coatings, which are candidates for RLV nozzle applications for the purpose of assessing performance capability in simulated rocket nozzle environments. An industry/Government team composed of representatives from Rocketdyne, Aerojet, Pratt and Whitney, Southern Research Institute, MSFC, and LeRC was formed to define and conduct the robustness testing project. The initial step was the identification of critical parameters for material selection including constituents, processes, reinforcement architectures, and oxidation protection mechanisms. The team then defined preliminary requirements for the operational environment and established the types of tests to be used to assess performance capability for mission requirements. Preliminary requirements were established using the Space Shuttle Main Engine combustion gas environment as a baseline; operating temperatures in the range of 2,800 to 3,100 °F; and a 20-mission lifetime, with a 500-sec duration for each mission. Tests include baseline tensile, stressed oxidation, oxidative fatigue with thermal cycling, and thermal expansion. The elevated temperatures (two will be selected) and stress levels for the stressed oxidation and oxidative fatigue tests will be defined based on preliminary design and operational requirements analyses. Preliminary material system selections were made including potential suppliers recommendedd by industry team members. Critiques of team material selections were

TABLE 7.—***Nozzle material selections for robustness testing.***

Item / Material	Manufacturer	Yarn	Yarn Ht.	Fiber Arch.	Yarn Ends	Interface Coating	Matrix	Densification	Oxide Inhib.	Coating
1. Enhanced C-SiC	Dupont Lanxide	1K T–300	1,700 °C	2D Plain	19/in	PyC Alpha-3	SiC	Isothermal	Yes	CVIP
2. STD C-SiC	Dupont Lanxide	1K T–300	None	2D Plain	19/in	PyC Alpha-3	SiC	Isothernal	No	CVIP
3. C-SiC	BFG	1K T–300	1,800 °C	2D Plain	19/in	PyC	SiC	Isothermal	Yes	CVD SiC
4. CTD C-C	CCAT	1K T–300	1,700 °C	2D Plain	30/in	PyC	C	Phen. Impreg.	No	Pack SiC
5. Hi NIC SiC	Dupont Lanxide	1K Hi Nicalon	None	5 HS	17/in	PyC Alpha-3	SiC	Isothermal	Yes	None
6. Hi NIC SiNC	Dow	0.5K Hi Nicalon	None	2D Plain	16/in	Prop Non C	SiNC	PIP	"Yes"	None
7. Hi NIC–C	BFG	0.5K Hi Nicalon	None	2D Plain	16/in	PyC	C	Isothermal	No	SiC
8. CTD C-C	CCAT/Amercon	1K T-300	1,700 °C	2D Plain	30/in	PyC	C	Phen. Impreg.	No	Si_3N_4

sought from the suppliers as well as recommendations of their "best" materials to meet the requirements. Recommendations were also received from experts at the Air Force Materials Laboratory at Wright Patterson Air Force Base. The basic material systems selected were carbon matrix and ceramic matrix composites reinforced with either carbon fiber (T-300) or silicon carbide fiber (Hi-Nicalon). Detailed descriptions of the particular variations and the material supplier are provided in table 7. Orders were placed with suppliers in June 1996. Tests will be conducted at Southern Research Institute and LeRC.

The second critical technology to enable the use of composite material systems for nozzle extension applications is the capability to nondestructively inspect the components. The objectives of the NDE methodology assessment task are to evaluate and subsequently downselect viable NDE techniques for selected composite material systems. An industry/Government team of NDE specialists from Aerojet, Pratt & Whitney, Rocketdyne, Southern Research Institute, MSFC, and LeRC was formed to define and conduct the project. Discussions were held to identify the concerns and needs of the RLV main propulsion system prime contractors and to determine the capabilities of the suppliers. Based upon this information and input provided from the composite nozzle material systems robustness testing team, standard specimens were designed containing prescribed flaws representative of naturally occurring and critical defects. These are described in table 8 for the two material types, coated carbon-carbon and coated carbon-silicon carbide. The specimens were ordered and will be produced with those manufactured for the materials robustness testing task. Each of the test articles will be inspected at MSFC and LeRC and will be available for inspection by all industry team members. Appropriate NDE techniques in existence at each facility will be evaluated as well as selected promising new techniques available within the NDE community. Detection capabilities and limitations data base for these specimens will be established. Based upon evaluation of detection capabilities, applicability to subscale and full-scale composite nozzles, cycle time, and cost, downselection of NDE techniques will be made. Reference specimens will be available for future NDE calibrations.

TABLE 8.—*Defect test articles and materials for NDE methodology assessment task.*

Defect Type	Defect Description	Defect Level	Coated C-C	Coated C-SiC
I.	Density Variation	Nominal Less 15% Less 30%	2×(2×8 in) 2×(2×8 in) 2×(2×8 in)	2×(1.3×8 in) 2×(1.3×8 in) 2×(1.3×8 in)
II.	Interfacial Bonding	Optimized Less Than Opt. Poor Bonding	2×(2×8 in) 2×(2×8 in) 2×(2×8 in)	- - -
III.	Simulated Delams	Best Effort 2.0 mil Thick Strips 5.0 mil Thick Strips	2×(2×8 in) see II a 2×(2×8 in) 2×(2×8 in)	2×(1.3×8 in) see II a 4×8 2×TH. see III b
IV.	Distorted Plies	Nominal 15° 30°	2×(2×8 in) see II a 2×(2×8 in) 2×(2×8 in)	- - -
V.	Inherent	As Sorted	2×(2×8 in)	2×(4×4in)
VI.	Machined	TBD/ASTM	2×(2×8 in)	2×(4×4in)

Results from both tasks will be summarized in the *1997 MSFC Research and Technology* report.

Sponsor: RLV—Long-Term/High-Payoff Technologies Program

University/Industry Involvement: Rocketdyne, Pratt & Whitney, Aerojet, Southern Research Institute, DuPont Lanxide Composites, C-CAT, Dow, B.F. Goodrich, Amercon

Biographical Sketch: Dr. Raymond Clinton is a supervisory aerospace materials engineer with NASA's Materials and Processes Laboratory at the Marshall Space Flight Center, specializing in nonmetallic materials development and evaluation for rocket engine applications; composite materials (polymer matrix, carbon matrix, and ceramic matrix) selection, processing, material property characterization testing, performance evaluation and verification testing; development of material property databases for design and analysis; and program planning. He holds a Ph.D. in aerospace engineering from the Georgia Institute of Technology.

Sensor Technology

A Gaseous Hydrogen Detector System Based Upon a Solid State Silicon Microsensor

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The Lead Detection for Launch Vehicles program has focused this past year on two vehicle efforts: The DC–XA and the LASRE (Aerospike engine flight test experiment on SR–71 aircraft) programs. Hydrogen leak detection systems have been provided to both of these programs to support flight test operation. The majority of the effort has been spent on the system supplied to MDA for the DC–XA.

The DC–XA system consists of four controller boxes each supervising the operation of eight sensors for a total of 32. Each of the boxes communicates with a ground computer via a launch stand umbilical connection as well as with the flight test telemetry system (FTTS) on the vehicle. This arrangement is shown in the block diagram of figure 81.

Each controller box consists of four printed circuit boards: the microprocessor (MIC) board, the sensor interface (SIF) board, the telemetry (TLM) board and the power (PWR) board. The MIC board contains the microcontroller and the supporting circuitry necessary to supervise and direct the operation of the eight sensors under its control. The SIF board contains the circuitry needed to multiplex the inputs and outputs to and from the microcontroller. The TLM board provides the data buffering necessary to support the electrical and protocol interfaces to the FTTS. The PWR board converts the standard 28 Vdc into the various voltages required by the other three boards. These four boards are stacked up and mounted in an enclosure as shown in figure 82.

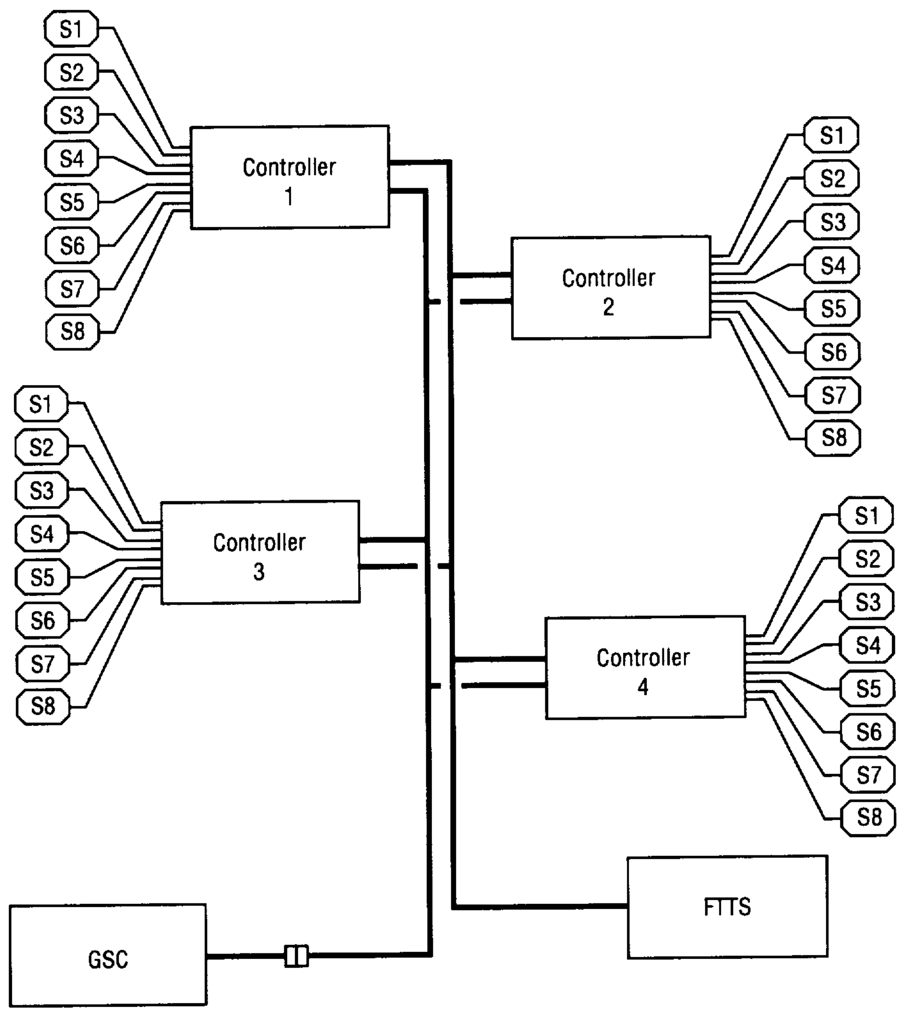

Figure 81.—DC–XA connection scheme.

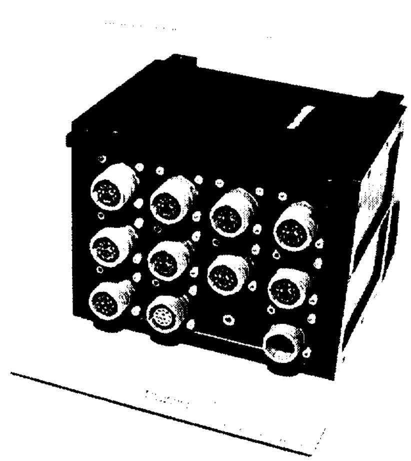

Figure 82.—DC–XA controller.

The sensor assemblies consist of a small circuit board that contains the sensing device, an op-amp and some discrete components. The sensing device is a 16-pin dip-style integrated circuit with holes in the lid to allow gas flow to the circuit element and are manufactured by Sandia Labs. The sensors contain a hydrogen-sensitive transistor, a hydrogen-sensitive resistor, a temperature sensor and a heating element. The transistor provides sensitivity to H_2 for very low concentrations, in the range of 0 to 1 percent. The resistor senses H_2 concentrations in the 1- to 100-percent range. The temperature sensor and the heating element are used to maintain a desirable operating temperature for the chip. The circuit board is mounted in a vented enclosure as shown in figure 83.

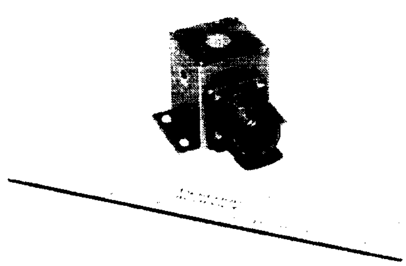

FIGURE 83.—DC–XA sensor.

Fabrication, testing and integration support were the tasks involved in supplying the DC-XA leak detection system to MDA.

Fabrication consisted of circuit board assembly, harness assembly and machining of the enclosure. Of the four controller circuit boards needed for each controller, the MIC and the SIF already existed. The PWR board was a new circuit board that closely resembled an existing design. The TLM board was an original design. The MIC, SIF and PWR boards as well as the harness assembly and enclosure machining were performed by Aerojet. The design and construction of the TLM board was performed by MSFC.

Testing of the telemetry interface involved travel to Gulton Data Systems with the assembled system for evaluation in their test setup. This testing revealed an oversight in the communication protocol that was resolved by changes to the microcontroller firmware. Vibration testing exposed a number of mechanical weaknesses in the circuit cards that required substantial rework and repair. Calibration of the system involved temperature calibration of the on-chip temperature sensor. This was followed by exposure of the 32 sensors to various concentrations of hydrogen at controlled temperatures. The calibration data were incorporated into the conversion equations used to calculate percent H_2 content from the controller's raw 12-bit readings.

Integration support involved checkout and test of the system at Huntington Beach after the system was installed in the vehicle. System signal continuity was checked by applying heat from a heat gun to each of the sensors. This verified the mapping of sensors to physical locations on the vehicles as well as signal integrity. The ground connection through the umbilical and the FTTS connection was also verified.

After the vehicle was delivered to WSMR, effort was spent to establish the ground communications link, configure the ground computer software and operate the system during ground tests and flights.

The original plan had the ground computer in the FOCC area and connected via a fiber-optic modem to the umbilical connection on the stand 3 miles away. This arrangement presented some difficulty in that the protocol of the modems being used was basically incompatible with the protocol used by the four controller boxes. The resolution was to place the ground computer in the GPA trailer at the pad with a direct wire connection to the umbilical. The ground computer was then operated remotely by a second computer in the FOCC area that was serially linked via the modems and the appropriate software package. This resolved the communication issue.

The ground computer software was completed and installed at WSMR. This yielded percent hydrogen readings that compensated for temperature variation. The qualitative nature of the readings seem to indicate consistent operation of the system. While monitoring fueling operations prior to flights 2 and 3, for example, it was observed that procedures such as the initiation of tanking and the onset of the various purges produced responses by the sensors that were uniform, similar and apparently repeatable. The absolute magnitude of the readings, however, was questionable.

After Flight 4 and the loss of the DC–XA vehicle, the telemetry data from the last flight were examined for any suggestion of the presence of excessive hydrogen. The data from one of the four controller boxes were entirely absent from the recorded data stream, and one other box dropped out prior to the end of the flight. The data that were available, however, indicated hydrogen levels no greater that those seen in previous experience.

The SR–71 system is basically a scaled-down version of the DC–XA system. It consists of a single controller box with eight sensors attached. The box communicates with the data logging system through the serial (umbilical) interface. The controller consists of MIC, SIF and PWR boards arranged in an enclosure as shown in figure 84.

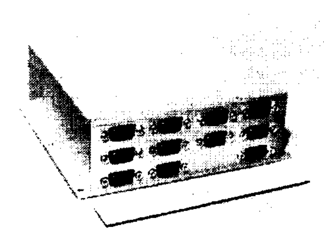

FIGURE 84.—LASRE (SR71) controller.

The development of the SR–71 system made use of existing hardware to the maximum extent possible due to the aggressive delivery schedule. The MIC board came from the original DC–X system and the SIF and PWR boards were spares form the DC–XA effort. The sensor assemblies, shown in figure 85, were also spares that were available. The system was delivered to NASA Dryden in late April. It has not yet been used in support of an engine test.

Sponsor: RLV—Long-Term/High-Payoff Technologies Program

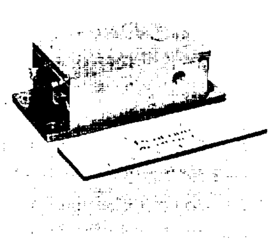

FIGURE 85.—LASRE (SR71) sensor.

Industry Involvement: Gary Paterson/ Aerojet Propulsion

Biographical Sketch: W.T. Powers is a senior measurement systems engineer in the Instrumentation Branch of the Astrionics Laboratory of MSFC. He holds a bachelor of science in electrical engineering, minors in mechanical, nuclear and physics, from Tennessee Polytechnic Institute. Powers has 33 years service with NASA, and primarily deals with development of advanced sensors and measurement, acquisition, and processing systems.

Gaseous Leak Imaging by Raman Radiation Capture

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The period FY96 covers work that forms the conclusion of one contract increment and the majority of another contract increment.

One year ago a confocal telescope prototype had been constructed, and demonstration of proof of the concept was still underway. The goal was a simple 11×11 pixel image of a hydrogen leak inside a small test chamber.

Figures 86 and 87 display the layout of the confocal telescope breadboard. Figures 88 and 89 display data obtained using the breadboard. Figure 88 proves that it is possible to obtain a Raman scattering signal using a continuous wave (CW) probe laser. The background was aluminum at a

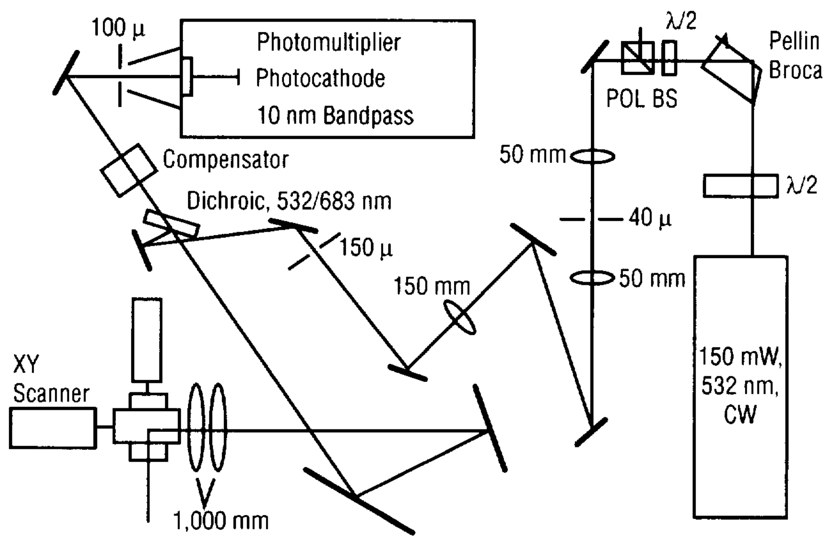

FIGURE 86.—Confocal telescope breadboard layout.

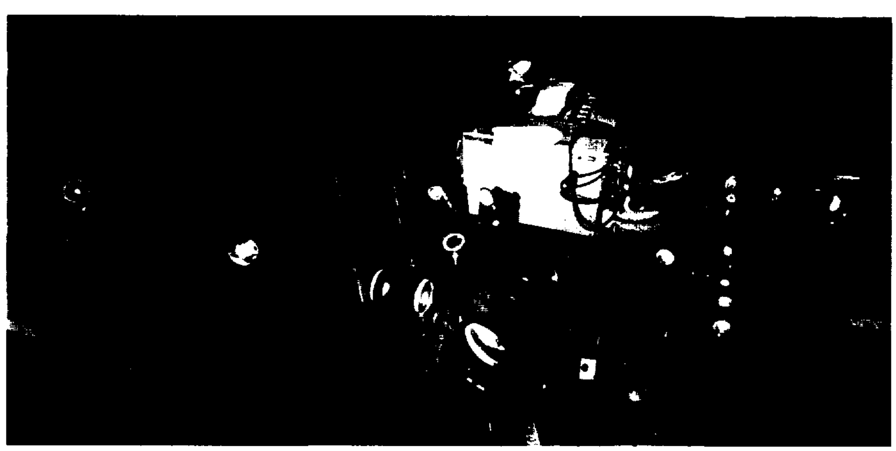

FIGURE 87.—Laboratory breadboard.

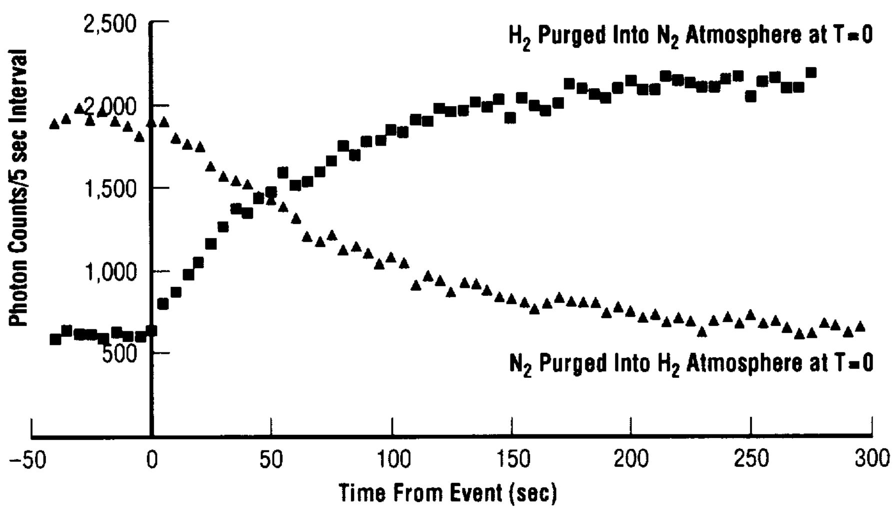

FIGURE 88.—Signal plus fluorscence versus time as chamber is filled and purged of H_2 content.

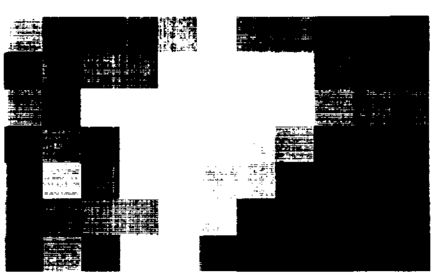

FIGURE 89.—Simple plume image 7×12.

distance of 70 cm (from the probe focus). Using the previous breadboard, it was impossible to obtain any signal even when using a pulsed laser and a 5 ns time gate. Figure 89 represents the first hydrogen leak image ever obtained using this new technology.

The confocal telescope breadboard can have its performance improved considerably by using a more elaborate narrow band filter. Use of a pulsed laser would greatly increase signal quality. The fact that data could be obtained using a CW laser opens the possibility of using a CW laser in a fully developed unit.

In March 1996 the project was refunded under a different program. The image of figure 89 was obtained by laboriously scanning the scene by hand and purging the chamber between pixels. The next step is to install a fast control system which can turn the confocal telescope breadboard into a real-time imaging system. The target imaging rate for the current phase is 300 pixels/sec.

The control system needed to drive the image system must be fast, must be built cheaply, and cannot use conventional software such as LabVIEW due to the performance requirements. A conventional PC hardware platform was long ago chosen for development to allow usage of lab computers. Extended DOS was chosen as the software platform to avoid 16-bit limitations, which are severe, and avoid dependence on slow and complex operating systems. The software effort is loosely categorized as an object oriented architecture, which allows maximum flexibility.

One software innovation which is mature is the cloning of 32-bit-protected mode-interrupt handlers written in C to real mode 16-bit mode, which converts each real-time interrupt function into a dual mode function. This avoids mode shifts upon an interrupt. This feature may be important as the software is migrated to a PC/104 platform.

Figures 90 and 91 display the software architecture which is being written. At present the software is being integrated with the circuit shown in figure 92 to give maximum imaging speed. The goal of the current phase is to demonstrate a real-time imaging capability.

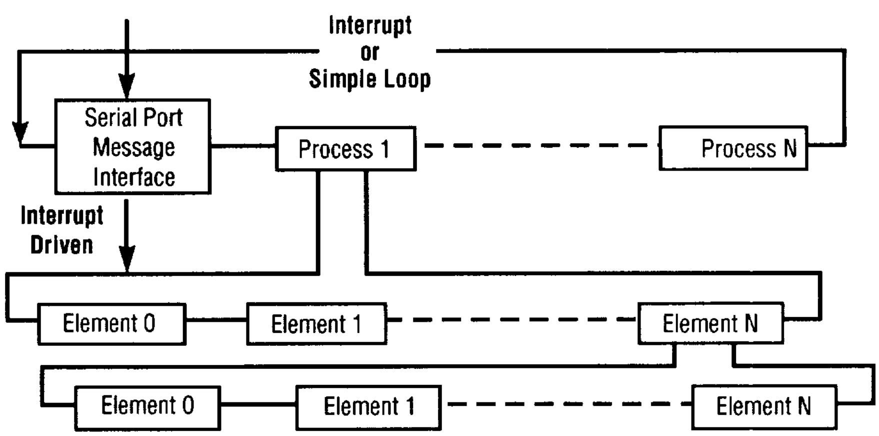

FIGURE 90.—Scheduler for background process (PC/104 system). Scheduler can nest: registry allows all elements (i.e., class instances) to point to one another. Each element can respond to queries via serial port for debugging.

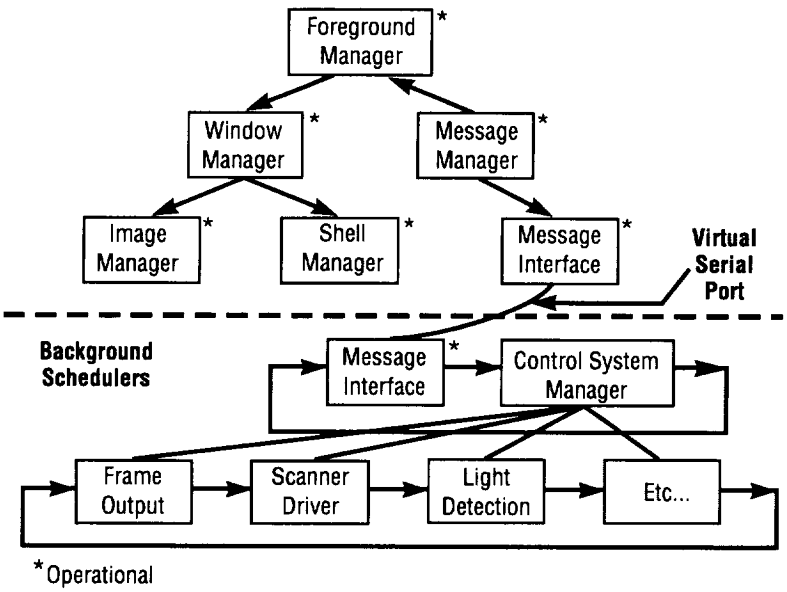

Figure 91.—Software architecture.

It turns out that the software being written is ideal for use on other projects, such as other smart sensors and networked control systems. One possibility is a health maintenance network of spacecraft sensors. One factor which helps this extensibility is the fact that the software is DOS-based. PC/104 embedded controllers can run extended DOS. The current software already contains the most important features needed to run the real-time portion (also called the background process) on an embedded controller. What remains is to actually rearrange the software classes such that they will compile and run on both a standalone PC and an embedded controller.

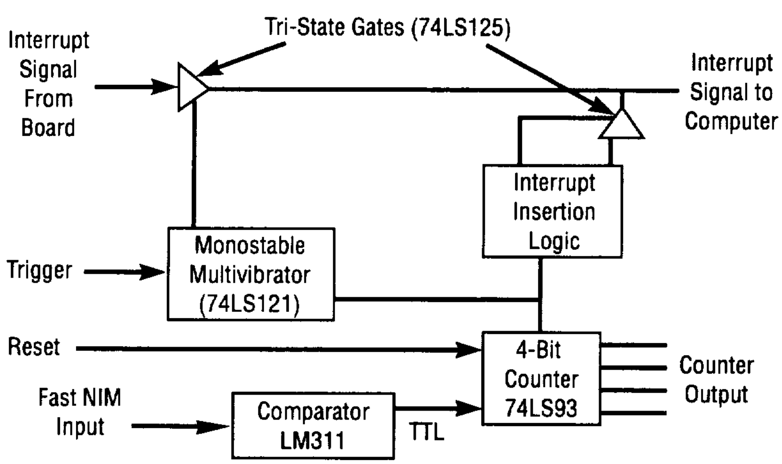

Figure 92.—Interface circuit block diagram.

When the background process software migrates to an embedded controller, the component which remains on the console PC, called the foreground process, can evolve into a standard PC application. This enables the author to migrate the foreground classes onto an advanced operating system such as Windows NT, which enables graphics windows and integrated network support. Thus the foreground application can evolve into an application which runs across the Internet, allowing more than one console to operate or monitor a network of sensors. (Use of simple device drivers could allow the background process to run under Windows NT at reduced speed.) The sensors themselves can easily be turned into Internet nodes among other protocols. This is exactly the sort of development needed to create the next generation of spacecraft control system. In addition, the software could be used in commercial applications that require flexibility and high performance.

Thus the goal of producing the first hydrogen leak imaging system is coincident with that of producing the software needed on the next generation of spacecraft. An ideal set of software components would have foreground and background classes which could be used under different combinations of desktop PC's and embedded controllers, and various combinations of operating systems.

Sponsor: RLV—Long-Term/High-Payoff Technologies Program

Biographical Sketch: W.T. Powers is a senior measurement systems engineer in the Instrumentation Branch of the Astrionics Laboratory of MSFC. He holds a bachelor of science in electrical engineering, minors in mechanical, nuclear and physics, from Tennessee Polytechnic Institute. Powers has 33 years service with NASA and primarily deals with development of advanced sensors and measurement, acquisition, and processing systems.

An OPAD System to Fly on DC–XA

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For several years, MSFC engineers have been collaborating with other NASA centers, Government agencies, universities, and businesses in attempts to apply spectrometric analysis to the monitoring and diagnosis of rocket engine health. The Space Shuttle Main Engine Technology Test-Bed (SSME TTB) in Marshall's west test area has been home during this time to several incarnations of sensor systems designed to identify traces of metals in the exhaust. These efforts have met with satisfying and encouraging results. Instruments for this purpose are grouped together under the technology entitled optical plume anomaly detection (OPAD).

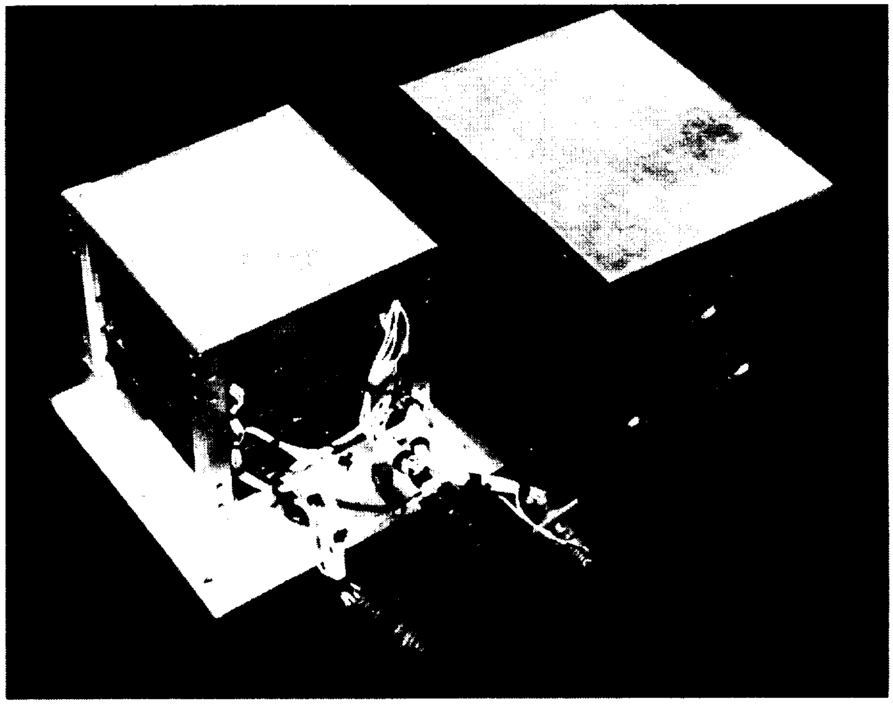

FIGURE 93.—DC–XA OPAD control computer assembly.

While advances were being made in the technology required to actually accomplish optical plume analysis, the question was being asked: "Will it fly?" For this reason, the opportunity to put a test instrument aboard DC–XA was met enthusiastically. The objectives of this endeavor were fairly basic: First, to fly a working version of an OPAD instrument; second, to do it using inexpensive commercial off-the-shelf (COTS) hardware where possible; and third, to collect useable data.

A decisive first step involved choosing a hardware platform upon which to build. Although it was relatively young, the PC/104 format was promising as a miniature computer standard with a rapidly growing vendor base. This format restricts computer cards to approximately the dimensions of a 3-in floppy diskette, with 0.6 in separating cards in a stack. The potential thus existed for a control computer box measuring no more than 6 in in any one dimension.

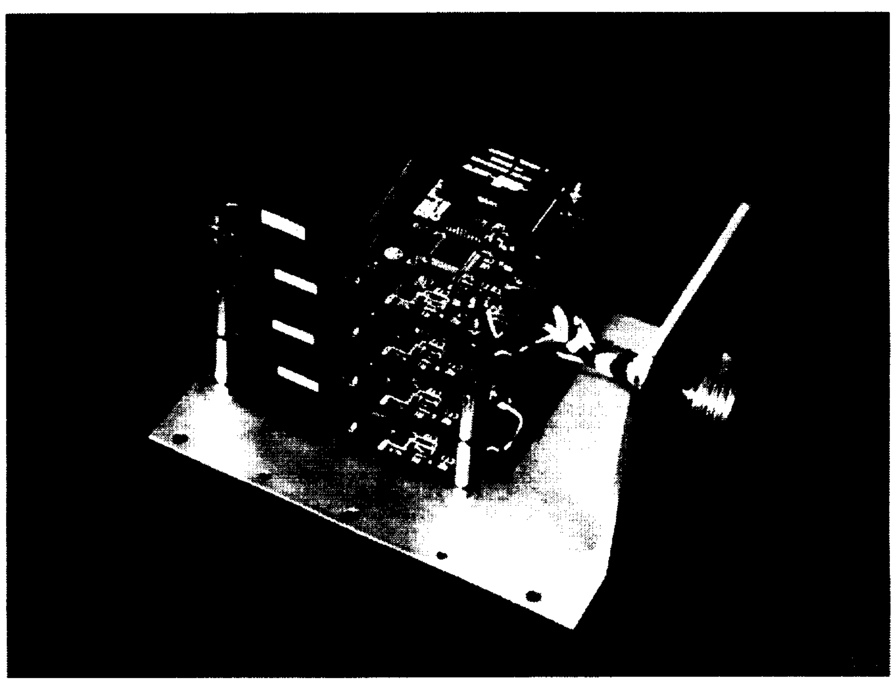

Figure 94.—DC–XA OPAD spectrometers assembly.

No single PC/104 vendor had all of the component cards required to assemble a complete system. For this reason, the central processing unit (CPU) card and analog-to-digital converter card were purchased from Real Time Devices (RTD), the 16-megabyte flash disk card came from M-Systems, the enhanced serial communications card (ESCC) from WinSystems, and the dc-to-dc power supply from Tri-M. The ESCC was capable of extended temperature range operation (about –40 to +80 C), while the remaining boards were screened for this capability at an extra charge. Additionally, a standard temperature range video card was purchased from RTD for use only during system development.

The individual cards were modified in that on-board jumpers were soldered in place, all connections to the outside world were made using soldered wire rather than connectors, wire bundles and socketed chips were tied down with lacing cord, and the clock battery was sandwiched between cards using RTV. All of the flight cards were stacked with stainless steel standoffs and installed in a custom enclosure from Parvus Corporation. Cost of the computer cards was approximately $4,000, and the custom enclosure was an additional $1,000.

Software was developed in Borland C++ on a separate desktop computer, then ported to the control computer using LapLink. The compiled executable was targeted to the DOS environment. Modifications of the executable at the launch site, and downloading of test data in some instances, were accomplished on a ground connection to the CPU card's built-in serial port through a vehicle umbilical; unfortunately, this link was limited to a rate of 9,600 baud, a relative snail's pace by current standards.

The spectrometer units were housed apart from the control computer. Ocean Optics supplied four ruggedized miniature spectrometers, one per engine, which were stacked using stainless steel standoffs. Each spectrometer unit was different from the standard COTS unit only in that the optional lens assembly in the optics section was mounted in epoxy for stability. Cost of the four-unit stack was approximately $4,000. It was mounted in a custom enclosure produced in-house at MSFC.

Light from the engine plumes at the base of the vehicle had to be collected and presented to the spectrometers in the avionics rack near the top of the vehicle. For this purpose, each unit had a 40-ft quartz optical fiber which ran to a miniature telescope assembly near one of the engine nozzles. Fibers were purchased in custom lengths from Ocean Optics, for about $400 each. Arnold Engineering Development Center designed and produced the telescopes in-house.

Before each test of an OPAD system, a series of calibrations must be performed to ensure that test data subsequently collected is meaningful. Such a series includes scans of the optical field in ambient light, followed by scans with a calibrated wavelength source, then a final scan with a calibrated intensity source. The first of these is subtracted to help negate the effects of ambient light and electronic "dark current" noise. Wavelength data allows correlation of individual data points to specific wavelengths. Finally, intensity calibration helps to determine the relationship between an intensity count for a given data point and the actual optical intensity received at the engine telescope.

Static firings preceding the first flight of the DC–XA allowed attempts to finalize procedures and verify the system, since installation in the vehicle was the first time it was completely assembled. While data were collected before and during these firings, procedural and hardware problems prevented successful collection of both valid calibrations and test data during any given test. On the other hand, it was very encouraging that the electronics operated at all under the extreme conditions of the launch site during these tests.

The experiment hardware continued to operate during four subsequent flights. However, telemetry downlink failure during the first flight prevented collection of any flight data whatsoever. Then, the system failed to receive its startup signal from the vehicle computer on the second flight. Data was successfully collected during the third flight, but the calibration data was found to be invalid. Finally, the fourth flight yielded success. Engine ignition and shutdown

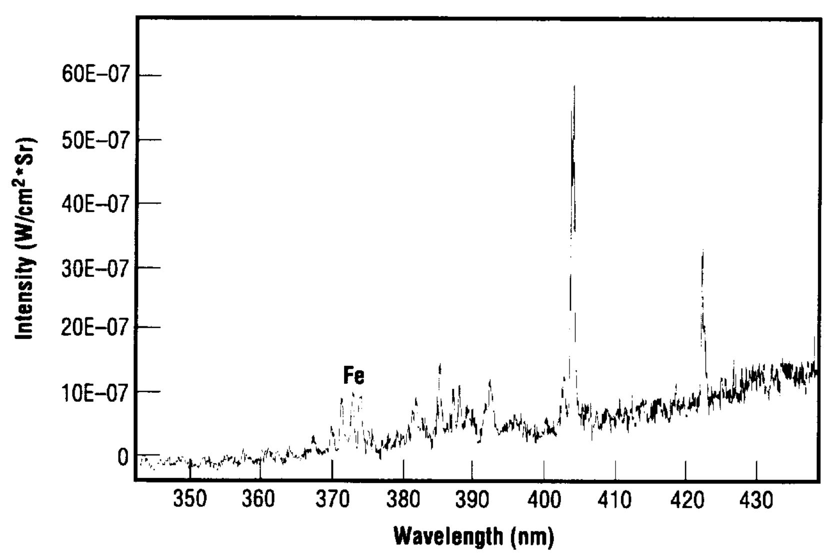

Figure 95.—DC–XA engine two emission spectrum at T+3 sec (Flight 4).

were detected in this data, as evidenced by spectral activity. Figure 95 shows emission activity at engine start plus 3 sec.

Flight four was unexpectedly the last flight of the DC–XA. Upon landing, the vehicle failed to deploy one of four landing legs, fell over, exploded and burned. Amazingly, the OPAD boxes were not consumed by the oxygen fire or the subsequent few hours of exposure to the burning vehicle. In fact, the control computer is still operational, with the exception of its serial ground communication link; its survival can be attributed mostly to a rugged enclosure. The spectrometers, housed in a much lighter and poorly sealed enclosure, did not fare as well though located mere inches from the control computer. All of the vendors have expressed interest in examining their components in hopes of learning from this incident.

Technically, all of the project's basic objectives were met. An OPAD system built with COTS hardware was flown to several thousand feet, and valid data were collected. Even though only one set of data from one engine for one flight was the immediate final product, a wealth of information was gleaned to benefit future generations of rocket-propelled vehicles. The exercise itself emphatically pointed out the necessity for rethinking aspects of ground-based OPAD hardware in order to adapt and harden it for vehicle operations and flight. Calibration procedures must be reworked to make them more compatible with the launch pad environment. The fact that flight conditions include the use of cryogenics in the vicinity of the OPAD instruments presents it own set of complications. In addition, problems experienced with serial ground communication pointed out that remote computing, as it relates to the requirements of this type project, is a very young technology.

Sponsor: Reusable Launch Vehicle Program Office

Industry Involvement: Real Time Devices, Inc.; M-Systems Inc.; Parvus Corporation; Tri-M Systems; WinSystems, Inc.; Ocean Optics, Inc.

Other Involvement: USAF/Arnold Engineering Development Center

Biographical Sketch: Marshall Clinton Patrick is an electronics engineer in the Instrumentation Branch at MSFC. He specializes in electronics design, data communication, and small systems integration. Patrick earned his electronics and computer engineering degree from the University of Alabama in Huntsville in 1986 and has worked for NASA for 15 years.

Optical Plume Anomaly Detection—Engine Diagnostic Filtering System

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The development and testing of new sensor capabilities to address the increasing demands for rapid assessment of rocket engine health has led to the use of plume emission spectroscopy and advanced data analysis techniques. Several years ago, the Space Shuttle Main Engine (SSME) became the subject of a project at MSFC to look at techniques for detecting anomalies in the operation of rocket engines through observation of the exhaust plume. Since then, plume emission spectroscopy has recorded many nominal tests, and the qualitative spectral features of the SSME plume are now well-established, leading to definition of the optical plume anomaly detection (OPAD) system.

The operational health of an engine is examined through the acquisition of spectrally resolved plume emissions and the subsequent identification of abnormal emission levels in the plume indicative of engine degradation or component failure. Since the amount of energy emitted from the plume due to radiation of a given species becomes a highly nonlinear function with increased specie concentration >> hardware erosion, development of a process necessary to define these abnormal emission levels presents numerous challenges. The optical plume anomaly detection-engine diagnostic filtering system (OPAD–EDIFIS) is the defined process to accomplish the tasks. OPAD–EDIFIS will make analysis fast, reliable, and readily adaptable to other rocket engines.

OPAD–EDIFIS is a comprehensive/complex platform of various modules representing the combined efforts of MSFC, Ames Research Center (ARC), the Air Force's Arnold Engineering Development Center (AEDC) at

Tullahoma, Tennessee, University of Alabama at both Tuscaloosa and Huntsville, Dr. Wray Buntine, an ARC subcontractor, and T. L. Wallace, a graduate student. In its present form, it embodies gigabytes of code/data with various graphical display capabilities. The "real-time" version(s), currently under development, will exist as a stand-alone subset of the EDIFIS.

Basically, the analytical modules consist of:

- Preprocessing codes;
- Spectral codes;
- Neural networks; and
- An optimization/fitting routine.

A typical spectrum generated has three components: A dominant component due to both equilibrium and chemilumenescent emission of the OH molecule generated by the hydrogen burning SSME; a background continuum component due to an unbound state of H_2O and the unavoidable measurement of scattered background light; and possibly a metallic component indicating metal erosion. Several metals of interest radiate in the OH region. Unfortunately, the complex interaction of the OH and water vapor emissions are poorly understood and little quantitative data are available that would permit development of an accurate model. Ames Research Center and Dr. Wray Buntine have developed statistical/filtering preprocessing techniques to address this problem, isolating the metallic components of the spectrum. Figure 96 isolates three metals of interest in test 901–853, engine 0523 failure of HPFTP/AT Unit 6–4 at Stennis Space Center in January, 1996. Elements Cr, Co and Ni are plotted for the test duration. (Saturated lines at shutdown are omitted.)

A line-by-line (LBL) atomic spectral model developed by T.L. Wallace predicts the spectrum for a given metallic species, using

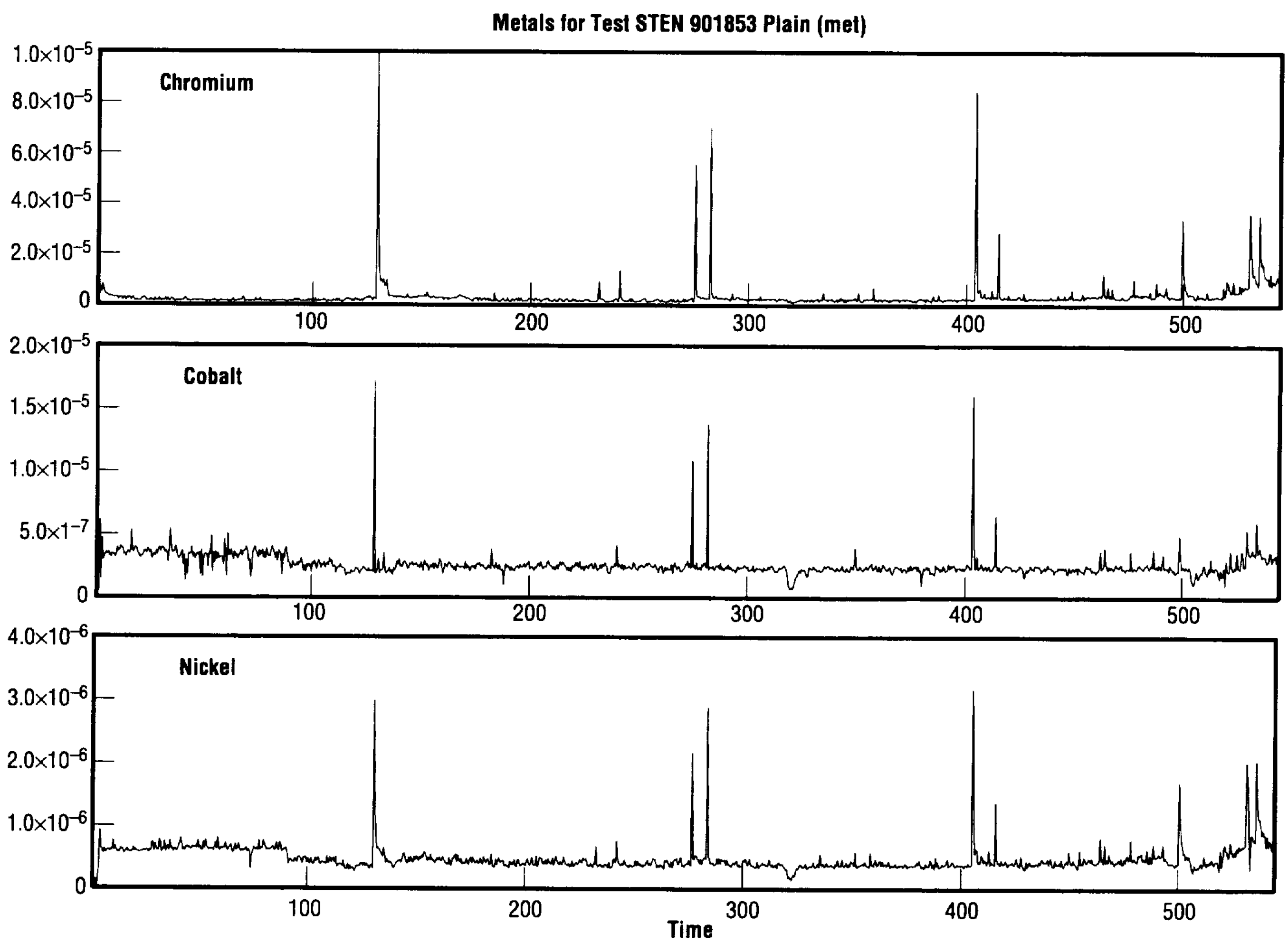

Figure 96.—Cr, Co, Ni erosion.

inputs such as number density, broadening parameter, temperature and pressure. Recently, the focus of efforts related to this module shifted towards validation of the integrated spectral analysis system and spectral model. In particular, work has been undertaken to validate the radiative transport, self absorption and collisional line-broadening mechanisms, and chemical depletion rates to produce error propagations and uncertainties. Code validation is an essential part of spectral analysis, and is required in order to accurately determine species densities from spectral measurements. In late 1995, the SSME was deliberately seeded with known concentrations of two elements at MSFC's Technology Test-Bed (TTB). (Unfortunately, the TTB was closed before additional seeding tests could be conducted.) Spectral data collected by the OPAD system provided confirmation and essential validation data for the spectral model and data processing methodologies. The success of this validation process was evident in MSFC's contribution to the failure investigation of engine 0523 undergoing tests at SSC. While details of this effort will be reported in upcoming technical conferences, the study to determine mass loss estimates for this failure can be briefly summarized as follows:

- The study made certain assumptions of 100 percent RPL, 100-cm observation path length, uniform distribution of eroding material, and steady-state erosion during each 0.5-sec integration interval;
- The study, due to time constraints, addressed only certain periods of a specified set of erosion events; not all erosion activity was present in the entire test;
- The study quantified two of approximately nine elements identified in the erosion events. SSME seeding data is presently limited to chromium (Cr) and nickel (Ni). Coincidentally, Cr and Ni are primary constituents of the alloys reported lost; and
- Pratt & Whitney measurements of mass loss during post-test hardware tear down and inspection totaled approximately 94.45 grams. The MSFC EDIFIS process predicted 37 grams.

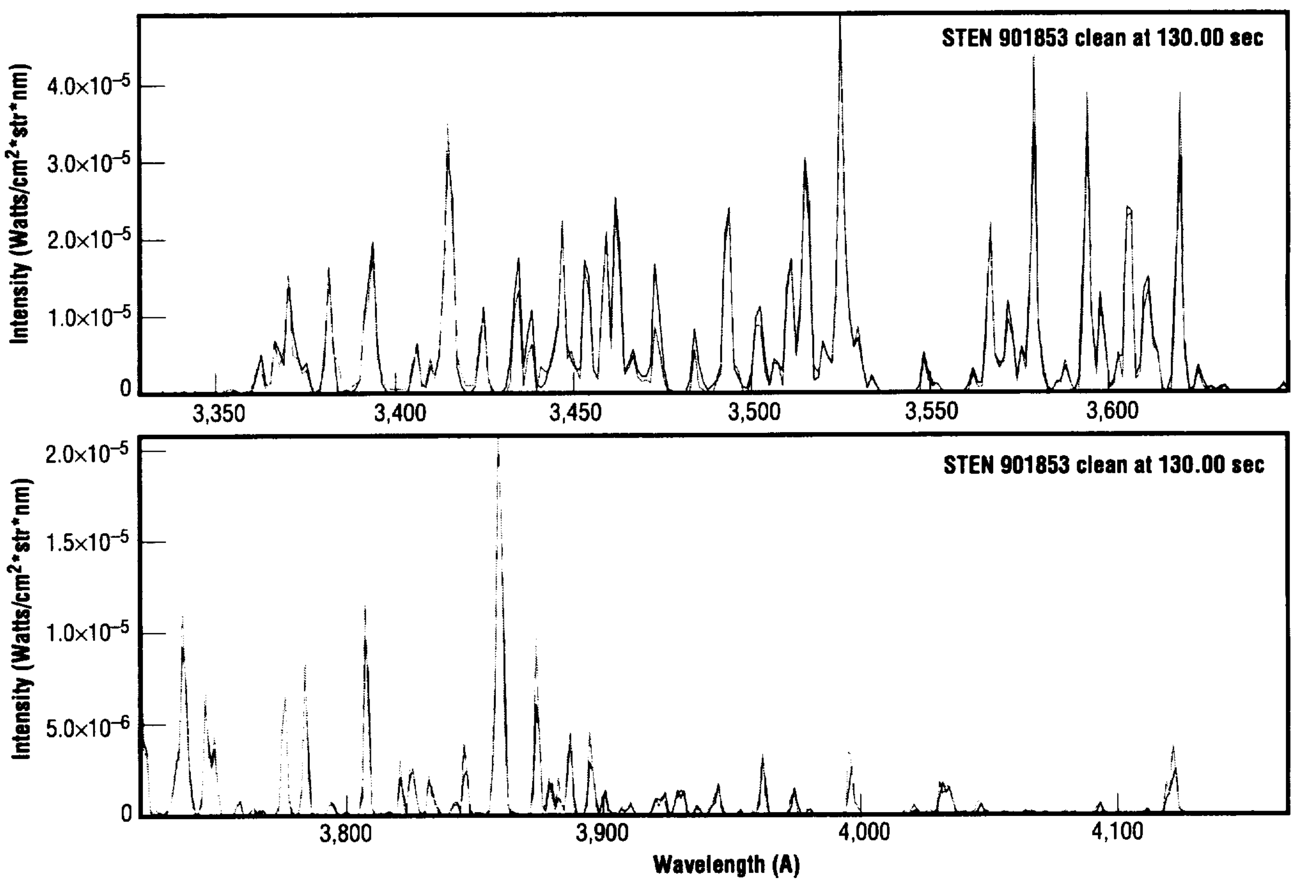

FIGURE 97.—Optimization/fitting results for 130-sec event.

While error and uncertainty analyses are underway, the predicted spectral results are almost indistinguishable from the actual failure event data and rank among the best to date for such complex spectral data.

What is required for the determination of mass loss is the inverse of the spectral model. Given a spectrum, predict combustion temperature and element concentrations (i.e., number density and broadening parameter). The fourth module listed above, optimization-fitting routine, was first used as part of the EDIFIS for the engine 0523 failure investigation. These nonlinear fitting routines on approximately 15 variables using spectral radiation models for 10 atomic species for a total of some 1,500 atomic lines required around 1 hr on an MIPS 8,000 per 0.5 sec of test data, before the fitting converged to approximately 5 percent RMS error. Note the overlay of theoretical versus actual test data in figure 97. While the results are indeed impressive, the computational time requirements have to be addressed for inflight/real-time systems.

The third module, neural networks, can solve the inverse problem to the spectral model by "learning" how it works. Initially, only minimal accuracy of the neural networks may be required, at which point the optimization/fitting algorithms would complete the predictions. As the EDIFIS work continues, however, neural networks may provide the ultimate solution for inflight "real-time" applications. The University of Alabama at Tuscaloosa has developed a preliminary set of radial basis function (RBF) networks—one network for each element of interest. This set recently evaluated the entire engine 0523 failure test (which lasted around 553 sec) for seven elements in approximately 2.6 min. Temperature, number density and broadening parameter predictions are plotted for three elements, Cr, Ni and Co, respectively, in figure 98. Note from column two of figure 98, when compared to figure 96, how well the neural nets recognize the major events for each of these elements. Improvements in speed and accuracy of the neural networks through the use of better training

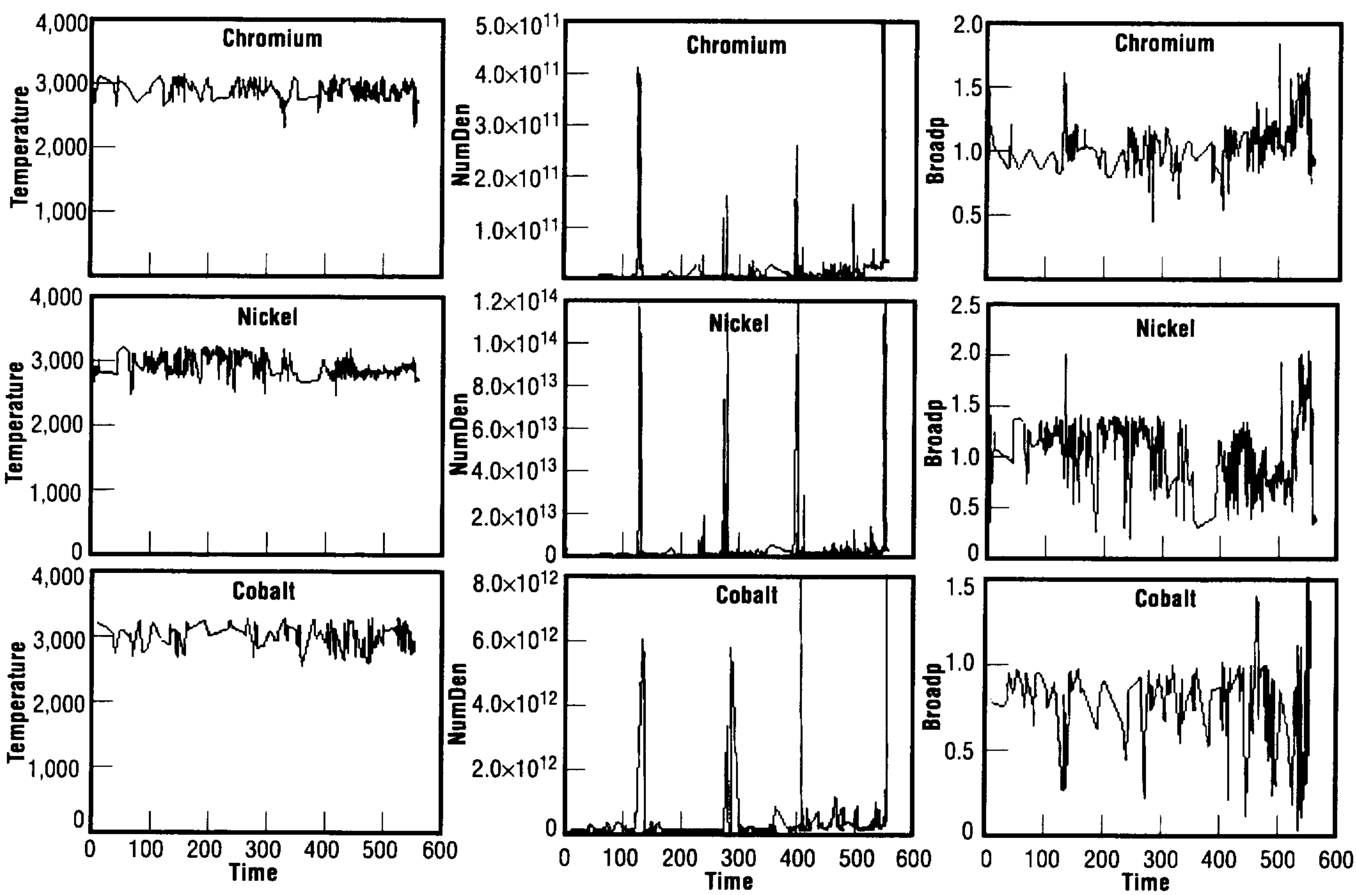

Figure 98.—Temperature, number density and broadening parameter neural net results for Cr, Ni, Co.

data can be realized, and such efforts are underway.

Integration of the modules to provide a response time equal to sampling time is a primary goal for the OPAD–EDIFIS system. An investigation is underway by the University of Alabama in Huntsville, Department of Electrical and Computer Engineering, to look at processing improvements through computer architecture and conversion of various software codes into a form which is easily parallelizable.

Wallace, T.L.; Powers, W.T.; and Cooper, A.E.: "Validation of UV-VIS Atomic Spectral Model for Quantitative Prediction of Number Density, Temperature and Broadening Parameter." 1995 JANNAF Exhaust Plume Technology Subcommittee Meeting, October 1995, MSFC, AL (restricted).

Benzing, D.A.; Whitaker, K.W.; and Krishnakumar, K.: "SSME Condition Monitoring Using Neural Networks and Plume Spectral Signatures." AIAA no. 96-2824, Lake Buena Vista, FL, 1996.

Sponsor: NASA Headquarters, Office of Space Science

University/Industry Involvement: University of Alabama, Huntsville; University of Alabama, Tuscaloosa; Vanderbilt University; Tennessee Technological University

Biographical Sketch: Anita Cooper is an electronics engineer in the Instrumentation Branch of the Astrionics Lab at MSFC. She conducts and manages research for the optical plume anomaly detection program to enable development and application of plume spectroscopy technology to rocket engines. Cooper earned her bachelor of science in physics from Athens State College and has worked for NASA for 7 years.

Nonintrusive Measurement of Fluid Flows in High-Pressure, High-Speed Cryogenic Regimes

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The purpose of this work is to measure volumetric flow rate of cryofluids under single-phase and some two-phase conditions. The cryofluids flow inside a thin-walled conduit at velocities that can exceed 35 m/sec (115 ft/sec). Flow is measured ultrasonically by using external ultrasonic transducers that clamp onto the outside of the conduit. This type of noninvasive flow measurement is desirable in many applications in general and specifically in applications such as the lox and LH_2 ducts of the Space Shuttle Main Engine (SSME).

The small clamp-on ultrasonic transducer (fig. 99) developed under Contract NAS8-38429 was measured in the contrapropagation mode, single-phase LN_2 flowing inside space shuttle ducts having diameters either near 33 mm (1.30 in) or near 100 mm (3.93 in) and wall thickness near 3 mm (0.12 in). Flow velocity ranged between ~0.1 (3 ft/sec) and 6 m/sec (19.7 ft/sec). In another test (conducted in July 1996 at the BETASSO water treatment plant in Boulder, CO.) the transducers operated in the contrapropagation mode in conjunction with a commercial portable ultrasonic flowmeter (Panametrics' Model PT868). Dr. Jim Siegwarth of NIST/Boulder was a collaborator in this test (fig. 100) in which water was flowing (up to 37 m/sec (121 ft/sec)) in the low-pressure oxygen turbopump (LPOT) turbine drive duct (58.42 mm (2.3 in) ID×4.19 mm (0.165 in) wall).

The long-term objective of the program is to measure lox and LH_2 flowing inside the ducts of the SSME. The preliminary piggyback testing was done with lox flowing in SSME's high-pressure oxygen turbopump (HPOTP) discharge duct (111 mm (4.37 in) ID×4.45 mm (0.175 in) wall) and in the fuel pre-burner (FPB) supply (50.7 mm (1.996 in) ID×3.23 mm (0.127 in) wall) at the MSFC test stand. The

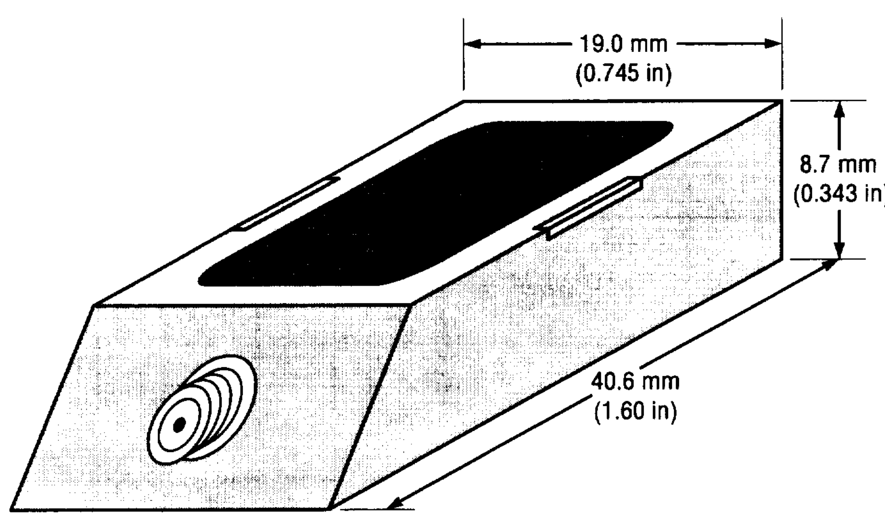

FIGURE 99.—Small mass clamp-on transducer, mass=29 grams, frequency 500 kHz.

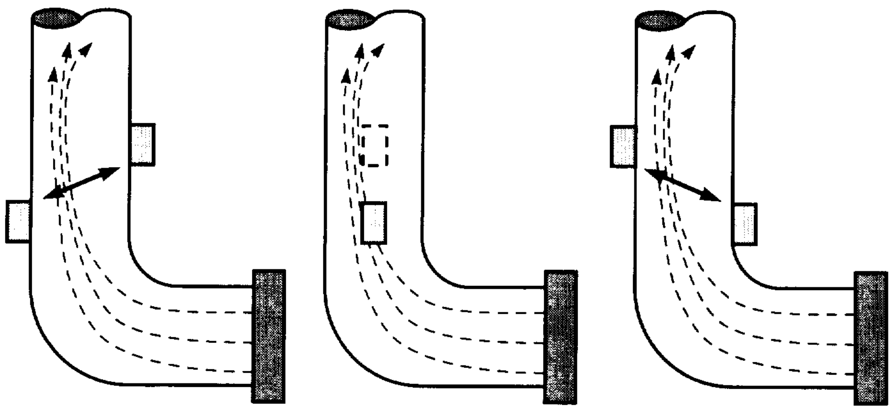

FIGURE 100.—Test with water flowing (up to 37 m/s) inside the LPOT turbine drive duct. In (a) the flow velocity, measured along the path represented by the double-arrowed line, was lower than in (c). However, the average of the flow velocities in (a) and (c) was approximately equal to the flow velocity in (b). A practical observation can be drawn from the test. To avoid the influence of swirl due to the upstream elbow: (1) a one-path flowmeter system should have a pair of transducers mounted in a plane such that it is perpendicular to the plane of the elbow as in (b); or (2) a two-path flowmeter system should have two pairs of transducers mounted in the same plane as the plane of the elbow as in (a) and (c) combined. Note: The flow lines are hypothetical.

transducers and their couplant survived the duct vibration and the cryogenic temperature of the lox. The available commercial flowmeter systems, however, have not yet successfully measured flow in the contrapropagation mode in these tests.

Our plans are to conduct more tests to better understand the "violent" conditions (flow turbulence and duct vibration) of the SSME ducts. Tests will be performed with the transducers operating in the contra-propagation and reflection modes in conjunction with Panametrics' commercial flowmeter. Tests will first be conducted in laboratory water or LN_2 flow loop. Later tests will be conducted on the lox duct of the SSME at the Stennis Space Center test stand. It appears that the high-velocity, highly turbulent, cryo conditions may require signal processing methods that are more robust than those that were commercially available during the year covered by this reported. Such improved methods are already under development for high-flow highly turbulent fluids, especially gases, and should be ready for testing in the coming year on single- and two-phase cryofluids.

Lynnworth, L.C.; Matson, J.E.; Nguyen, T.H.; Powers, W.T.: "Small-Inertia Clamp-on Cryogenic Flowmeter Transducer." *1992 Conference on Advanced Earth-to-Orbit Propulsion Technology*, vol. I, pp. 207–216, May 19–21, 1992.

Lynnworth, L.C.; Nguyen, T.H.; Liu, Y.; and Stein, P.: "Clamp-on Flow Velocity and Density Transducers for Liquid Nitrogen and Other Cryogenic Applications, Especially in Thin-Walled Conduits." *1994 Conference on Advanced Earth-to-Orbit Propulsion Technology*, vol. I, pp. 97–104, September 1994.

Sponsor: RLV—Long-Term/High-Payoff Technologies Program

Biographical Sketch: W.T. Powers is a senior measurement systems engineer in the Instrumentation Branch of the Astrionics Laboratory of MSFC. He holds a bachelor of science in electrical engineering, minors in mechanical, nuclear and physics, from Tennessee Polytechnic Institute. Powers has 33 years service with NASA and primarily deals with development of advanced sensors and measurement, acquisition, and processing systems.

Development of 8-Channel, 16-Bit Smart Card for Pressure Transducers

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The term "smart sensor" has been used in a number of different ways, ranging from sensors incorporating an active device to provide a more reliable interface to the sensor, to integrated sensors with a electronic circuit block including both digital and analog circuitry which becomes a "smart" periphery of a control system. However in the recent past, a broad definition has been achieved whereby a smart sensor is defined as one that is capable of:

- Providing a digital output;
- Communicating through a bidirectional digital bus;
- Being accessed through a specific address; and
- Executing commands and logical functions.

An 8-channel, 16-bit smart card for use in propulsion applications as shown in figure 101, has been designed, developed and fabricated to incorporate diagnostic and signal conditioning electronics. The three most important areas in the development of this 16-bit smart card are:

- Multiplexing of 8-channel inputs;
- Analog/ Digital conversion; and
- The processor which interprets decisions and implements those decisions.

The three main parts of smart DAQ board are shown in figure 102. This card has the following characteristics:

- Output is 16 bits;
- It has two data buses utilizing 485, each capable of addressing four sensors;
- It has fault detection capability to verify that the sensor is operational;
- It has an output code for sensor identification; and

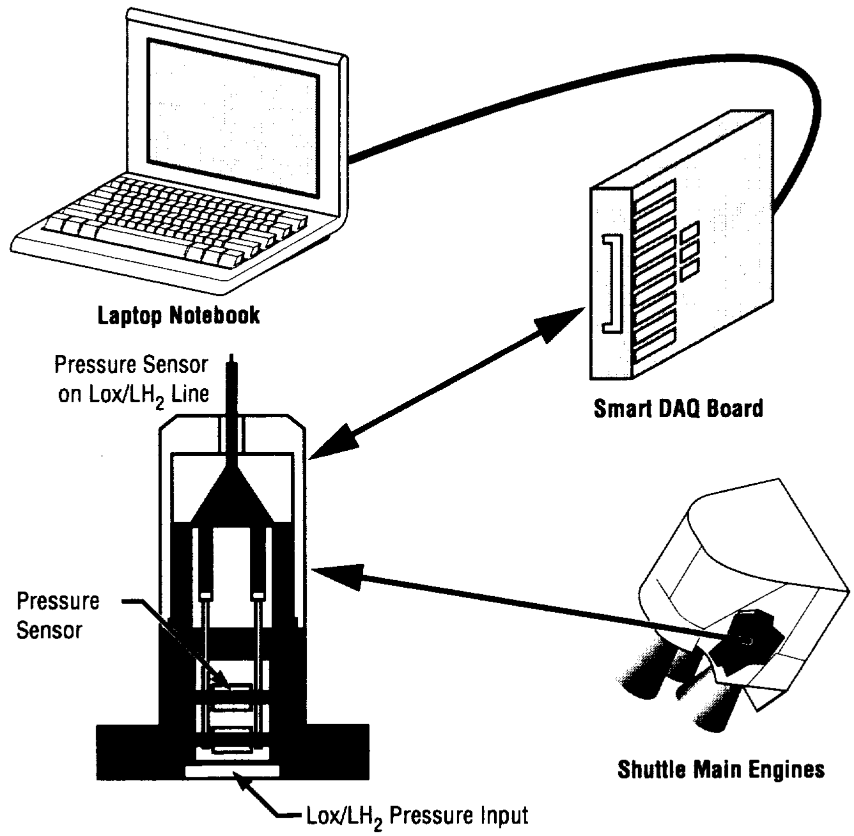

FIGURE 101.—Cryogenic smart sensor—system component diagram.

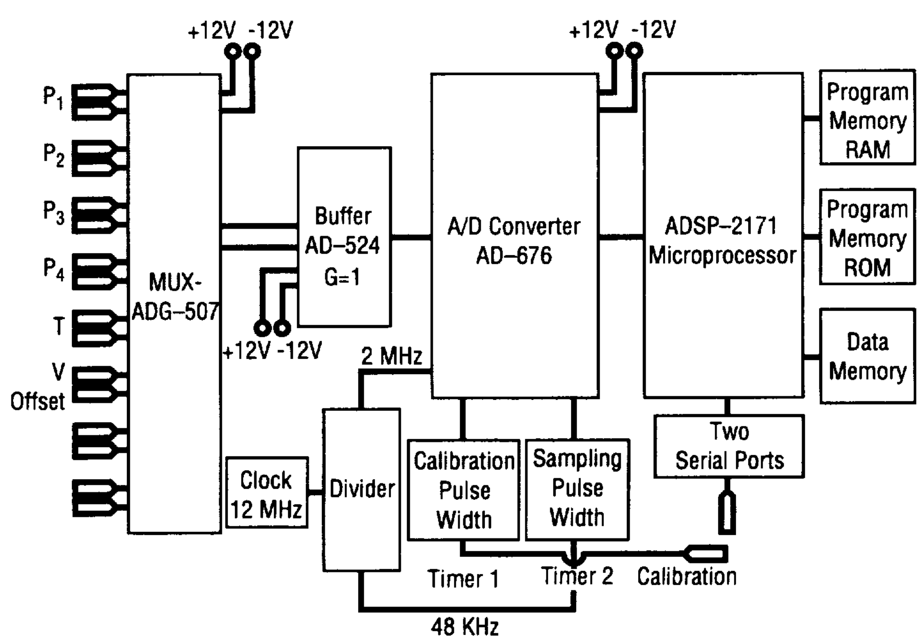

FIGURE 102.—Eight-channel, 16-bit smart card main functional components.

- It is capable of downloading calibration coefficients including zero, sensitivity, thermal, and other parameters required for conversion of sensor voltage output to engineering units, to a calibration table in the sensor process.

Reducing the number of leads is an important function for a majority of sensors. Data multiplexing as shown in figure 102 can not only reduce the amount of circuitry required for the sensor, but also reduces the number of external leads by multiplexing in sensing arrays and systems that require the simultaneous measurement of many signals in order to accurately measure the parameter of interest.

The second block (AD–676) provides digital output. Once the sensor data is digitized, a variety of signal processing schemes can be used to correct errors. These include offset cancellation, autocalibration, self testing, fault detection, correction and linearity correction. Another advantage is to perform some of these functions using a remote host processor rather than to implement them at the sensor site.

The third block of the smart DAQ card is ADSP–2171, a microprocessor which controls and manages the overall system. This processor interprets the information, makes appropriate decisions, and implements them.

Sponsor: RLV—Long-Term/High-Payoff Technologies Program

Biographical Sketch: W.T. Powers is a senior measurement systems engineer in the Instrumentation Branch of the Astrionics Laboratory of MSFC. He holds a bachelor of science degree in electrical engineering, and minors in mechanical, nuclear and physics from Tennessee Polytechnic Institute. He has 33 years of service with NASA and primarily deals with the development of advanced sensors and measurement, acquisition, and processing systems.

Long-Term/High-Payoff's OMS IVHM Tested—First Pneumatic System With Fully Automated Checkout

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The use of single-stage-to-orbit (SSTO) technologies to reduce the operations costs for the X–33/RLV programs provides the opportunity to reduce the recurring production and refurbishment costs associated with the present external tank and solid rocket boosters on the Shuttle. However the implementation of SSTO dramatically increases the number of fluid components and complexity; fluids already represent the largest operational driver on the present orbiter. Several system level technologies (i.e. common commodities, EMA's, etc.) have been recommended to help reduce these operations costs; however there is still a need to address the recurring costs associated with checking out the fluid components every flight or during standardized maintenance periods. This requires on the Space Shuttle a large number of test ports, quick disconnects and ground support equipment to accomplish individual component checkout (fig. 103).

With the increased emphasis and planning on the use of integrated vehicle health management (IVHM) as a key to reducing operations costs on X–33/RLV, there is a need for real-life applications in genuine flight and operational environments. In addition, with the realization that the Shuttle will be flying many years before an RLV can replace it, many of these technologies can be cost effectively retrofitted on the shuttle. This IVHM system automates test and checkout requirements for the Orbital Maneuvering System/Reaction Control System (OMS/RCS) pneumatic systems that could take up to 1 week (2 shifts/day) and could require over 40 ground connections to the flight vehicle (quick disconnect (QD) mate, leak test each QD, etc.).

FIGURE 103.—Complex GSE replaced with small on-board components.

The Shuttle OMS/RCS, which has some of the most stringent operational checkout requirements, was chosen to demonstrate this technology. It is especially challenging due to its high usage of redundant components, the checkout requirements, and the lack of sensors with the data resolution/response required. This drives the current use of manpower and ground support equipment (GSE) intensive operations to perform all of the necessary checkout requirements. With existing instrumentation the required checkout data cannot be determined with just "in-flight" evaluation.

The operational and maintenance requirements specification document (OMRSD) for the OMS/RCS pneumatic components was used as the evaluation criteria for technical success/failure. The goal was to recreate ground checkout configurations without the need for hook-up of external GSE and be able to gather/analyze equal or better test data. Rockwell developed and demonstrated an on-board bias and vent control unit (OBVCU) which was used to create unique checkout configurations such as biasing open the primary regulator for second regulator checkout. This series of sensors and solenoid valves is a key to performing isolation valve, regulator, and check valve check out without GSE.

A VME-based system was used for data acquisition and control stimulus. Coupled with the new Taber transducers on board, very high data resolutions will be possible. The system will acquire, display and record a true 100+ Hz sample rate. The VME is connected to a Sun Ultra Sparc workstation running G2 a real-time expert system program (fig. 104). G2 runs the automated control and analysis sequences and provides the graphical user interface.

FIGURE 104.—Data acquisition and control system.

Regulator testing requires:

- Regulated flow within OMRS limits (272 +5 –7 for primary, 279 +5 –7 for secondary);
- Lock-up pressure below OMRS limits (281 for primary, 288 for secondary);
- Response with in 3 sec to regulated flow limits; and
- Creep test to verify regulator leak rate is below 720 SCCH sum.

There are dual regulars on the OMS/RCS helium pressurization system. One is an active primary and the other is a backup with a higher set-point that automatically takes over if the primary fails to open. Regulator checkout on the OMS/RCS can be one of the more time consuming portions of the OMS/RCS Helium pressurization checkout The primary regulators required two additional transducers (P5 and P8) with high data resolution) and high sample for checkout. The secondary regulators need additional instrumentation and require a mechanism to bias open the secondary regulator without hooking up external GSE. Our approach was to use the existing on-board pressurant to bias the primary regulators. With the OBVCU the secondary regulators can be biased open to perform secondary regulated flow, lock-up, response and creep tests. The use of the OBVCU tied to our advanced checkout system allows all regulator checkout on a pressurization system to be accomplished within 1 hr. There are eight systems which could be tested in parallel using this IVHM approach in no more than one shift. All regulator checkout has been automated and demonstrated on the on OMS IVHM test-bed. The only additional work is the testing of acoustic emission and ultrasonic as an alternate leak detection method.

Required testing for the isolation valves requires combined leakage (NMT 720 SCCH if 3 of 4 regulators are less than 360 and the other is less than 1200 SCCH).

The current approach to performing isolation valve leakage is to put a delta pressure transducer across the check valve to assure no flow across it and measure the rise in pressure between the isolation valves and check valve. If there is flow across the check valve, it is backed up with a higher pressure to preclude the flow. This requires our OBVCU to back up the valve in order to avoid external connections traditionally needed to accomplish this test, which is currently performed every flight. Acoustic emission sensors have been mounted to try assigning leakage magnitude to an individual valve (an OMDP requirement).

Required testing for check valves specifies reverse leakage (360 SCCH) and flow verification (NMT 2.5 PSID).

The OMS/RCS quad check valve presented a particularly challenging component to apply IVHM to because of the requirements for verification of redundant elements and the need to configure for reverse leak check. We used a single delta P connected directly to the intermediate test ports This pressure transducer is capable of withstanding 1,000+ lb/in^2 pressure surges and also provides a polarity (+ or –) that allows any blockage or stuck poppet to be isolated to either flow path. Acoustic emission sensors were used to detect flow in each poppet of the quad check valve.

The combined reverse leakage across all quad check valve poppets was challenging for IVHM application because it required purposely configuring for reverse leakage. Our approach was to use the OBVCU to blow down the section between the isolation valves and the check valve. This creates a reverse differential pressure similar to that produced by the GSE, and with the addition of the transducer P5 added between the isolation valves and the check valves, allows a combined reverse leakage to be determined.

Requires testing for check valves/burst discs specifies burst disk leakage—0 allowable.

There is a combined burst disc and relief valve arrangement downstream of the regulators. The burst disc is checked every time the regulators are tested. The challenge here was avoiding the need to hook up the GSE. The approach was to combine the full range, high fidelity transducer with our 16-bit data acquisition. This test holds the best promise for application of acoustic emission or ultrasonic techniques since it requires a "leak/no leak" determination, not an actual quantification.

The OBVCU concept envisioned three valves used to either divert pressure to the regulators as a bias or vent to configure for leak checks.

Checkout is accomplished during any operational use. With this concept anytime the system is flowed is considered an opportunity to perform automated checkout. The operational times for OMS/RCS checkout are servicing, flight and deservicing. In this case the performance of automated checkout during deservicing holds the following advantages:

- The IVHM system can be driven by the ground checkout system alleviating the need to develop and implement expensive flight software/hardware changes.
- Since the OBVCU can only be activated on the ground its criticality and

associated failure modes are much more benign. The goal is to not have to put special checkout requirements on the OBVCU itself.

- If there is a failure detected in the flight components (or the OBVCU itself) there is now sufficient time and resources to proactively address the problem at the beginning of the flow eliminate the need to make ground connections except to a deservice line.
- The required high flow rates specified by the current OMRS requirements (not nominally available in-flight) are achieved.

One of the concerns with applying IVHM was that the addition of numerous components would add to vehicle weight, increase complexity, and increase vehicle component failures. With the checkout panels/QD's on the pods over 40 individual connections can be required during checkout. Each one must be leak checked and can obviously be a potential failure source. When addressed with the support GSE/facility, the judicious addition of a few sensors can look favorable in comparison. We have simplified the OBVCU concept at under 10-lb/pod.

A major issue that must be considered by any health management system is verification of the health of the instrumentation and data acquisition components. A variety of self-test and diagnostic techniques were applied to verify the health of the IVHM system.

G2, by Gensym, is being used as it readily supports the ability to quickly adapt the software from one test configuration to another with its flexible and rich syntax set. In designing the automated checkout software, object-based reasoning is utilized throughout. An intuitive GUI (fig. 105), which is both a real-time display and a system model, shows state and component attributes.The system records and automatically runs a statistical process control evaluation to determine out of family results, and performs a regression to predict future health of components.

The first fully automated checkout of a pneumatic system in a launch vehicle has been proven in an operational test-bed using off-the-shelf technologies (table 9).

As prior to this work no pneumatic system on a launch vehicle had ever been fully automated, this project demonstrates the feasibility of fully automating even heavily redundant systems using vehicle health management. Some of the general conclusions components reached are:

- Vehicle health management emphasis should shift from a focus on in-flight checkout to checkout through operational use (flight, service, de-service, etc.).
- With the application of IVHM the use of redundancy to increase overall mission reliability need not entail increased and complex test and checkout requirements.
- Through the judicious choice of when and how IVHM components are applied, they need not significantly increase vehicle LRU replacement rates, add additional failure points, engender new checkout requirements for the IVHM system itself, increase weight, etc. In addition, when the overall system (vehicle plus ground structure) including the facility, GSE, test ports, etc. are considered, IVHM can dramatically reduce system complexity, cost, failure rates, etc.
- All of the frequent checkout requirements on the OMS/RCS could be performed using IVHM techniques made up of off-the-shelf components and/or proven technology. Most of the innovation was at the integration and application level. This holds the promise of near-term application to vehicles such as X–33 or the Shuttle.
- Many of the component or element testing (such as element test reverse leak

TABLE 9.—*OMS/RCS frequent checkout and required IVHM.*

Technique Test	High Res X-Ducer's	100 Hz Sampling	P5 0–400	P8 0–400	P2 0–100	ΔP 0–15	T5	T8	OBVCU Valves	Expert S/W
Prime Regulators										
• Flow			X							X
• Lock-up			X							X
• Response		X*	X							X
• Creep	X		X	X			X	X		X
Secondary Regulators										
• Flow			X						X	X
• Lock-up			X						X	X
• Response			X						X	X
• Creep	X	X*	X	X			X	X	X	X
Iso Valves										
• Leak	X		X	X			X	X	X	X
Check Valve										
• Flow						X				X
• Rev. Leak	X		X	X			X	X	X	X
Burst Disk										
• Leak	X				X					X

*Requirement for RCS only

check of the quad check valve) performed at intermediate or depot maintenance periods such as OMDP on the orbiter were not readily solvable with off-the-shelf or proven instrumentation techniques. The application of yet unproven nonintrusive techniques such as acoustic emission, Hall effect, etc. hold the best hope for addressing these requirements.

- The philosophy of checkout through operational use versus only in-flight checkout allows much of the IVHM software to reside on the ground system. This means the software is more amenable to upgrades, changes, reduced maintenance costs, etc.
- The collection and saving of test data/results allows for the potential correlation of past data to predict the future health of the component versus several failure modes. This demand management system allows for proactive replacement of failing parts, logistics stocking and replenishment based on actual component health, identifying of anomalous trends across vehicles, etc.

Sponsor: RLV—Long-Term/High-Payoff Technologies Program

Biographical Sketch: W.T. Powers is a senior measurement systems engineer in the Instrumentation Branch of the Astrionics Laboratory of MSFC. He holds a bachelor of science degree in electrical engineering, and minors in mechanical, nuclear and physics from Tennessee Polytechnic Institute. He has 33 years of service with NASA and primarily deals with the development of advanced sensors and measurement, acquisition, and processing systems.

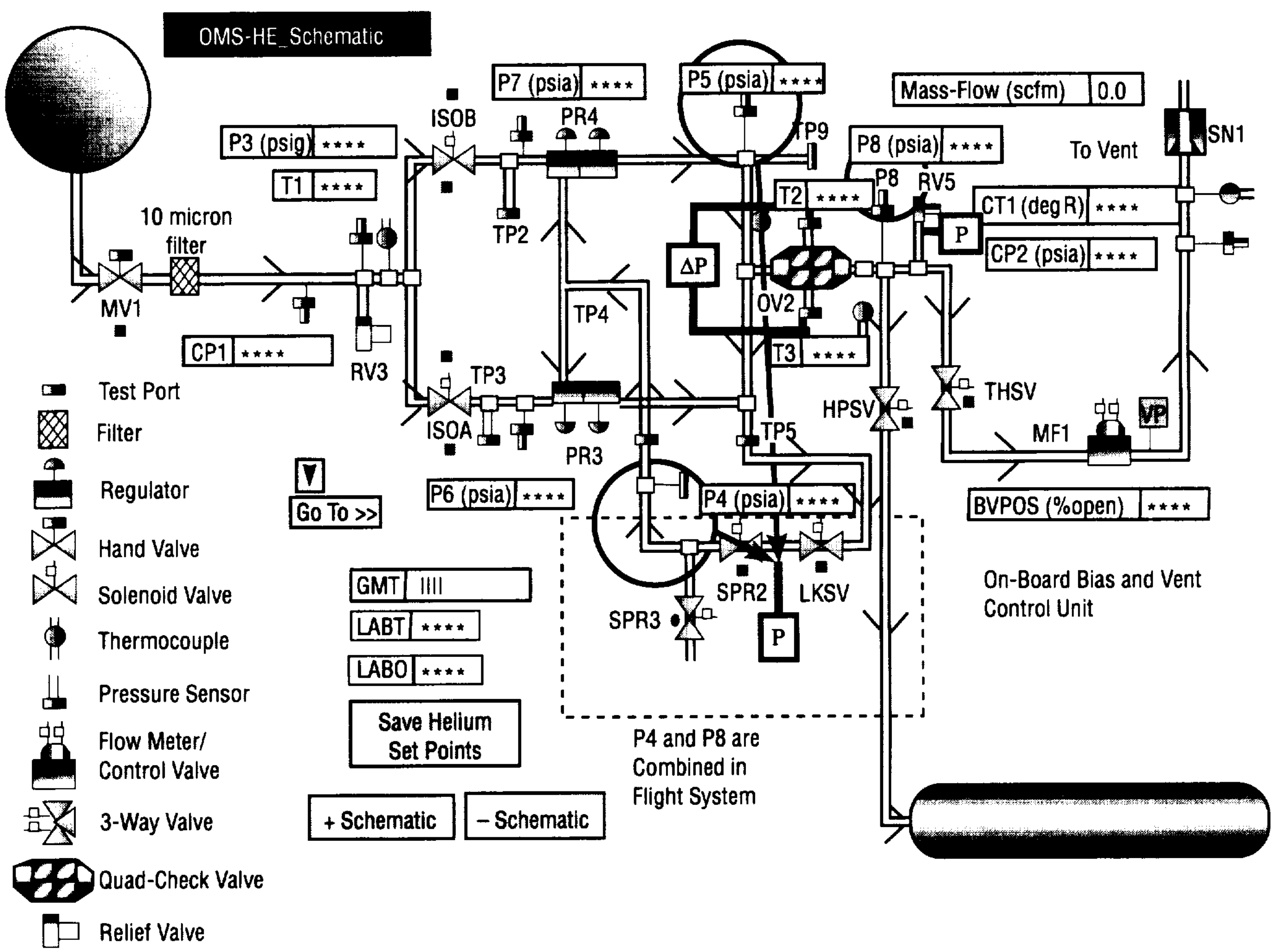

Figure 105.—OMS IVHM expert system screen.

Software Technology

Vehicle Health Maintenance and Analysis Using Advanced Statistical Methods and Adaptive Techniques

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The Center Director's Discretionary Fund proposal, Vehicle Health Maintenance and Analysis Using Advanced Statistical Methods and Adaptive Techniques, was funded in October 1995 for 2 years. The primary objective was to develop vehicle health monitoring algorithms using statistical methods, genetic algorithms, neural networks, expert systems, and fuzzy logic. These methods have been applied to several different kinds of problems with successful results.

The project discussed is detection of high-pressure fuel pump turbine blade breakage in real-time during the Space Shuttle Main Engine (SSME) ground tests. During two ground test firings, turbine blades have broken without the turbine exceeding the redline shut-down values. The first time this failure occurred, a technician manually shut down the engine after seeing an abnormal plume. The second time, redlines shut down the engine much later than the actual blade breaks occurred. Blade breakage can be located in post-test analysis, but cannot be monitored in real-time at present. This type of failure can destroy a high-pressure fuel pump valued at approximately $2 to 4 million and/or the engine valued at $40 to 60 million. If the blade breakage can be detected accurately, then the probability of extensive engine damage may be reduced and may reduce engine development costs.

To detect turbine blade breaks, an analysis technique was developed using algorithms in the following form: If A>B, then blades are breaking, where A and B can be averages, differences, normalizations, constants, transforms, or other rules joined by "and" statements. The inequality could be less than or equal to B or greater than B in all the evaluations. There are no constraints to how many relationships are evaluated. For example, a rule could be: If A>B and C=D and A<=E, then blades are breaking, where A, B, C, D, and E are values as defined above.

The analysis technique described above was applied to the data base from the first SSME failure and detected all five blade breaks with no false indications. Next, the technique was applied to other normal tests and one other test where turbine blades broke. On the larger data base, the rule detected the known blade breaks, but gave six false positive signals. Due to the desire to have zero good engine test terminations, the causes of the false signals generated by the analysis technique were carefully reviewed. As a result of the review, a simple modification eliminated all the false positive signals. The analysis technique then detected all six (100 percent) blade breaks out of 35 test runs and gave no false positive indications (0 percent) of failure. The 35 tests correspond to approximately 35,000 test samples in which the analysis technique never failed. The analysis technique form and values may require slight modification for SSME hardware changes, but should maintain high-fidelity results similar to those indicated above.

If the proposed analysis technique provides zero or near-zero false indications in all available test data, then the algorithm could be included in the ground test monitoring system and possibly in the engine controller for real-time vehicle health monitoring. Each detected blade failure could save a turbopump ($2 to 4 million) or an engine ($40 to 60 million). The same analysis techniques should be applicable to anomaly detection in other types of turbines, engines, and machinery used in industry.

Future work in this area will concentrate on using artificial intelligence to create sensor redundancy and sensor validation on engines, developing an adaptive health monitoring system that responds to small hardware changes, and chaining several small expert systems (as described above) together to create a real time diagnostic system for the SSME. Additionally, the techniques will be applied to power plant turbine generators for detection of broken turbine blades, which should save money and shorten downtimes.

Sponsor: Center Director's Discretionary Fund

Biographical Sketch: Anthony Kelley has been an electrical engineer with MSFC since 1985. He has a bachelor of science in electrical engineering from the University of Alabama in Huntsville and a master of engineering, operations research and industrial engineering, from Cornell University. He is currently designing and building data acquisition and control systems for various instruments flown on satellites, sounding rockets, zero-g planes, and the shuttle.

Modular Rocket Engine Control Software Update

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NASA is conducting studies with the goal of enhancing and furthering the technology base to support high-priority programs. To support the propulsion system activities, basic research and technology must be accomplished in the engine control and health monitoring arena. To accommodate evolving technologies this system must be modular to allow interface redesign as the system requirements change. Modular rocket engine control software (MRECS), which is being developed by Lockheed Martin Space Information Systems, is a research and technology effort whose primary purpose is to demonstrate software development and maintenance cost reduction by implementing a modular, flexible software architecture.

Approximately 35 people are presently working full time to support the development, verification, and validation of the Space Shuttle Main Engine (SSME) controller software. A significant percentage of the time and manpower required for this effort is the verification and validation of SSME software. Software logic changes, resulting from flight requirement changes and/or software logic corrections plus the need for special test software, have occurred at a relatively high frequency, each new software version requiring verification and validation. Sixteen software versions have been flown on 53 Space Shuttle missions since return to flight in 1988, an average of one new software version every 3.3 flights.

The purpose of the MRECS contract is to determine and develop an approach to modular rocket engine control software that will allow the incorporation of new system requirements and technology developments in sensors, actuators, input/output, connectors, and health/safety monitoring techniques with fewer software specialists, thus reducing costs. The modular software concept creates a "fire wall" between modules so that when code is changed, only the affected module needs to be reverified. Some of the logic errors discovered in the current SSME software might not have occurred with more compartmentalized software.

The Marshall Avionics System Test-bed (MAST) is being used to develop the MRECS software and for demonstrations of this software at key milestone events. The MRECS engine controller system was installed in the MAST laboratory for verification of the software. A demonstration of a sensor input task was performed in June 1995, with a proof-of-concept demonstration, including an engine health management task, held in September 1995.

The tasks planned for 1996 and 1997 were postponed so that MRECS could be used to support the firing of an SSME with a controller that uses a commercial off-the-shelf computer, operating in a predominately simplex mode. Lockheed Martin is developing the software using requirements derived from the SSME controller software requirements, as furnished them by MSFC. The test firing, which is known as PC Quickfire 2, is planned at Stennis Space Center in January 1997. This is the second of four planned testing phases. Phase 1 used a laptop computer and was conducted in February 1996. MRECS was not used on that test. Phases 3 and 4 are planned to follow and would consist of SSME tests with fully redundant and flight-worthy controllers, respectively. These would be further steps in the evolution of MRECS toward future space applications. No commitment to these phases has been made at this time, however.

MRECS will also be used to support a test firing in January 1998, of a low-cost booster technology propulsion test article. Requirements for this test are being written by MSFC. MSFC and Lockheed Martin will develop the software, starting with the existing modular design.

Modular main propulsion system software has been identified as a task item in the Reusable Launch Vehicle Long-Term/High-Payoff Technologies Program. Preliminary results from the MRECS contract indicate that it is the proper approach for future flight software. The testing currently planned should serve as further validation of this approach. The reduction in time and manpower required for the verification and validation of software should result in significant cost savings.

Sponsor: Office of Aeronautics

Industry Involvement: Lockheed Martin Space Information Systems

Biographical Sketch: Richard Beckham is a computer engineer in the Astrionics Laboratory at MSFC. His primary duty is the coordination and evaluation of requirements, development, testing, and flight support for the Space Shuttle Main Engine controller software. Since March 1995, he has been the contracting officer's technical representative for the Modular Rocket Engine Control Software contract. He holds bachelor of science and master of science degrees in electrical engineering from The University of Tennessee.

Optical Systems

Large Optic Coating Facility

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The Optics and Radio Frequency Division here at Marshall is in the process of converting a fully operational thermal vacuum test chamber, (fig. 106), into a multipurpose large optic coating facility. During the 1996 fiscal year, the thermal vacuum test chamber here at MSFC has become a lifesaver for two major projects—the Advanced X-Ray Astrophysics Facility (AXAF) and Space Station Alpha. It has contributed greatly by serving a dual role as a preliminary and certified bakeout chamber for AXAF, and as a test facility for the Space Station nonpropulsive vent test. In the near future, resistive and electron beam coating sources will be installed in this 18-ft-diameter chamber. This will give NASA the capability to coat large mandrels for replicated optics, large segmented and nonsegmented optics, and large polymer film type optics.

The large optic coating facility houses the thermal vacuum test chamber which will be converted into a large optic coating chamber. The vacuum chamber has a usable inner diameter of 15 ft and total outside length of 16 ft. On the chamber there are a multitude of ports for feedthroughs and fixturing. The chamber is housed in a class 10,000 cleanroom that has a 26-ft ceiling, two-piece monorail with a 1-ton crane, and 24-ft doors that allow entrance for large apparatus. The control center displays all the functions of the system, and has a 486 computer to monitor the interior temperature. The supporting crew of the chamber consists of four roughing pumps and blowers, two 48-in cryopumps, two 48-in gatevalves, and one 13,000-gal liquid nitrogen tank. The conversion from bakeout chamber into a large optic coating chamber is presently in progress.

The Fixture Design Branch here at MSFC is performing preliminary design, design and detailing to complete the conversion modifications. Equipment to be designed includes a protected shroud/liner, scaffolding to support evaporation sources, 12-ft-diameter optic support structure, and a replicated optic support structure. The optic support structures will contain rotary motion capability. Once the designs are completed the fabrication will begin. New equipment is being procured which will give this vacuum chamber the capability to perform thermal, electron beam and eventually sputtered coatings. The various types of coatings will include aluminum, gold, and magnesium fluoride just to name a few. The completion date for this large optic coating chamber is approximately June 1997.

The Optics and Radio Frequency Division plans to transform the large optic coating chamber into a world-class coating facility. This will allow NASA to achieve great accomplishments and benefit the corporate sector. Tasks we are pursuing include coating of large mandrels, segmented and nonsegmented optics, and large polymer film-type optics. A future objective for this vacuum chamber, should additional support become available, will be to perform multilayer dielectric coatings or perhaps multilayer x-ray coatings with "depth-graded d-spacing."[1] The coating possibilities for this large optic vacuum chamber are limited only by one's imagination.

[1]Joensen, K.P.; Hoghoj, P.; Christensen, F.; Gorenstein, P.; Susini, J.; Zeigler, E.; Freund, A.; and Wood, J.: "Multilayered Supermirror Structures for Hard X-ray Synchrotron and Astrophysics Instrumentation." Harvard-Smithsonian Center for Astrophysics, Reprint Series, no. 3732, 1993.

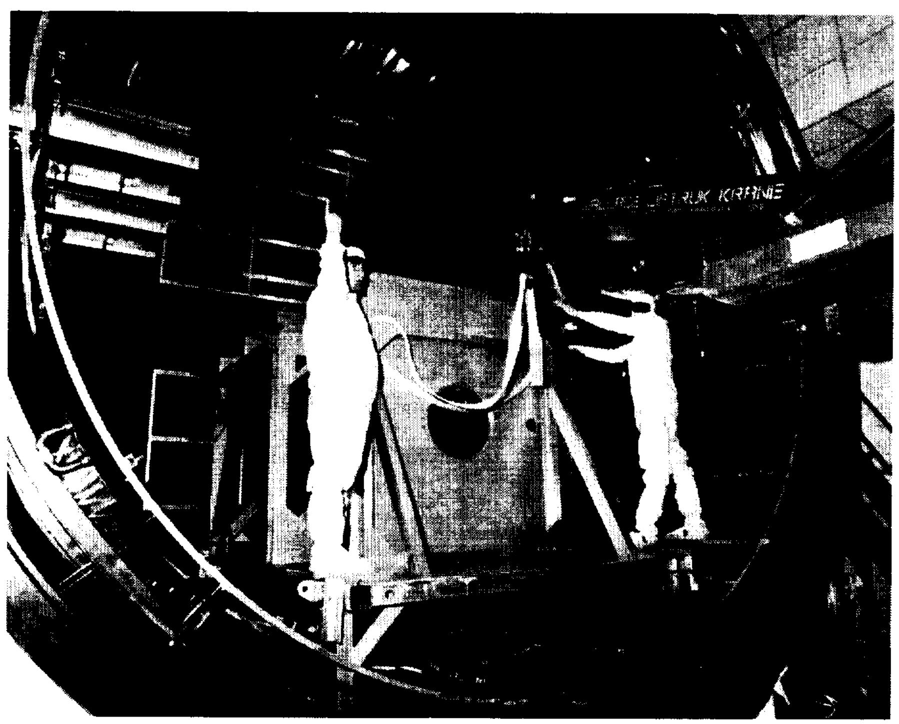

Figure 106.—Large optic coating chamber interior. NAS, Inc. personnel are shown removing an AXAF support structure.

Sponsors: Solar Thermal Upper Stage Flight Experiment (STUS); AXAF; *International Space Station*

Biographical sketch: Tommy Thompson is an optical physicist in the Optics and Radio Frequency Division at MSFC's Astronics Laboratory. He conducts scientific research on thin film deposition, surface roughness, optical phase conjugation, and x-ray coded masks. He earned a B.S. degree in applied physics from Alabama A&M University , and is pursuing an M.S. in thin film deposition from A&M. Thompson has been employed at MSFC since 1988.

Technology Mirror Assembly Testing

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The realignment of the technology mirror assembly (TMA) is completed, and x-ray detector assembly calibration rehearsal with the TMA at the X-Ray Calibration Facility (XRCF) at MSFC is underway. During the calibration rehearsal, several x-ray detector assemblies will be checked out with the TMA. The TMA alignment requirements are 0.75-arc sec relative tilt or 44-μm spot diameter.

The TMA was built in the mid-1980's as a part of the AXAF development program in order to gain valuable experience with grazing incidence mirror fabrication, metrology, and alignment techniques. Much of the experience was applied in fabrication and testing of the AXAF's high-resolution mirror assembly (HRMA).

The TMA's diameter is 410 mm, or approximately one-third of the HRMA's outer diameter, and half of HRMA's length. Its focal length is 6 m. TMA consists of a parabola and hyperbola mirror supported by graphite-epoxy cylinders which are supported by aluminum center aperture plates. Each of the mirrors is bonded to four invar pads. The pads are bonded to the graphite-epoxy mirror support.

The TMA was aligned and tested in the late 1980's at the XRCF. The alignment of the TMA was found to be unstable during the x-ray testing. Tested with a sensitive acoustical instrument, one of the graphite-epoxy pads indicated a difference in response and was suspected to be debonded or partially debonded from the TMA's parabola mirror. The TMA had been in storage since 1990. Classified as program critical hardware, it was taken out of storage in 1995.

Alignment of the TMA requires a specially built alignment instrument. This instrument consists of a Helium-Neon laser source, a rotating scanner, and a detector. The laser output, a beam from the TMA's focus to the exiting aperture, retroreflects off an 18-in-diameter precision flat mirror and double passes through the TMA and back onto the detector to analyze the relative misalignment of the TMA. Earlier alignment attempts determined that the alignment could be improved by applying external forces to the ends of the TMA.

In the first realignment attempt, the TMA was found to be misaligned and it required 56 lbf to align the hyperboloid to the paraboloid mirror. The alignment in 1989 required only 24 lb of lateral force to align the TMA. With the 56 lb of stainless steel weights, the TMA was aligned to 0.05 arc sec or 3-μm-diameter spot.

Since the TMA was not stored in a clean room, the TMA was subjected to a series of vacuum bakeout at elevated temperature of 110 °F until it passed the MSFC-SPEC-1238. Vacuum bakeout of the TMA was conducted to ensure that it would not contaminate the XRCF during testing. The TMA was brought to the XRCF for final alignment. There the TMA was found to be grossly misaligned (3 arc sec) with more than 100 lbf required to realign the TMA. In addition, another residual error term was much greater than before the vacuum bakeout. The residual error indicated comes from the same quadrant where the debonded pad is located. The cause of this additional error is not known with certainty, but it is known that graphite-epoxy is hygroscopic and changes shape when moisture escapes under vacuum bakeout. A spring-loaded device was fabricated and placed inside the TMA to pull on the paraboloid mirror to correct the residual error. Afterward, it required 80 lb of weight placed on each mirror to align the TMA. The residual error due to relative tilt was between 0.38 arc sec or 21 μm. The residual error due to the ovalized parabola mirror (delta-delta radius error) is 36 μm. The RSS spot size is 42-μm diameter.

During the calibration rehearsal, the x-ray spot diameter is well within specification and seems to be stable and repeatable.

The aligned TMA will be a valuable asset to the x-ray science community. The TMA will serve as an x-ray optical instrument for calibration of any future x-ray detectors in vacuum. The TMA, along with the XRCF at MSFC, will be available to serve the science community in x-ray instrument testings. The lessons learned from the TMA alignment will be valuable in future optical telescope engineering programs.

The TMA with a debonded pad is temporary cured with an internal fixture. Additional forces are needed to realign the TMA. Preliminary test data agrees with the data from the TMA alignment scanner.

Sponsor: AXAF Development Program

Biographical sketch: Ron Eng is an optical design engineer at the Optics Branch at MSFC. His accomplishments include the wide field angle lenses for the Lightning Imaging Sensor (LIS), Optical Transient Detector (OTD), and the Solar Vector Magnetograph. He received a B.S. degree in optics from the University of Rochester, and took additional graduate courses at the University of Rochester and the University of Alabama in Huntsville.

Specialized Optical Coating Solutions for Astronomical Instruments

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The performance of specialized astronomical instruments can often be greatly enhanced by the implementation of specialized optical coating solutions. These solutions may include the design and subsequent deposition of unusual multilayer coatings composed of dielectric materials, metals, or combinations of the two. Wavelength selective transmission coatings may be combined with specially designed reflective coatings in the same instrument in order to obtain the desired performance characteristics. The various coating design options, when included as a part of the initial system design, can be utilized to produce an instrument with optimum spectral and polarization response. In some cases, it is desirable to tune the optical properties of specific coating materials using process parameter modulations in order to obtain elements with demanding optical characteristics. The physical properties of coatings are characterized through the use of advanced surface morphology equipment such as atomic force microscopes, surface profilometers, and spectrophotometers.

A significant portion of the coating and surface morphology research conducted in the Optical Fabrication Branch at MSFC is directed toward the development of unique coating design solutions for optical systems with demanding performance characteristics. A Center Director's Discretionary Fund project initiated October 17, 1995, entitled "Development of Polarization Optics for High-Resolution Vector Magnetic Field Measurements," encompasses the development of wavelength selective transmission filters, reflective mirrors, and beamsplitters which introduce minimal instrumental polarization effects. One instrument which will benefit from this effort is the Experimental Vector Magnetograph (EXVM),[1] shown in figure 107. Scientists at MSFC's Space Sciences Laboratory use this instrument to characterize the magnetic field of the Sun by measuring the polarization of light in iron ion absorption bands at 525 and 630.2 nm wavelengths. Light

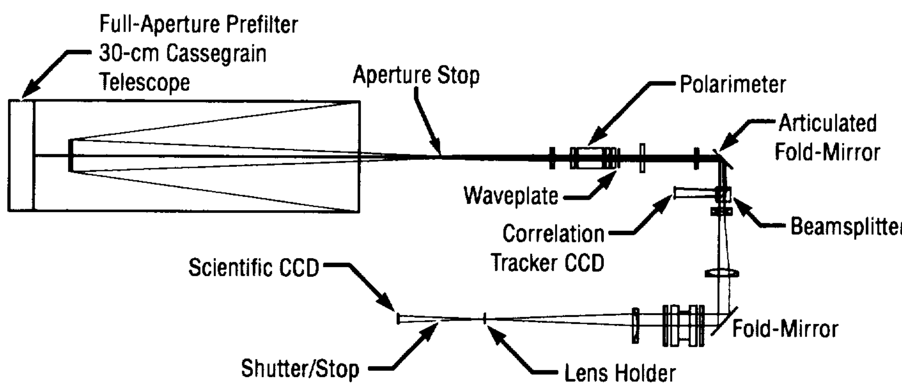

Figure 107.—Schematic of the Experimental Vector Magnetograph at MSFC. Specialized optical coating solutions are being applied to develop a full-aperture prefilter, specialized infrared transmitting nonpolarizing mirror coatings and a nonpolarizing wavelength selective beamsplitter which is used with the image motion compensation correlation tracker.

associated with the hydrogen-alpha line at 656.3 nm is also measured. A separate submission to the *1996 Research and Technology Report* by John Davis et. al. describes the use of wavelength selective mirror coatings designed to reflect light around the spectral regions described above while rejecting significant amounts of infrared, and in some cases visible, radiation. Development of a full aperture prefilter and a specialized beamsplitter has also been initiated. These optics will be coated in the near future in the existing 30-in Balzers coating system which is equipped with a Temescal four-pocket electron beam evaporation source and a advanced thin film optical monitor.

The EXVM beamsplitter is required to direct some of the light from the instrument into a motion compensating correlation tracker charge coupled device (CCD). The majority of the polarization sensitive light must be directed to the scientific CCD with an instrumental induced polarization of 0.1 percent or less. These requirements led EB52 personnel to design a specialized cube-type beamsplitter containing a specially designed all-dielectric coating. The transmission of the beamsplitter as a function of wavelength is shown in figure 108. It is clear that the design shown meets the requirements very well. There is very little separation between s- and p-polarized components of the transmitted light at the polarization-sensitive wavelengths. About 20 percent of the randomly polarized light around the hydrogen alpha line is reflected to the tracker. The difficulty of designing useable nonpolarizing cube-type beamsplitters, formed by cementing one coated and one uncoated right angle prism together, is described by Macleod.[2]

A National Research Council Fellow, Dr. Naba K. Sahoo, stationed at MSFC is investigating the properties of some specialized dielectric coating materials which may facilitate the design and fabrication of optimum broadband antireflection coatings and filters useful for numerous astronomical missions. Preliminary results indicate that optical properties of these materials can be modified via process parameter changes thus yielding inhomogeneous or graded index films. The films are being characterized via advanced surface morphology equipment such as the Optical Fabrication Branch's atomic force microscope. Dr. Sahoo is also developing specialized computer algorithms to model inhomogeneous coating designs and to predict the sensitivity of multilayer coatings to variations in individual layer parameters.

The utilization of specialized optical coating solutions for applications listed above, as well as other NASA and commercial applications, is expected to result in the fabrication of instruments that would not be possible by other means. Designers of optical instruments can now consider the use of nontraditional coating designs and exotic materials in order to meet the demanding requirements of future NASA programs.

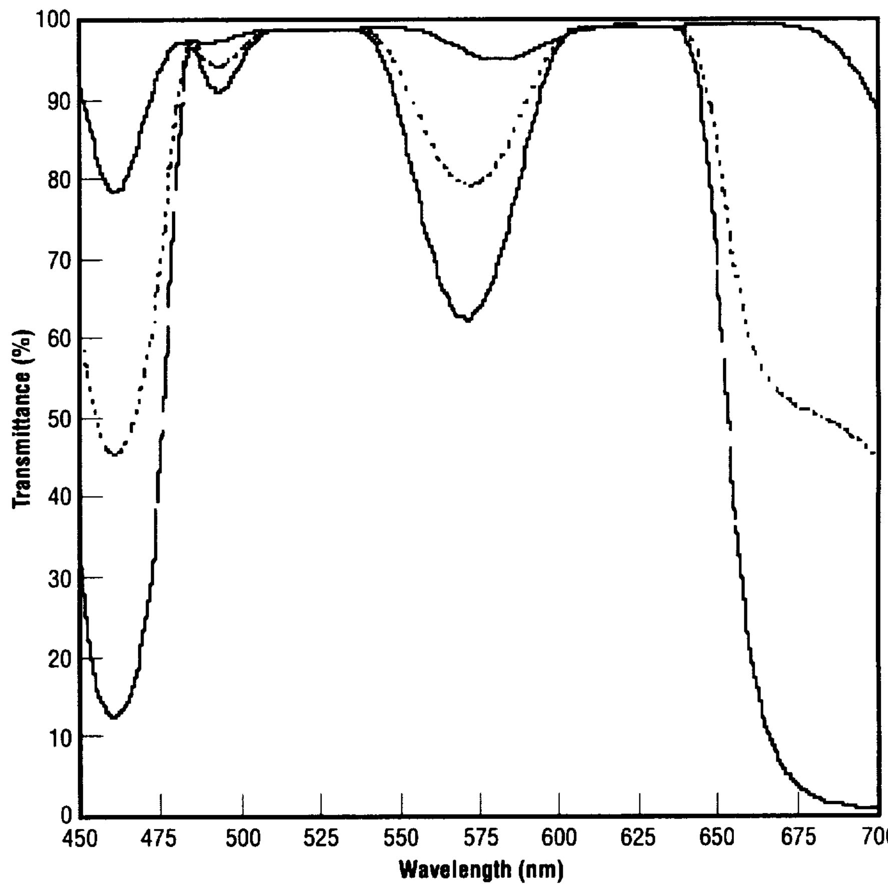

FIGURE 108.—This graph shows the expected transmittance as a function of wavelength for a cube-type beamsplitter containing an MSFC-designed all-dielectric coating. This beamsplitter is designed for use in the Experimental Vector Magnetograph at MSFC. The three curves indicate the transmission for light with three types of polarization. The top curve (solid) corresponds to p-polarized light, the middle curve (dotted) to random or unpolarized light, and the bottom curve (dashed) to s-polarized light.

[1]West, E. and Smith, M.H.: "Polarization Characteristics of the MSFC Experimental Vector Magnetograph." Polarization Analysis and Measurement II, *SPIE* vol. 2265, pp. 272–283, 1994. (Proceedings 1994 SPIE International Symposium on Optics, Imaging, and Instrumentation, San Diego, California, July 24–29, 1994).

[2]Macleod, H.A.: "Thin-Film Optical Filters." Macmillan Publishing Company, New York, 1986, pp. 148–154, 334–342.

Sponsors: Center Director's Discretionary Fund; The National Research Council.

Biographical Sketch: Dr. Alan Shapiro is a coating physicist at the Optics and Radio Frequency Division at MSFC's Astrionics Laboratory. He conducts research on specialized optical coatings, many of which are utilized for astronomical and astrophysics related programs. He also conducts research on the surface morphology of material surfaces. Shapiro earned his Ph.D. in condensed matter physics from the University of Illinois, Urbana-Champaign in 1987, after which he worked at International Business Machine Corporation, East Fishkill, NY. He has worked for NASA at MSFC since May 1989.

Edward West is a solar physicist in the Physics and Astronomy Division at MSFC's Space Sciences Laboratory. He worked at Johnson Space Flight Center as a solar observer during the Skylab missions. After the Skylab missions, he was transferred to the Solar Physics Branch to work with the vector magnetograph project. Since that time he has worked in both the hardware and software development of the vector magnetograph. His main research interests have been in the development of stable, high-resolution polarimeters for both ground-based and space-based solar magnetographs, in the development of real-time analysis techniques to be used in flare prediction, and in studies relating polarization measurements to magnetic field evolution and magneto-optic effects in sunspots.

Fabrication of Normal Incidence Mirrors by a Nickel Replication Process

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Space telescopes that are larger, lighter, and less costly than ever before are a step closer to reality due to a novel mirror fabrication technique under development at MSFC. Mirrors that are over 10 times lighter than current space technology will enable larger, lighter optical systems with unprecedented performance. Similarly, manufacturing costs are reduced since the critical and time-consuming task of grinding and polishing glass is eliminated.

Conventional mirror manufacturing techniques applied to large normal incidence mirrors are extremely expensive and time consuming as evidenced by the extreme cost of the Hubble Space Telescope primary mirror. Also, a conventional glass mirror must be relatively massive so that it can possess enough rigidity to be finished, ground and polished to its final figure. A conventional glass mirror must also survive the launch environment, making the mirror even heavier. The brittle nature of glass, combined with low strength and high-manufacturing costs, severely limits our ability to economically launch future astronomy missions the size of Hubble or larger. In short, higher performance in space optical systems cannot be realized until a lighter, more economical replacement to conventional glass mirror technology is developed.

Fabrication of normal incidence mirrors by nickel replication is an alternative to conventional mirror technology which exploits manufacturing economy in a low-weight system. Figure 109 depicts the process. As shown, nickel is electroplated onto a highly polished mandrel (typically aluminum) to a thickness of around 1 mm.

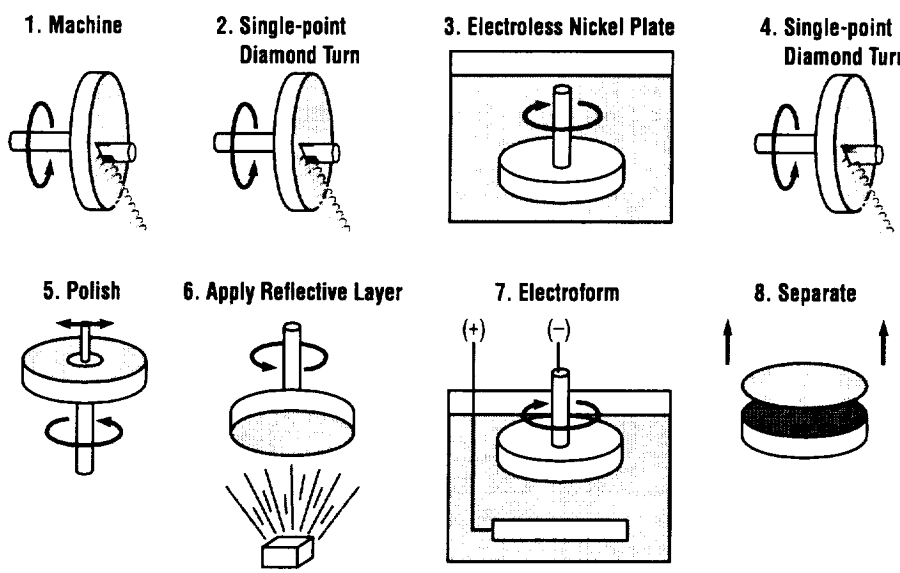

Figure 109.—Replication applied to normal incidence optics. (1) Machine; (2) Single-point diamond turn; (3) Electroless nickel plate; (4) single-point diamond turn; (5) Polish; (6) Apply reflective layer; (7) Electroform; (8) Separate.

Once the desired thickness is achieved, the nickel "shell" is released from its mandrel leaving an optical quality surface. The nickel shell (mirror) can then be laminated onto a lightweight composite structure thus producing a mirror 10 times lighter than that of conventional manufacture. Since the mandrel can be reused, multiple mirrors can be produced in a short time, thus allowing spare units, or multiple segments, of a larger mirror to be produced.

As mirrors are fabricated thinner, the effects of mounting and holding become increasingly sensitive to the optical surface. Fastening, bonding, and joining of typical optical substrates to adjacent structures are particularly problematic. These effects are known as "print-thru" or "quilting." In nickel replication techniques, these effects can be mitigated since the nickel electroplating process lends itself to the ability to plate to the optic an intricate array of flexures, or mounting provisions. The plating technique also lends itself to the ability to produce odd shaped mirrors which would be particularly difficult by conventional methods. This facilitates the production large segmented mirrors comprised of "petals" which would unfurl and lock into position upon insertion into orbit.

The fact that nickel can be fabricated in very thin sections, along with its characteristics of high strength, nonbrittle behavior, make it an excellent candidate for adaptive schemes as well. Adaptive schemes would be used to correct residual errors in the telescope due to inherent deployment errors, gravity release, and the like. Here, the thin nickel "shell," or membrane is actually "shaped" by an array of electromechanical or electrostrictive actuators. The application of adaptive schemes allows for residual correction of the optic, and/or compensation of errors and disturbances elsewhere in the optical path of the telescope. An example of this would be the correction of atmospheric disturbances in ground-based telescopes.

Current research is focused on the production of subscale prototype mirrors to be used in structural, environmental, and optical testing. The key parameters involve control of the plating bath so a mirror is produced having zero residual stress. Zero residual stress in the plating process produces a high-quality optic which truly replicates the optical prescription of the mandrel. As of this report, several one-quarter-meter-diameter mirrors have been produced with remarkable results. A larger half-meter-diameter mirror is scheduled for 1997. Upon successful completion of the half-meter program, it is hoped that a flight experiment can be scheduled to test the mirrors in an actual space environment at cryogenic temperatures.

This research will allow NASA to build the next generation of space telescopes with substantially lower cost and higher performance. The production of lightweight, low-cost, high-performance optics will usher in a new era for astronomy, and spawn countless benefits to the commercial and military sectors by allowing large, high-performance optical systems to be transported to places that are today impossible. The mass production of large, superprecision, intricate parts is now economically feasible; electroforming can produce parts in virtually any shape or form. Potential applications are limitless.

Sponsor: Office of Space Science

University/Industry Involvement: UAH/CAO, Darell Engelhaupt

Biographical Sketch: John Redmon Jr., is an opto-mechanical design engineer in the Optical Fabrication branch of the Astrionics Laboratory.

Next Generation Space Telescope

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The Next Generation Space Telescope (NGST) is a component of the origins program. The NGST will assist in determining the origins of galaxies, stars, and planetary systems. The baseline concept for the NGST is an 8-m-diameter, filled aperture telescope with diffraction limited performance at wavelengths between 0.5 and 5.0 µm, operating in a high-Earth orbit. The operating temperature of the optics will be 30 Kelvin. The launch vehicle is to be an Atlas IIAS with a 12-ft ID by 32-ft tapered faring. The weight of the optical telescope assembly is not to exceed 2,200 lb and the costs are not to exceed $100 million.

Two industrial teams and a Government team, including Goddard Space Flight Center, Marshall, and the Jet Propulsion Laboratory personnel, have each prepared preliminary designs and feasibility studies for NGST. Estimates of predicted performance, costs, weight, and launch volume have been included. MSFC members of the Government team were responsible for the optical telescope assembly. Key elements of this design include:

- Optical design: A 4 mirror, centered design that achieves diffraction limited performance at a wavelength of 2.0 µm over a 4 by 4 arc min field, has been prepared. The primary and secondary mirrors are much like a conventional Cassegrainian. The tertiary is a concave asphere located behind the primary. The quaternary is plano and is designed as a deformable mirror allowing wavefront correction.
- Structural design: An articulated design is required to fit the telescope assembly within the launch vehicle shroud. The primary mirror design provides an array of eight folding panels around a central

section. Four of the panels fold forward toward the secondary mirror location, and four of the panels fold backwards toward the instrument package for launch. All eight panels are deployed and locked in place on orbit. The secondary mirror is positioned near the vertex of the primary mirror for launch and is deployed in the required position on orbit by an expanding structure.

Primary Mirror Design: The principal elements in the primary mirror design are:
- The mechanisms that deploy and lock the segments in place;
- The mechanisms that phase and align the segments with the central segment; and
- The mirror substrate design itself, including material selection, method of support, and the fabrication approach.

The weight allocation for the primary mirror requires its areal density to be in the range of 5 to 7 kg/m^2.

While each of these areas presents formidable tasks, the design, fabrication, and testing of the primary mirror are believed to present the greatest challenge. The magnitude of this challenge is best understood when the requirements for the NGST primary mirror are compared to the Hubble Space Telescope (HST) primary mirror. The area of the NGST primary mirror is more than an order of magnitude larger than HST, while its areal density is 5 to 7 kg/m^2 compared to approximately 160 kg/m^2 for HST. Furthermore, the HST primary is a stiff monolith operating at near room temperature while the NGST primary is an articulated ensemble of compliant panels, deployed on orbit, operating at a cryogenic temperature.

The design, choice of materials, and the most effective fabrication approach have not been determined. Materials still under consideration are replicated electroformed nickel, silicon carbide produced either by vapor deposition or reaction bonding, glass or glass-like materials with an ultra-low coefficient of thermal expansion, composite materials, and thin membranes. A technology plan has been prepared and implemented to select the optimum design, material, and fabrication process for the primary mirror. The most promising technologies are being selected, and demonstration mirrors will fabricated. These mirrors will be concave, 0.5-m-diameter spheres. They will be tested interferometrically at room temperature and at cryogenic temperatures to determine and compare figure, power, smoothness, and microroughness at the two temperatures. Tests to determine structural properties, including launch survivability, will also be conducted.

At the completion of this phase, a down selection to two approaches will be made. Subscale panels will be fabricated using each approach. Each panel will be integrated with a backing structure and tested optically and mechanically. The final design, material, and fabrication technique to be used for the flight mirror will be selected based on the results of this testing.

Sponsor: Office of Space Science

Biographical Sketch: Howard Hall has more than 40 years of experience in the fabrication and testing of large optical systems and components. He currently is the team lead, Optics Fabrication, in Optics Branch of the Optics and RF Division of the Astrionics Laboratory. Hall graduated from the University of Michigan with bachelor degrees in engineering mathematics and chemical engineering.

Replicated X-Ray Optics

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The objective of this research is to demonstrate large, lightweight, high-performance x-ray optics. These optics will enable future x-ray astronomy missions such as the High Throughput X-Ray Mission (HTXS), which is now in the mission definition phase as a follow-on to the Advanced X-Ray Astrophysics Facility (AXAF).

The replicated x-ray optics program at MSFC began in 1992 when the design of the spacecraft for the spectroscopy portion of the AXAF mission (AXAF–S) was assigned to the Center. The baseline optics for this mission were grazing incidence epoxy replicated foil mirrors (Serlemitos, et. al.). A group at MSFC proposed to develop electroformed nickel replica (ENR) mirror which would offer four to eight times better resolution than the baseline optics. Grazing incidence mirrors are exactly analogous to the primary mirror of a conventional telescope—they collect the incident radiation and concentrate it onto the detector. The essential difference is that the wavelength of the incident light is much shorter—1 to 12 Å in the case of x-ray mirrors versus 4,500 to 7,000 Å for the mirrors in a visible light telescope. In order to obtain efficient reflection at these short wavelengths, the angle of incidence must be very nearly 90 degrees. At these very large angles of incidence, the incoming light "grazes" along the surface—hence the term grazing incidence optics. The very short wavelength also makes the performance of the mirrors very sensitive to slight irregularities in the surface. Even a slight roughening of the surface can cause scattering of the incident light, resulting in a "halo" surrounding each image.

Grazing incidence x-ray optics are manufactured by first creating a "master"—a form whose surface has the inverse shape that the final optic should have. In the case of grazing incidence optics, the master has the appearance of two truncated cones with the base of the smaller cone joined to the larger cone at the plane of the truncation. The outer diameter of this shape ("mandrel"), which is typically made of aluminum, is covered with plated nickel-phosphor alloy, which is hard, amorphous, and can be polished to an extremely smooth surface. The proper optical shape ("prescription") is machined into the plated surface, using an ultraprecision machine and a single-crystal diamond as a cutting tool. The surface is superpolished and is then ready for use to replicate the actual mirror.

To replicate a mirror, a thin (1,000 to 1,500 Å) film of gold is applied to the surface in a vacuum chamber. Then the mirror is placed in a nickel sulfamate plating bath, where a 0.1- to 1.0-mm thick layer of nickel is electrolytically deposited over the gold film. This process is controlled so there is negligible internal stress in the nickel to avoid warping the mirror later when it is removed from the mandrel. At the end of the plating process, the mandrel and mirror assembly is removed from the bath, cleaned and then is ready for removal of the mirror from the mandrel. To remove the mirror, the entire mandrel/mirror assembly is chilled. Since the core of the mandrel is aluminum and the mirror is nickel, the aluminum contracts more quickly when cooled than does the nickel. This results in a force developing which eventually exceeds the adhesion of the gold to the nickel-plated surface of the mandrel, causing the mirror to separate from the mandel. The mirror can then be removed from the mandrel, and is ready for use. The mandrel is unharmed by this procedure and can be used to manufacture additional mirrors.

During the year, two grazing incidence replicated x-ray mirrors were manufactured and tested. These mirrors were 1/10-scale models of the innermost mirror pair used in the mirror assembly for the AXAF instrument and were ≈62 mm in diameter at the large end, tapering over a length of 175 mm to a small end diameter of ≈59 mm. The first mirror had on-axis x-ray performance of ≈8 arc sec full width at half maximum and half-power diameters of ≈15 arc sec at a x-ray energy of 4.5 keV, increasing to 27 arc sec at 8.0 keV. The second mirror had slightly lower performance at the lower energy but was nearly the same at 8.0 keV. These results are much improved compared to the larger mirrors built in 1992 and 1993.

After x-ray tests of the initial set of mirrors, a series of experiments were conducted to make mirrors that were much lighter weight. Mirrors with a wall thickness as thin as 0.1 mm (0.004 in) were successfully electroformed and removed from a mandrel. Of course, the thinner the walls of the mirror, the more flexible the mirror becomes. To restore much of the stiffness lost when the walls are thinned, a mirror was made with external reinforcing rings at each end and in the center (fig.110). This mirror weighs only 20 percent of the mirrors which were tested earlier. This mirror (and others similar to it) are awaiting testing at MSFC.

The primary NASA program to benefit from this technology development is the High Throughput X-ray Spectroscopy Mission (HTXS) which has been proposed as a follow-on to the AXAF mission, scheduled for launch in September, 1998. The HTXS mission, as currently envisioned, would consist of six x-ray telescopes, each on a separate satellite. The mirror assembly of each of these satellites would consist of 80 individual x-ray mirrors, nested to save space. The HTXS mission schedule has baselined the launch of the first telescope in the 2004 to 2005 time frame.

The techniques for electroforming precision optics have a number of applications in the commercial sector, a few of which are described here:

- Low-cost precision optics. Most of the effort in the replicated optics process is in

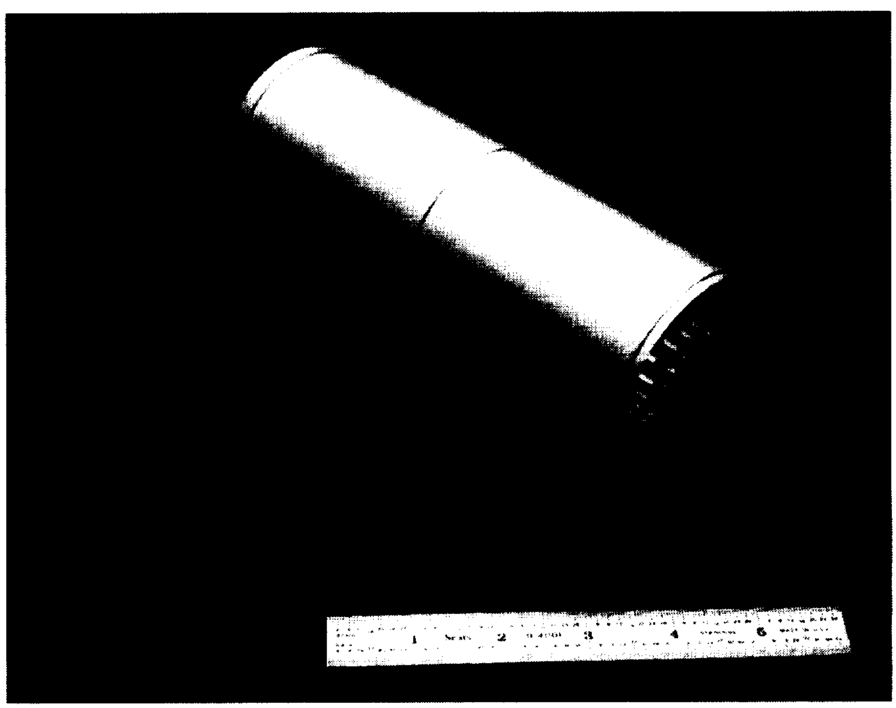

Figure 110.—Ring-reinforced x-ray mirror.

creating the master surface from which the replicas are made. Multiple replicas can be generated at low unit cost. These optics could be used in mass-produced applications where the precision requirements exceed those obtainable from other replica materials such as plastic.

- Precision manufacturing of components. A nonoptical application of the low-stress process that has been refined in the research is electroforming components where close dimensional tolerances must be maintained. The low-stress technique helps insure that the shape of the finished part very closely duplicates that of the master surface used to create it. A specific case is creating replicas for pressing CD's (both digital audio and data (CD-DA and CD-ROM)). The replicas for pressing the individual CD's must be quite flat or the resulting product will be rejected. The low-stress process has been used to improve the yield in this manufacturing process.

Development of precision electroformed grazing incidence optics for x-ray applications continued during 1995 and 1996. Two mirrors manufactured at MSFC were tested and shown to have quite good performance. Additional mirrors with reduced weight have been manufactured and are awaiting testing.

Sponsor: Center Director's Discretionary Fund; Office of Space Science

Industry/University Involvement: University of Alabama in Huntsville—Center for Applied Optics

Biographical Sketch: William D. Jones is senior research engineer in the Optics Branch at MSFC. He is a graduate of the University of South Florida.

Lidar Testing

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Coherent lidar testing, performed in FY96 for scientific and/or engineering purposes, included two airborne programs and one ground-based program in which lidar groups from several agencies and companies participated. The cooperative efforts allowed pooling of resources and expertise to accomplish the research objectives, and resulted in cost savings through the use of existing equipment and sharing of data.

The Multi-center Airborne Coherent Atmospheric Wind Sensor (MACAWS) is an airborne, scanning coherent Doppler lidar designed to acquire remote multi-dimensional measurements of winds and absolute aerosol backscatter in the troposphere and lower stratosphere. These measurements enable study of atmospheric dynamic processes and features at scales of motion that may be undersampled by, or beyond the capability of, existing or planned sensors. MACAWS capabilities enable more realistic assessments of concepts in global tropospheric wind measurement with satellite Doppler lidar, as well as a unique capability to validate the NASA Scatterometer. MACAWS consists of a Joule-class carbon dioxide (CO_2) coherent Doppler lidar on a ruggedized optical table, a programmable scanner to direct the lidar beam in the desired direction, and a dedicated inertial measurement unit to account for the variable aircraft attitude and speed. MACAWS was flown for the first time in September 1995, and a second time in June 1996, aboard the NASA Ames Research Center DC–8 aircraft, over the eastern Pacific Ocean and western United States. MACAWS was jointly developed by the lidar atmospheric remote sensing groups of Marshall, the National Oceanic and Atmospheric Administration (NOAA), the Environmental Technology Laboratory and the Jet Propulsion Laboratory (JPL). Existing components were used where possible to minimize costs. The CO_2 lidar transceiver was provided by NOAA, based on their highly successful WindVan system. MSFC provided an existing scanner and inertial measurement unit, and JPL provided an existing optical table. Some modifications were required to ensure DC–8 compatibility and flight safety.

The MSFC lidar atmospheric remote sensing group cooperated with the Air Force, Wright Laboratory in their Ballistic Winds program. A flashlamp-pumped, chromium, thulium:yttrium aluminum garnet (Cr,Tm:YAG) 100-mJ, 7-Hz lidar transceiver, built for MSFC by Coherent Technologies, Inc. under Small Business Innovative Research (SBIR) and RTOP funding, was used by the Air Force to improve the accuracy of air drops by a factor of 2 to 10 times over conventional methods. Unguided, parachuted cargo and conventional bombs, dropped from aircraft, are affected by the winds between the aircraft and the ground. The cargo release point can be adjusted to compensate for the intervening winds if they are known. Conventional methods of obtaining the winds such as rawinsondes are not always available and an alternate method of using the aircraft true air speed at various altitudes to infer winds is incomplete and compromises aircraft safety. The MSFC lidar transceiver was ruggedized by the U.S. Air Force and installed in a C–141, profiling winds beneath the aircraft in real-time in a series of tests from June 1995 through March 1996.

Because of its potential for efficient, compact, and long-lived operation with diode-pumping, new eye-safe, 2 μm lidar technology using thulium- and/or holmium-doped solid-state lasers is being considered for satellite-based wind sensing as well as other airborne and ground-based wind sensing applications. The lidars rely on signals backscattered from entrained atmospheric aerosols to make the wind measurement. Knowledge of atmospheric backscatter levels is necessary to specify such lidar parameters as output power and telescope aperture size to ensure that wind measurements can be made reliably at the locations and to the altitudes required. A backscatter measurement program was conducted in FY96 using an existing Air Force 2 μm lidar to collect nominally weekly, calibrated backscatter data at various locations in the United States. The data were collected by Coherent Technologies, Inc. under contract to MSFC.

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Sponsor: Mission to Planet Earth

Biographical Sketch: Steve Johnson is an electrical engineer in the Electro-Optics Branch at MSFC working on space-based, airborne and ground-based coherent lidar systems and components. He received a BSEE from Purdue University in 1977 and an MSEE from the University of Alabama in Huntsville in 1987.

Technology Development for Satellite-Based Laser Wind Sensing

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This paper discusses the technology needed to profile the Earth's winds from space with a pulsed laser radar (lidar or ladar) system; the status of the key system components; and the efforts being made at MSFC, NASA Langley Research Center (LaRC), and NASA Jet Propulsion Laboratory (JPL) to develop the required technology.

Global climate change scientists, atmospheric dynamics researchers, and numerous agencies such as NASA, NOAA, DOD, and DOE greatly desire continuous, global measurements versus height of the tropospheric wind. The necessary attributes of this difficult measurement are good horizontal and vertical coverage and resolution, horizontal vector accuracy of about 1 m/sec, and very low bias. Numerous studies over the past 20 years have consistently identified pulsed coherent detection laser radar (lidar) as the optimum and perhaps unique technique to fulfill the measurement requirements.

Despite 30 years of successful wind profiling with coherent lidar—from laboratories, trailers, trucks, airplanes, and ships—the coherent lidar technology was not ready for space science missions. Key attributes that take on enormously amplified importance for space flight include mass, volume, pulse energy, electrical efficiency, launch survival, eye safety, and lifetime. Almost all the coherent lidar wind measurements for 30 years have employed CO_2 lasers. The first wind profiling with the newer emerging solid-state laser technology began in the late 1980's. Although the solid-state laser technology trailed CO_2 lasers in pulse energy, maturity, and wind measurement heritage, the obvious analogy with electronic integrated circuits led many people to grant solid-state lasers a brighter future for space-based sensing in the categories of mass, robustness, and lifetime.

In FY93, NASA Headquarters began funding a NASA multi-center program to enable a solid-state coherent Doppler lidar system to perform the difficult space mission. MSFC manages and participates in this effort that includes technology development at LaRC and JPL. Naturally, early emphasis was on development of the required pulsed transmitter and continuous-wave (CW) local oscillator (LO) lasers, which attract the greatest attention in a lidar system. But analysis revealed that other key coherent lidar components also needed performance confirmation and/or development, and funding has allowed some work in these areas by MSFC in FY94 to 1996.

In 1993, MSFC also began a series of in-house studies to try and reduce the cost and spacecraft accommodation requirements of a coherent Doppler lidar wind profiling instrument. These instrument-mission point designs were called Autonomous Earth Orbiting Lidar Utility Sensor (AEOLUS), and examined the possibilities with both solid-state and CO_2 laser technology (fig. 111).

Figure 112 shows a possible block diagram of a solid state coherent Doppler lidar system for space-based tropospheric wind profiling. Key elements that NASA has either begun to develop or plans to develop include:
- The pulsed laser transmitter;
- The frequency-agile (tunable) local oscillator (LO) laser;
- The signal detector used to heterodyne two optical signals;
- An optical derotator;
- An optical fiber-based interferometer to assist heterodyning;
- A lightweight scanner;
- An optical lag angle compensator (LAC);
- Lidar auto alignment technology; and
- System integration and demonstration.

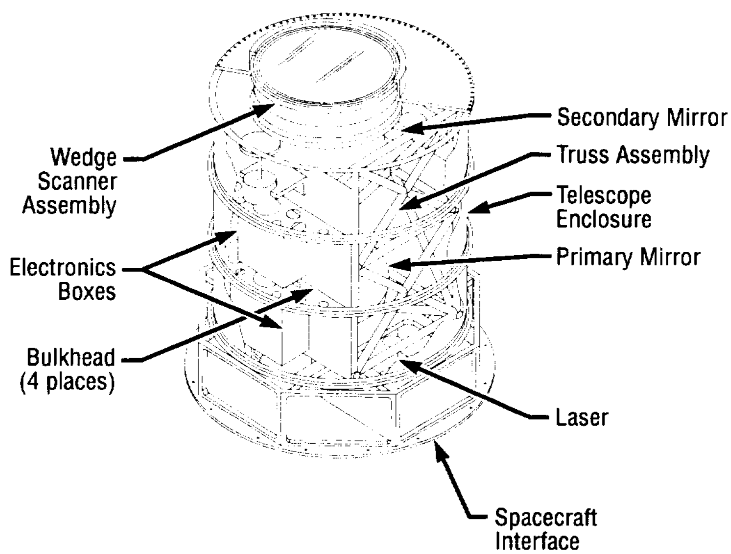

FIGURE 111.—AEOLUS Coherent Lidar design.

The pulsed transmitter laser is the "heart" of any lidar system. The transition of a space-based coherent lidar mission from "technology demonstration" to "science mission" can be related to the sensitivity or size of the lidar system. The five primary parameters which determine a lidar's sensitivity are laser pulse energy, optical diameter, transmitter/receiver alignment, orbit height, and laser beam nadir angle. Although frequently debated, the "transition" pulse energy occurs somewhere around 200 mJ for reasonable values of the other parameters. Since FY93, LaRC has been developing a 500-mJ-pulsed solid-state laser for MSFC. Delivery is expected in FY97. LaRC is using the material Tm,Ho:YLF to make the 2.06-μm wavelength, diode-pumped, 10-Hz pulse repetition frequency (PRF), 5 percent electrically efficient, linearly polarized laser. The beam quality must be excellent to avoid heterodyne losses. The pulse spectrum must be narrow and well behaved to allow accurate velocity estimation. A major milestone occurred in early FY97 when LaRC demonstrated 700-mJ pulse energy at 1 Hz PRF. Recently, Coherent Technologies, Inc. (CTI) won a NASA SBIR Phase II contract to build a 500-mJ, 10-Hz, diode-pumped slave oscillator breadboard. This will be delivered to MSFC in March of 1998. MSFC had previously procured a 100-mJ, 6-Hz, flashlamp-pumped laser from CTI in 1993. This laser was loaned to the U.S. Air Force Wright Laboratory, who flew it on a C–141 as part of the Ballistic Winds program. The successful wind profiles with the MSFC laser represent the current pulse energy record for solid-state coherent lidar wind measurement.

In order to allow prospective lasers to be tested, MSFC developed a Laser Characterization Facility (LCF) during FY93. The LCF has been used to characterize several lasers for the U.S. Air Force, LaRC, and others.

A typical altitude proposed for the lidar wind instrument is 350 km. At lower altitudes, atmospheric drag increases. At higher altitudes, the range squared effect on the lidar's signal-to-noise ratio (SNR) hurts the system sensitivity. At 350 km, the spacecraft and instrument have a tangential velocity of about 7,700 m/sec. Since good horizontal coverage is desired, and since accurate horizontal winds require laser shots at the same location from two perspectives, a continuous or step/stare conical scan is usually baselined. For a typical nadir angle at the instrument of 30 degrees, the Doppler shift of the light backscattered from the aerosol particle targets will vary with the azimuth angle of the conical scan over ±3.9 GHz. If uncompensated, this Doppler shift would stress the specifications of the optical detector, preamplifiers, A/D converters, and data rate. Therefore a tunable, controllable solid-state CW local oscillator laser is required to compensate for the spacecraft forward velocity, and possibly to compensate also for the Earth's rotation (465 m/sec at the equator). Since FY93, JPL has been developing this laser for MSFC, and delivery is expected in FY97. JPL demonstrated the 8-GHz tuning specification in early FY97.

MSFC is ensuring the compatibility of the lasers being developed by LaRC and JPL, and their joint compatibility with the space wind mission. The MSFC LCF will also be used to characterize the JPL laser.

If the pulsed laser is the "heart" of the coherent lidar system, then the optical heterodyne detector represents the "eyes." It must meet several specifications simultaneously. These are efficiency, bandwidth, linearity, saturation level, active area, and uniformity. Excellent wind velocity measurement is possible with only about 50 photons striking the detector, and less than 10 "coherent" photoelectrons contributing to the signal current. A key parameter, the heterodyne quantum efficiency, is not well understood or measured by detector manufacturers. Yet it is crucial since the SNR is proportional to it. Gain or loss in this parameter means good or bad news for the required laser pulse energy and/or the optical mirror diameter. MSFC developed a Detector Characterization Facility (DCF) during FY94 and FY95 for the purpose of allowing characterization of an assortment of candidate detectors. Several detectors have been procured and are being tested. Specialty and custom detectors may be

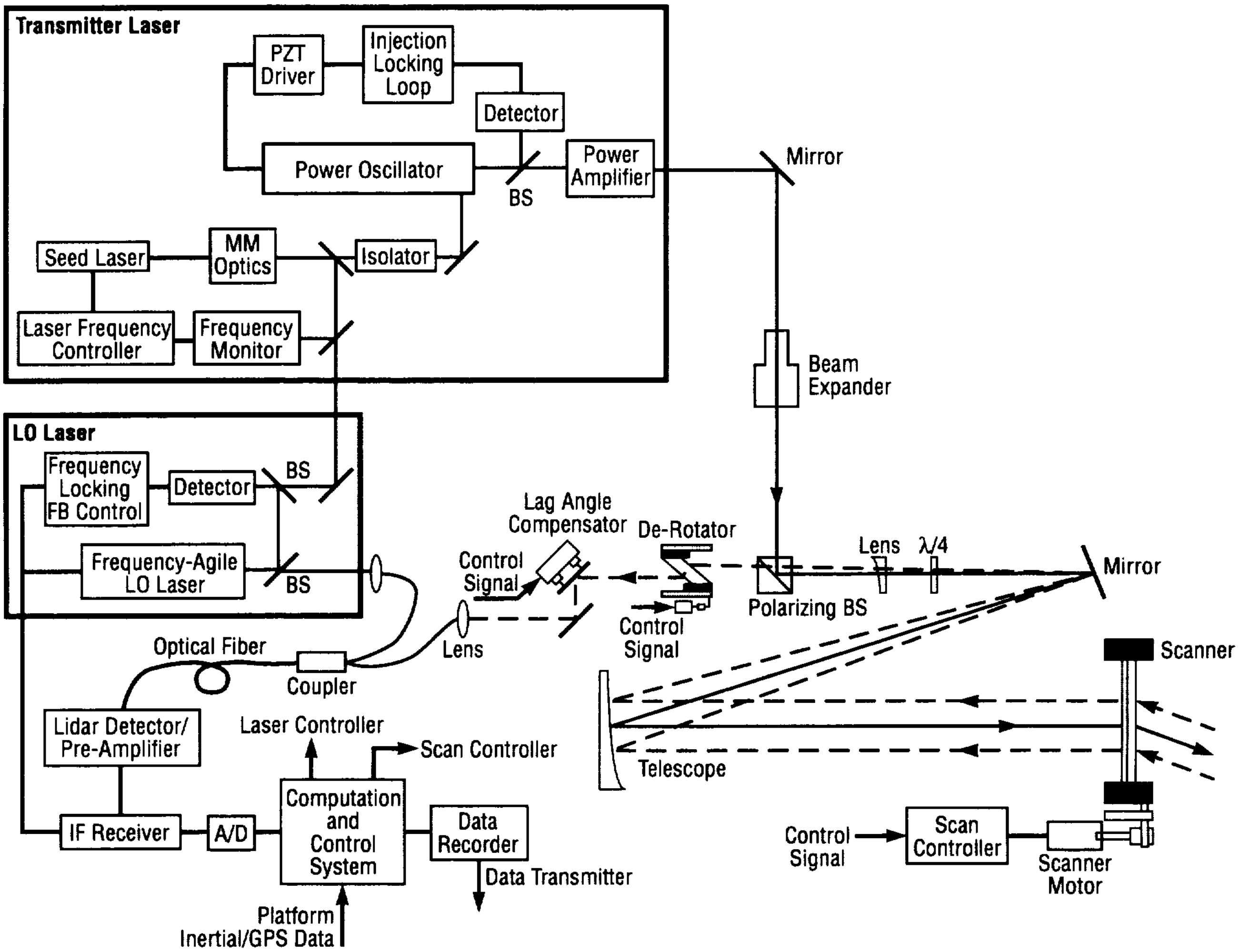

FIGURE 112.—Coherent Doppler Lidar System block diagram.

procured depending on the performance of commercial detectors, and on the envisioned receiver configuration of the space instrument.

The backscattered photons must be collected and well aligned with the LO photons in direction, curvature, and polarization. In the case of a continuously rotating scanner, the 2 to 3 m/sec round trip time of light to the atmosphere and back will produce an error in alignment when the backscattered photons enter the lidar through the scanner in its new position. The job of the optical derotator is to realign the signal photons. Studies of this element began at a low level in FY95. A novel derotator was invented by engineers at the University of Alabama in Huntsville (UAH), who have applied for a patent. Further refinement will continue in FY97 as part of an overall optical subsystem design.

Optical fibers may be used instead of free-space propagation for some or all of the photon paths within the coherent lidar system. With the assortment of optical fiber tools such as variable ratio couplers, pigtailed detectors, and robust connectors, the reliability of the lidar system alignment may be improved. Furthermore, components may be separated for electromagnetic interference (EMI), heat removal, or other reasons, rather than being forced close together on one optical bench. The MSFC DCF has been enhanced during FY96 to allow study of the performance of optical fibers for 2-μm coherent detection. Several candidate components have been procured and laboratory measurements have recently begun.

Conventional means to effect the required conical scan of the transmitted laser beam include a rotating telescope, a rotating flat mirror, and a rotating wedge. Each of these has disadvantages for space applications such as mass, volume, electrical power requirements for rotation, or center of mass displacement from axis of rotation. The recent development of diffractive and holographic optical elements (DOE, HOE) holds much promise of a significantly lighter and more benign scanner. MSFC began studying and procuring experimental HOE's and DOE's in FY95. To date, the necessary clear aperture of 50 cm and preservation of beam quality have not been demonstrated simultaneously with efficient deflection of laser light by 30 degrees. Several promising development efforts are now underway including a joint effort with UAH, a partnership with the Army/MICOM, and a NASA SBIR contract. Any sufficiently successful HOE or DOE will be tested in a 2-μm coherent lidar system for its performance impact.

Just as the optical derotator compensates for the continuous rotation of the scanner during the "echo" time of the photons, a LAC is needed to compensate for the continuous nadir rotation (orbiting) of the spacecraft, for the varying scanner and spacecraft orientation during receipt of the signal photons from the "thick" tropospheric target, and for any misalignment information available to the control computer before the return of the signal photons.

For the "short" optical wavelength of 2 μm, and for larger optical mirror diameters, this fine-tuning of the transmitter and receiver axes prevents significant loss of SNR. MSFC began to study this technology at a low level in FY95, and has contracted with UAH engineers to do investigation and design in FY97.

It is anticipated that a space lidar will maintain alignment through a combination of passive and active feedback loop techniques. However, the optimum mixture of techniques, and the optimum technology are not known. MSFC hopes to receive funding to develop this technology in FY97.

Demonstration of successful operation of all the developed technologies as a system is extremely important for a coherent lidar instrument. MSFC is planning to test each new technology individually in a coherent lidar system; eventually leading to wind profile measurement utilizing all of the novel technology. A novel compact, thermally stable coherent lidar beam expanding telescope has been invented by UAH engineers under contract to MSFC. A 25-cm version of the telescope was ordered and was delivered to MSFC in November of 1996. This will be tested in a coherent lidar system and then used itself to test the other novel technology. Performance will be compared with the predicted performance using the MSFC coherent lidar wind measurement computer simulation developed by UAH. The lidar will be used to collect atmospheric data for NASA scientists. The 500-mJ-pulse energy will allow wind and aerosol backscatter measurements at much higher altitudes than currently possible. Packaging of the lidar for NASA aircraft science missions is also a possibility.

For more information, see our WWW site: http://eo.msfc.nasa.gov

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Sponsor: NASA Headquarters, Office of Aeronautics

University Involvement: University of Alabama in Huntsville

Biographical Sketch: Dr. Michael J. Kavaya is chief of the Electro-Optics Branch in the MSFC Astrionics Laboratory. He received his BSEE from Purdue University, and his MSEE and Ph.D. EE from the California Institute of Technology. He has worked at MSFC since 1991.

Mission Operations

Applied Virtual Reality at MSFC

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Application of virtual reality (VR) technology offers much promise to enhance and accelerate the development of space systems infrastructure and operations while simultaneously reducing developmental and operational costs. From control center design analyses to extravehicular activity (EVA) operations development to mission and science training for crew and ground controllers, VR can provide cost-effective methods to prepare for and conduct space flight operations.

A VR applications program has been under development at MSFC since 1989. The objectives of the MSFC VR applications program are to develop, assess, validate, and utilize VR in hardware development, operations development and support, mission operations training and science training.[1] One of the goals of this technology program is to enable specialized human factors analyses earlier in the hardware and operations development process and develop more effective training and mission support systems.[2]

The MSFC VR systems reside in the Computer Applications And Virtual Environments (CAVE) Laboratory. Until recently, the CAVE Lab VR system (the "Legacy VR System") consisted of VPL Research, Inc. Eyephones (Models 1 and LX), DataGloves, and VPL software (Swivel 3D, Body Electric, and ISAAC), Polhemus Isotrak and Fastrac spatial tracking systems, two Macintosh IIfx computers and two Silicon Graphics Inc. (SGI) graphics computers (4D/310VGX and 4D/320VGXB). The CAVE Lab VR capabilities have now been upgraded. Sense8, Inc. WorldToolKit has replaced the VPL software. It runs on an SGI Indigo2 High Impact (250 MHz, 128 MB memory, 4 MB Texture memory, 4 GB disk, impact channel option (ICO)). Other additions include Kaiser Electro-Optics VIM 1000 HRpv and VIM 500 pv head-mounted displays (HMDs), the StereoGraphics Corp. CrystalEyes2 three-dimensional stereo eyeware (two pair of glasses), the Ascension Technology Corp. "Bird" spatial tracking systems (two) and the Crystal River Engineering, Inc. Acoustetron II 3D Sound Server. EXOS, Inc., under a Small Business Innovative Research (SBIR) Phase II contract, developed and delivered a sensing and force-reflecting exoskeleton (SAFiRE) for the hand. This device provides force-reflecting feedback to the fingers and hand as the user touches and grabs virtual objects. Other CAVE laboratory equipment includes SUN Microsystems, Inc. SUNSparc 20 and SUNSparc 10, a Panasonic AG–1960 VCR, and the Videonics MX–1 NTSC digital video mixer.

The development of several VR applications are currently underway. These include:

- Spacelab stowage reconfiguration training: The essential feature of this application is a virtual Spacelab module (VSLM). It involves using this VSLM during the last 6 to 9 months before launch. There are always late changes to on-board stowage. As changes are made, the MSFC Payload Crew Training Complex (PCTC) training mockup is updated. It is desirable to allow the crew the opportunity to tour the mockup to "see" the latest stowage configuration. This helps to "internalize" the location of items within the Spacelab module. Unfortunately, as the launch date approaches, access to the crew becomes increasingly limited, particularly during the last 3 months when the crew is dedicated primarily to the Johnson Space Center (JSC).

Figure 113.—Sensing and force-reflecting exoskeleton (SAFiRE) in action. International Space Welding Experiment (ISWE) on monitor.

A VSLM with the updated stowage configuration would enable a more convenient, even remote, method to "visualize" changes in stowage locations. Updated VSLM files could even be electronically transmitted to JSC for the crew to "tour" on the JSC VR system. To further enhance this training application, using both the MSFC and JSC VR systems simultaneously, the users could enter and interact within the same VSLM at the same time, even though they are physically located in different states. This would permit, for example, a mission specialist at JSC to be accompanied by the stowage manager or a payload specialist at MSFC for the stowage "walk-thru."

The pathfinder Spacelab for this VR application is the second International Microgravity Lab (IML–2). A VSLM with two "stocked" lockers has been developed along with application-unique kinematic and object behavior attributes.

Modeling and functional evaluation on the Legacy VR System is complete. Porting to the new VR system and further enhancements (including expanded functionality, texture mapped photos from the PCTC mockups, etc.) are planned. Analog empirical studies as well as crew and Payload Operations Control Center (POCC) cadre assessments are proposed. Evolution to the *International Space Station (ISS)* U.S. lab element is proposed.

- VR human anatomy teaching: The objectives of this project are to develop, evaluate, and utilize a VR application of a human cadaver for use in the classroom. The expectation is that this immersive learning environment affords quicker anatomic recognition and orientation and a greater level of retention in human anatomy instruction. This is a pathfinder for developing and assessing VR applications to be used for science training. A unique feature of this project is that the target platform must be inexpensive enough to be affordably placed in the classroom (currently a Pentium-based PC). A "virtual cadaver" with abdomino-pelvic organs is being developed.

Modeling and functional evaluation on the Legacy VR System is complete. Portage to WorldToolKit for Windows and Pentium PC is complete. In the coming year, more organs and a skeleton will be added to the model. Three-dimensional sound will be added to the major organs. An empirical study comparing the learning of gross anatomy in the VR human cadaver versus the current method of instruction will also occur during the coming year. Assessments will include whether the students learned faster, gained a deeper level of understanding, and/or had longer retention. In subsequent years, more detail (subdivided organs, texture mapping, etc.) and networking will be added. Teaching efficacy will continue to be empirically assessed.

- International Space Welding Experiment (ISWE) analytical tool and trainer: The objectives of this project are to develop, evaluate, and utilize a VR application of the ISWE for use in support of upcoming Neutral Buoyancy Simulator (NBS) tests and in training the flight crew and POCC cadre in general orientation, procedures, and location, orientation, and sequencing of the welding samples and tools. Since some of the hardware and operational analyses have already occurred in the NBS, ISWE will serve as a test case for this technology. Analytical results from the NBS and VR can be compared. The ISWE is a cooperative venture between the Paton Welding Institute of the Ukraine and MSFC. It will involve the use of an existing Ukrainian electron beam welder to be located in the cargo

FIGURE 114.—Immersive VR with head-mounted display and DataGlove.

bay of the orbiter. The ISWE is planed for flight as an element of the fourth United States Microgravity Payload Mission (USMP–4), currently scheduled for October 1997.

- Teleoperations using virtual reality: The *ISS* modules will be linked together using devices known as "common berthing mechanisms" (CBM's), the mating portions of which must be aligned within plus-or-minus 1 in and plus-or-minus one half-degree on each axis prior to activation of the automatic closure latches which draw the two station elements together. In the current design, positioning of the elements is performed by either the Shuttle or Station RMS (remote manipulator system) under man-in-the-loop control from on board the Shuttle nor Station. Unfortunately, neither a direct or video view of the berthing interface from useful vantage points is available in most scenarios.

This project proposes an alternative control scheme which involves replacement of the boresight camera with a precision video alignment sensor (already developed for autonomous rendezvous and docking), which would provide the CBM relative position and attitude data to a real-time computer graphics system generating stereoscopic views of the mechanisms and their surroundings. These views would be presented to the operator using a head-coupled head-mounted display, creating a sense of visual presence in the manipulator workspace. The operator will thus be able to see the mechanisms depicted from any useful vantage point desired simply by navigating to and looking in that relative direction. RMS handcontrollers have been integrated with the CAVE Laboratory VR system and linked with a high-fidelity simulation of the Shuttle RMS performing Space Station element berthing. Further refinements and tests are planned.

Several future VR applications are being planned. These include:

- A microgravity science glovebox (MSG) analytical tool for use in training the flight crew and POCC cadre in general orientation and procedures, as well as for use in design analyses and operations development; and

- Further development and assessment of the use of immersive VR for *ISS* payload training for the flight crew and POIC cadre. Of particular interest is the capability of remote, multiperson, interactive simulations and the ease with which training simulators can be reconfigured to support increment-specific integrated training. This activity plans to make advances in four classes of payload training for the flight crew and POIC cadre. These classes are: Payload systems, facility systems, element spatial orientation and stowage configuration, and science education.

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Sponsors: International Space Welding Experiment; Microgravity Science Glovebox; Equal Opportunity Office; Center Director's Discretionary Fund; Summer Faculty Fellowship Program; Community College Enrichment Program; Engineering Technology Base

University/Industry Involvement: Boeing; Antares; Oakwood College, Huntsville, AL; Alabama A&M, Huntsville, AL; Calhoun Community College, Decatur, AL; University of Tennessee at Chattanooga

Biographical Sketch: Joe Hale is team leader of the Human Engineering and Analysis Team in the Mission Operations Laboratory. He received a B.A. in psychology from the University of Virginia in 1976, an M.S. in applied behavior science (psychology) from Virginia Tech in 1981, and an M.S. in systems management from the Florida Institute of Technology in 1990. He developed and currently directs the MSFC Computer Applications And Virtual Environments (CAVE) Laboratory which includes the MSFC immersive virtual reality laboratory and test-bed. Hale is also a certified human factors professional (CHFP) (Board of Certification in Professional Ergonomics).

Polymer Waveguide Output Couplers

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Researchers are currently investigating numerous applications of optics to information processing problems. Integrated optics, in particular, is being researched as a mechanism to increase information exchange speeds and capacities beyond electronic limitations. To accomplish these increases, optical devices are interspersed with electronic devices. This allows designers to take maximum advantage of the benefits from both optical and electronic technologies. Integrating optical circuits with electronic circuits requires small feature sizes, high efficiency to minimize power consumption, conversion between optical and electrical signals, nonplanar interconnections, and manufacturing compatibility.

To address the problem of nonplanar interconnections fabricated in materials compatible with electronic fabrication technology, waveguide output couplers were designed and fabricated in Norland Optical Adhesive (NOA) No. 81 and AMOCO Ultradel 9020D polyimide. The output couplers were implemented using periodic relief gratings (fig. 115) on a planar waveguide (fig. 116). Design theory of the couplers was based on the perturbation approach. Coupling of light from waveguide propagation modes to output radiation modes can be described by coupled mode theory and the transmission line approximation of the perturbed area (grating structure). Using these concepts, gratings were accurately designed to output a minimum number of modes at desired output angles.

Waveguide couplers were fabricated and analyzed for structural accuracy, output-beam accuracy, and output efficiency. The results for the two different materials are compared. Applications for these couplers include data bus and clock distribution system interfaces requiring coupling to out-of-plane detectors.

This research was conducted as a joint effort between MSFC and the U.S. Army Missile Command Weapons Sciences Directorate Research, Development, and Engineering Center. The research was initiated in March 1994 and concluded in March 1996. The research was supported by MSFC under a Center Director's Discretionary Fund activity in the area of binary optics.

The objective of this effort was to design and produce waveguide couplers for efficient optical coupling between nonplanar devices. Couplers of this nature will be required for effective optical interconnections between electronic components. Rectangular relief diffraction gratings were investigated as a method of providing efficient nonplanar coupling. In addition, efficient integration of optical and electronic components requires compatible material and fabrication processes. Optical polymers were evaluated for electronic component compatibility, fabrication repeatability, and optical device efficiency.

Gratings were fabricated in both the NOA and Amoco materials with 1 μm feature sizes. Figure 117 illustrates the expected output angles for the fundamental mode of either material.

Several characteristics of the fabricated couplers were evaluated. These characteristics include waveguide thickness, output power, number of output angles, near-field output profile, and the far-field output profile. Fundamental mode coupling

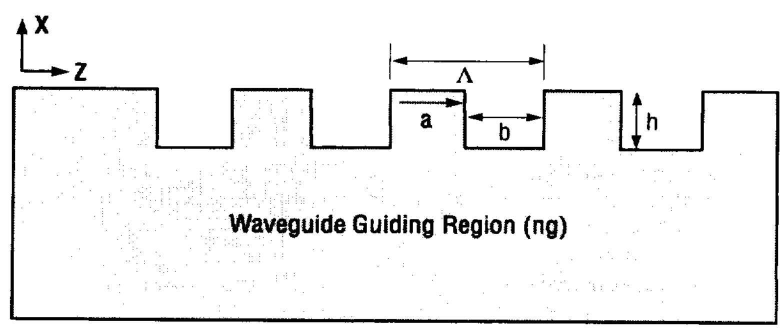

Figure 115.—Basic relief grating structure.

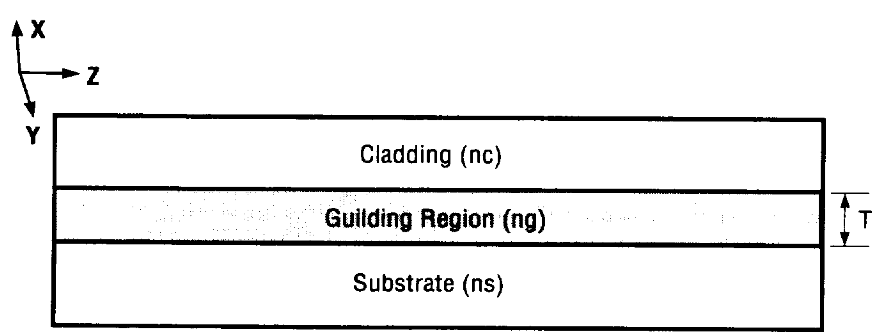

Figure 116.—Planar waveguide structure.

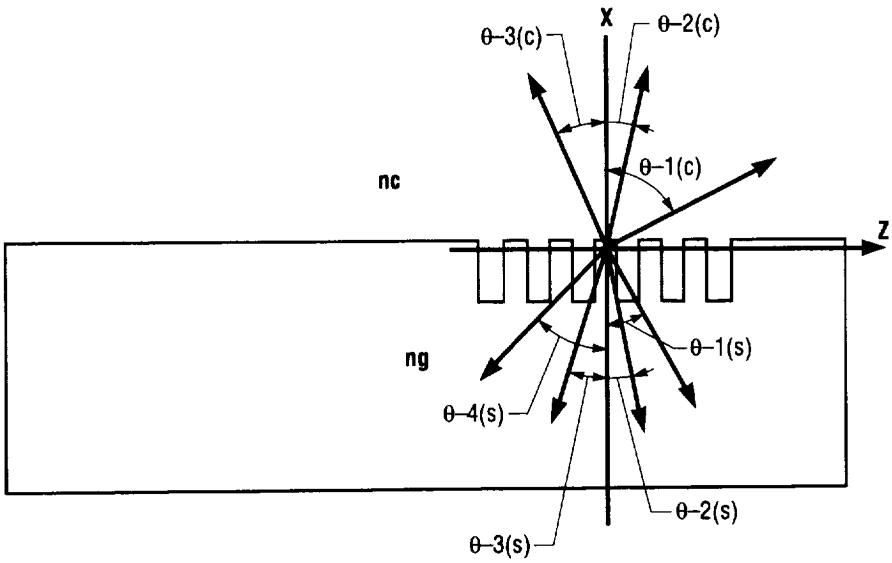

FIGURE 117.—Coupler output angles for the fundamental waveguide mode.

efficiencies of 69.39 percent and 74.28 percent were measured for the NOA and Amoco materials, respectively.[1]

Preliminary results of this research were presented at the 1995 Society for Photo-optical Instrumentation Engineers (SPIE) International Symposium in San Diego, California. These results were published in the conference proceedings.[2]

There are several applications which could utilize coupler designs based on this approach. Among these are optical interconnections of various types and optical gyroscopes. Using optical coupling in systems provides several benefits both to NASA and commercial applications. Using the results of this research, efficient couplers can be designed yielding high bandwidth, electromagnetic interference (EMI) immunity, negligible beam interference, large fanout, higher interconnection complexity, and ground loop isolation. These characteristics may be used to simplify systems and reduce weight of both space and other commercial applications.

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Sponsor: Center Director's Discretionary Fund

Biographical Sketches: Michael D. Watson is the lead engineer for HOSC Remote Services Systems. He has been a member of the Mission Operations Laboratory since April 1989. Currently, he is responsible for defining, designing, and developing remote services systems and concepts for the Huntsville Operations Support Center (HOSC). These responsibilities address services for the Spacelab, Space Shuttle, *International Space Station*, and Advanced X-Ray Astrophysics Facility (AXAF). Watson earned a bachelor of science in electrical engineering from the University of Kentucky in 1987 and a master of science in engineering in the Electrical and Computer Engineering Department from the University of Alabama in Huntsville in 1996.

Dr. Helen J. Cole is an optical physicist in the Electro-optics Branch of MSFC's Astrionics Laboratory. She has been a member of that lab since May of 1991. She is currently responsible for diffractive optics research efforts as they relate to MSFC's participation in a 2-1/2-year DARPA-sponsored technology reinvestment project (TRP) activity. MSFC and MICOM are partners with four industrial participants that will consider commercialization issues, and space and military insertion points for the technology. Cole holds a B.S. in mechanical engineering from the University of Wisconsin, and a Ph.D. in mechanical engineering from the University of Alabama in Huntsville.

Expert System Software Assistant for Payload Operations Control Team

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The Payload Operations Control Center (POCC) at MSFC has been the leader in innovative approaches to payload operations since 1987. Beginning with the flight of the Astro–1 Spacelab mission, POCC operations personnel in the Mission Operations Laboratory at MSFC have been concerned with operational efficiency and reducing the cost of Spacelab payload operations, while maintaining a high level of responsiveness to the science user's requirements and mission needs. A labor intensive area for flight preparation has been the development of special software and ground displays to monitor critical telemetry of payloads and Spacelab payload support systems. Additionally, the real-time mission support task of monitoring this data during flight has often required two payload system engineers (PSE) to provide timely and adequate response to anomalies and to assess potential problems identified in telemetry before they develop into major concerns. In an effort to find better and more cost effective ways of addressing these payload operations needs, the Office for Life and Microgravity Sciences and Applications at NASA Headquarters provided funding for an integrated team of McDonnell Douglas carrier subsystem experts, Teledyne Brown payload experts, and NASA MSFC operations control experts to develop and deploy a mission software knowledge base using the McDonnell Douglas Optimized Advanced System Integration and Simulation tool developed in the G2 expert system environment. G2 is a commercially available product developed by the Gensym Corporation. The broad objective of this G2-based application was to demonstrate the enhancements and cost savings that can be achieved through expert system software utilization payload operations in a ground control center. Spacelab provided a valuable proving ground for this advanced software technology—a technology that will be exploited and expanded for future *International Space Station* operations.

So, when the STS–75 mission launched on February 22, 1996, the operations personnel in the POCC welcomed a new member to their team. This new member was not a trained engineer, but rather a trained computer. The Operations Execution Assistant (OEA) expert system accurately and tirelessly watched both United States Microgravity Payload–3 and Tethered Satellite System–1R (USMP–3/TSS–1R) flight telemetry during the entire mission. Users were provided data via graphic interfaces on any off-nominal conditions that occurred on orbit. The focus of the tool was to demonstrate payload command and control efficiency improvements through the use of "smart" software which monitors flight telemetry, provides enhanced schematic-based data visualization, and performs advanced engineering data analysis. Features for the STS–75 mission included schematic-based monitoring of 512 telemetry readings using an intuitive object-based graphical user interface, exception limit monitoring, a messaging system, advanced diagnostics, real-time plots, trend analysis, automated malfunction procedure execution, crew message downlink, data logging, and quick recall of stored telemetry through a near real-time plot utility. The OEA knowledge base was hosted on a SunSparc20 workstation which received the real-time telemetry via an

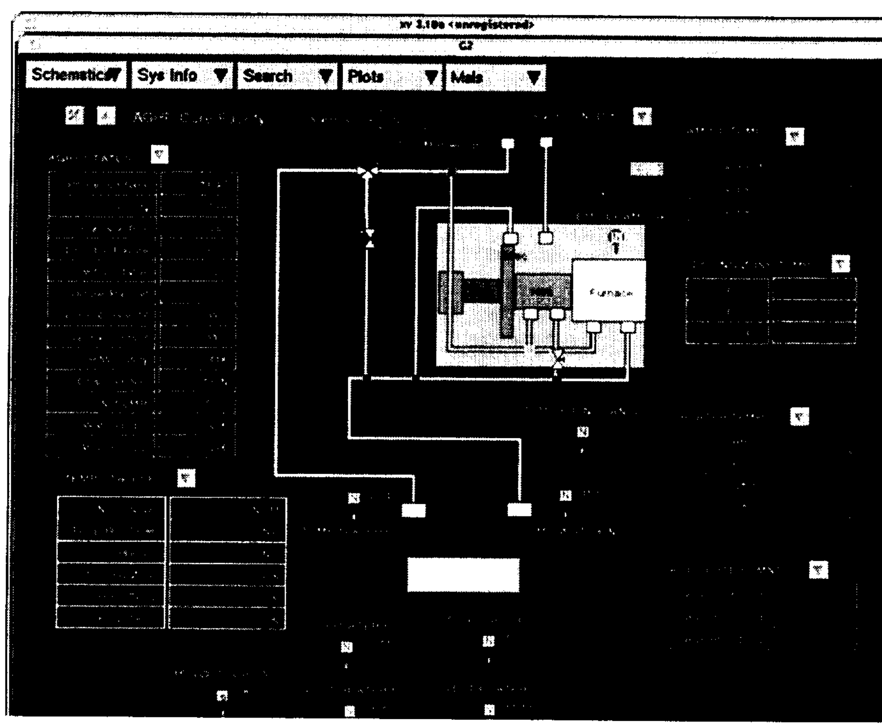

FIGURE 118.—Various workspaces provided by the Operations Execution Assistant (OEA) show the schematic-based data visualization which includes animation, the real-time data plotting, and the expert system messaging panel.

asynchronous data subset that was fed to the system once per second through a custom G2 Standard Interface bridge. The bridge C code decoded the raw data block, performed engineering units conversion, and passed changed data into the OEA system. Figure 118 shows a typical OEA tool display. The OEA expert system tool was labeled as "invaluable" and "indispensable" by the POCC operations personnel who used it. In the software debrief held after the USMP-3/TSS-1R mission, Richard Weaver, one of the Payload Systems Engineers from Teledyne Brown Engineering, stated, "It would not have been possible for one position (one person) to effectively monitor all the subsystems for this complex mission had it not been for the OEA tool." The OEA was also used successfully on the Life and Microgravity Science (LMS) mission in June 1996 and is being prepared for the Microgravity Science Laboratory mission planned for March 1997.

In conclusion, expert system technology has great potential for effective use in the payload mission operations environment. The environment nature of commercial tools like G2 greatly reduces the manpower necessary to develop and deploy payload operations support systems like OEA and simultaneously multiplies a single operator's ability to monitor telemetry and respond in a timely manner. These kinds of systems will become increasingly important to NASA during the Space Station era as the need for reduced operations cost increases.

Sponsor: Office of Life and Microgravity Sciences; Spacelab Payload Projects Office

Industry Involvement: McDonnell Douglas Aerospace

Biographical Sketch: Mark N. Rogers has been with Marshall since 1991. Completing his bachelor of science in electrical engineering at the University of Alabama, he began his career developing payload operations concepts for the Space Station. Rogers has served as experiment computer operator for the ATLAS-3 mission and as operations controller for the LMS mission. In 1996, Rogers received the NASA Special Service Award for innovation in the application of expert systems to payload flight operations. Currently, Rogers is a team member in the Flight Control Branch and is responsible for the development of operations concepts for future NASA payload projects.

Richard Mark McElyea has been with Marshall since 1981. Completing his bachelor of science in industrial and systems engineering at the University of Alabama in Huntsville, he began his career developing simulation hardware and software to support payload flight crew training. In 1983, McElyea moved from crew training to payload operations control where he served as operations controller for the Astro-2 mission. Currently, McElyea is a team lead in the Flight Control Branch and is responsible for the development of operations concepts for future NASA payload projects. He was awarded the NASA Exceptional Service Medal in 1995 for outstanding leadership in the management of continuous improvements in Spacelab operations.

Computerized Prediction of Extravehicular Activity Task Feasibility

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The difficulty of accomplishing work in extravehicular activity (EVA) is well documented. It arises as a result of motion restraints imposed by a pressurized spacesuit in a near-vacuum and of the frictionless environment induced in microgravity. The appropriate placement of foot restraints is crucial to ensuring that astronauts can remove and drive bolts, mate and demate connectors, and actuate levers. The location on structural members of the foot restraint sockets, to which the portable foot restraint is attached, must provide for an orientation of the restraint that affords the astronaut adequate visual and reach envelopes.

Previously, the initial location of these sockets was dependent upon the experienced designer's ability to estimate placement. The design was tested in a simulated zero-gravity environment; spacesuited astronauts performed the tasks with mockups while submerged in water. Crew evaluation of the tasks based on these designs often indicated the bolt or other structure to which force needed to be applied was not within an acceptable work envelope, resulting in redesign. The development of improved methods for location of crew aids prior to testing would result in considerable savings to the design effort for EVA hardware. Such an effort to streamline EVA design is especially relevant to *International Space Station (ISS)* construction and maintenance. Assembly operations alone are expected to require in excess of 400 hr of EVA. Thus, techniques which conserve design resources for assembly missions can have significant impact.

An experiment has been conducted at Marshall to test the efficacy of a human modeling software package in placement of foot restraint sockets. An ISS assembly mission which is being managed as a Marshall payload was used as the experimental test situation. The mission is the delivery of the Space Station remote manipulator system to the U.S. Laboratory on Assembly Flight 6A. The robot will be carried to orbit in the orbiter payload bay on a Spacelab logistics pallet. CAD models of the space hardware, including the foot restraint, were incorporated into the package, and a model of the space suit was acquired and modified for the human model. Limits of motion were placed on the suit based on mobility studies published in NASA standards documentation.[1,2] A series of simulations was run, in which the astronaut model performed bolt-removal and cable-connection tasks from the foot restraint inserted into sockets placed on the hardware. Locations of the sockets based on these simulations were used to develop neutral buoyancy mockups. An evaluation of the design was conducted in the Marshall Neutral Buoyancy Simulator (NBS). A team of six astronauts rated each of the tasks for ease of accomplishment.

The foot restraint support is jointed to provide 4 degrees-of-freedom. It can thus be configured and oriented in different directions from a given socket. In the course of the modeling, 9 socket sites were identified to support the 17 tasks. The placement of the socket by modeling was considered successful if the astronaut evaluators rated the task as acceptable. The accuracy of the location of the sockets was 94 percent. This is a higher rate of reliability than is typically achieved; it resulted in a time-efficient test, and design changes after the test were minimized. In addition to simple placement of the sockets, the modelers attempted to predict the joint settings required to reach the task. Success in this effort results in reduction of test time and is used to develop on-orbit procedures. For the four settings, the astronaut evaluators made no changes 79, 78, 78, and 59 percent of the time; in these cases, the modeled predictions were accepted as correct. This level of accuracy was considered by the crew to be both high and valuable to test conduct. Marshall is now refining the models and will compare a new set of predictions with crew evaluations in an upcoming test at the NBS.

[1]NASA-STD-3000; vol. 1. Man-Systems Integration Standards, Rev. B, 1995.

[2]Pantermeuhl, J.D.: EMU Reach And Proximity Modeling Data. LMES-31732, Lockheed Engineering and Sciences Company, Houston, 1995.

Sponsor: Space Station Program Office/ Payload Projects Office

Other Involvement: Johnson Space Center

Biographical Sketch: Charles Dischinger is a human factors engineer in the Mission Training Division of the Mission Operations Laboratory. He is responsible for human/ machine interface design for Marshall payloads. He received the M.S. degree in biology from West Virginia University in 1981 and has worked for Marshall for 2 years.

Space Environments and Effects

Space Environments and Effects Program

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A hazard to all spacecraft orbiting the Earth is the existence of a harsh environment with its subsequent effects. Some of these environmental hazards, such as plasma, extreme thermal excursions, ionized radiation, and meteoroids result from natural sources. Others, such as orbital debris and neutral contamination are induced by the presence of spacecraft themselves. This subsequently can produce damaging or even disabling effects on spacecraft, its materials, and its instruments. In partnership with industry, academia, and other Government agencies, the Space Environments and Effects (SEE) Program defines the space environments and advocates technology development to accommodate or mitigate these harmful environments on spacecraft; hence the technology is transferred to spacecraft developers for incorporation in design. The SEE Program establishes new plateaus of technical capability to reduce the cost of NASA's science and exploration missions which enables new and more challenging missions. The SEE Program also provides leading-edge exploratory and focused technology to promote continued U.S. preeminence in space. Figure 119 shows the relationship to other space flight programs.

The objectives of the SEE Program are to develop, verify, and transfer space environment and effects technologies that are required to design, manufacture, and operate reliable, cost-effective spacecraft. In order to satisfy these objectives, initial research proposals were solicited through a NASA Research Announcement (NRA) in the areas of engineering environmental definitions, environments and effects guidelines, assessment models and data bases, and flight/ground simulation/technology assessment data. Utilizing a peer review process that included nongovernmental reviewers, 18 proposals were selected for initial funding. Each winning proposal was assigned to a NASA Center based on the residence of the Technical Working Group chairperson for that particular discipline under which the proposal was categorized.

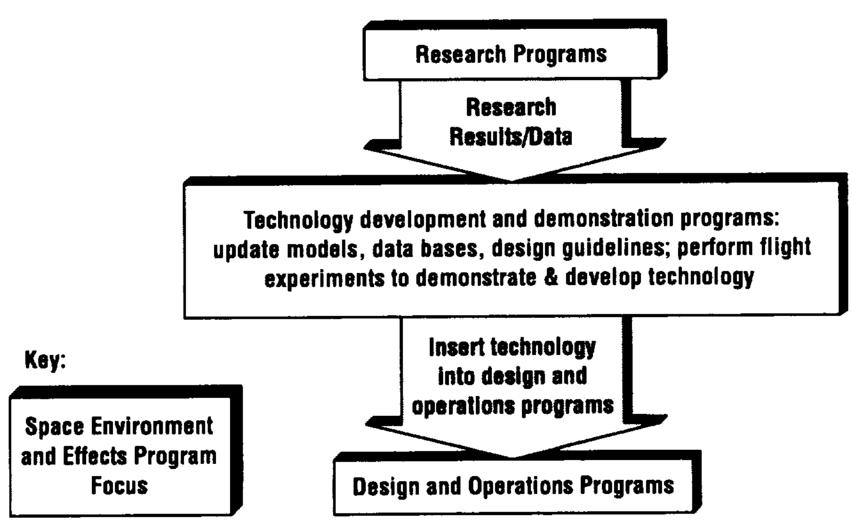


FIGURE 119.—Relationship to other programs.

Two examples of these technology development activities are as follows:

1) The Ionizing Radiation Environment and its Effects on Satellites.

This effort developed an improved model of the ionizing radiation environment in space and its effects on satellites. It is a user-friendly computational tool for use by the aerospace community. It estimates single-event effect rates as a guide to:

- Electronic parts selection for spacecraft; and
- Demonstrate compliance of a proposed spacecraft design regarding reliability and operability.

2) Development of Design Standards and Guidelines for Electromagnetic Compatibility and Lightning Protection for Spacecraft Utilizing Composite Materials.

This effort will develop design guidelines relating to electrical bonding, shielding, fault current carrying capability, and lightning protection for aircraft and aerospace vehicles using composite materials. The guidelines will contain the results of the following:

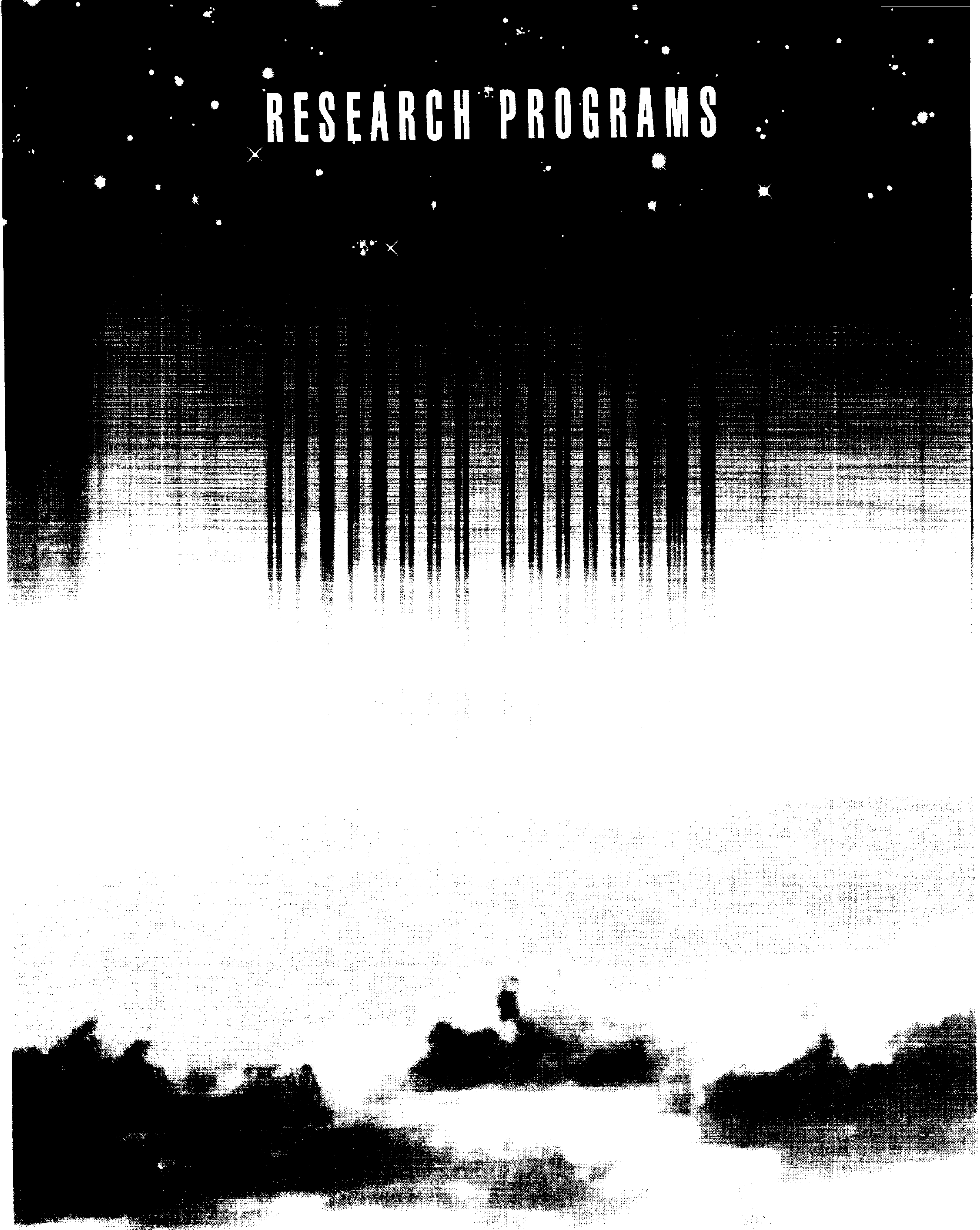
- Development of a data base that identifies electrical properties of nonmetallic composite materials used on spacecraft, satellites, and aircraft;
- Results of tests to determine fault carrying current capability of selected materials; and
- Results of simulated lightning tests to determine effects of high currents especially across joints in composite materials.

Most of the 18 activities are 3 years in duration ending in 1997. As the SEE Program receives the technology deliverables, the program actively pursues the integration of these new technologies into spacecraft design.

Sponsor: Office of Aeronautics

Biographical Sketch: Billy Kauffman is an aerospace engineer working with AST, studying the flight vehicle atmospheric environment. In this position, he plans, coordinates, and participates in engineering research activities as they apply to NASA's SEE Program. Kauffman establishes liaison with management and technical echelons of other laboratories and offices of MSFC, NASA Headquarters, other NASA Centers, government agencies and private industry involved in the SEE Program. He also participates in research studies relative to the improvement of engineering models and guidelines, develops publications and provides forums that aid in the transfer of technical information within the NASA SEE community. Kaufman earned his B.S. degree in mechanical engineering in December 1987 at the University of Alabama in Huntsville.

RESEARCH PROGRAMS



The Marshall Space Flight Center has traditionally maintained a strong, peer-reviewed research program responsive to the NASA Strategic Plan. Specifically, our research directly supports three of the four Strategic Enterprises:

Enterprise	**Research Area**
Mission to Planet Earth	Earth System Science
Human Exploration and Development of Space	Microgravity Science
Scientific Research	Physics and Astronomy

Earth system science focuses on understanding the Earth as an integrated environmental system, with emphasis on the hydrology cycle. Research includes theoretical and experimental studies of atmospheric and surface processes, environmental effects, and global change phenomena. It includes the development of advanced measurement techniques and missions to advance the associated scientific knowledge of planet Earth.

Microgravity science emphasizes the use of the low-gravity environment of space as a tool for materials science and biotechnology. The space growth and characterization of electronic and photonic materials and protein crystals is emphasized and is correlated with extensive laboratory research. Improved techniques are studied for crystal growth, thin film fabrication and on-orbit materials characterization.

Physics and astronomy research is directed toward high-energy astrophysics, solar physics and space physics. The astrophysics studies include gamma-ray and x-ray astronomy, and high-energy cosmic-ray physics. Solar physics focuses on understanding the role of magnetic fields in solar processes. Space physics activities involve the measurement and modeling of ion and plasma processes in the ionosphere and the magnetosphere.

MSFC is committed to communicating our science to the public more effectively and in enabling the productive use of science and technology in the public sector. Additional information is available on the World Wide Web at http://www.ssl.msfc.nasa.gov/.

Gregory S. Wilson
Director
Space Sciences Laboratory

Microgravity Science

Germanium Directional Solidification in United States Microgravity Laboratory-2

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***Special Notice:** This research task is being performed as a part of the cooperative agreement for microgravity research between MSFC, the Universities Space Research Association, and the University of Alabama, Huntsville. The principle investigator for the investigation is: Manfred Lichtensteiger/USRA 205–544–7798 E-mail: manfred@mgrav1.msfc.nasa.gov*

The primary purpose of this task is an assessment of the change from crystal growth furnace (CFG) to gravity gradient (GG) attitude during the second United States Microgravity Laboratory (USML–2) mission in an otherwise steady-state growth system using the demonstrated capabilities of the interface demarcation technique which are briefly outlined below. Thus, it will be possible for the first time to quantify a tolerable deviation of the space shuttle microgravity environment from ideal microgravity conditions. This information should prove useful in defining parameters for future materials processing in space.

Materials processing in space is an important aspect of the commercial utilization of the space environment by taking advantage of the tremendous reduction of the gravitational force acting on a crystal growth system (microgravity environment), representing a decisive advantage for producing high-quality crystalline materials. The production of such high-quality crystals in space processing invariably implies defect-free large crystals without compositional inhomogeneities.

The growth and solidification of materials implies a temperature gradient across a solid/melt interface in pure materials, and additional solute concentration gradients in doped semiconductors. However, such temperature and solute gradients in a normal gravitational field induce free convection in the melt, and the accompanying generation of changes in density and latent heat of fusion at the interface strengthen or weaken these gradients.

These gradients and the propagation velocity of the interface are coupled in a complex way to the shape of the solid/melt interface during the solidification process. This dictates strict control of the thermal and solute environment in the melt, crystal, and the containment ampoule inserted in the processing cartridge in the CGF. Hence, it is mandatory to develop a thorough understanding of the thermal properties involved in the solidification process prior to attempting any correlation of a ground-based crystal growth experiment to its duplicate in a microgravity environment.

Gallium-doped single-crystalline germanium was chosen as a model substance since its thermo-physical properties are well understood. In this growth system, the passage of well-defined electrical pulses of approximately 20A/cm^2 current density across the solid-melt interface of the solidifying crystal introduces localized changes in the dopant segregation behavior at the interface (interface demarcation).

Although nontrivial — the heights of the interface demarcation lines to be observed are in the nanometer range — differential interference contrast optical techniques fairly readily resolve these features on highly polished and carefully etched crystal segments grown, and thus allow the determination of the shape of the interface. With knowledge of the pulse repetition rate, these interface demarcation lines can be used to measure the instantaneous microscopic growth rates throughout the grown material. The accompanying microphotograph (fig. 120) demonstrates the power of this technique: It shows a segment of the

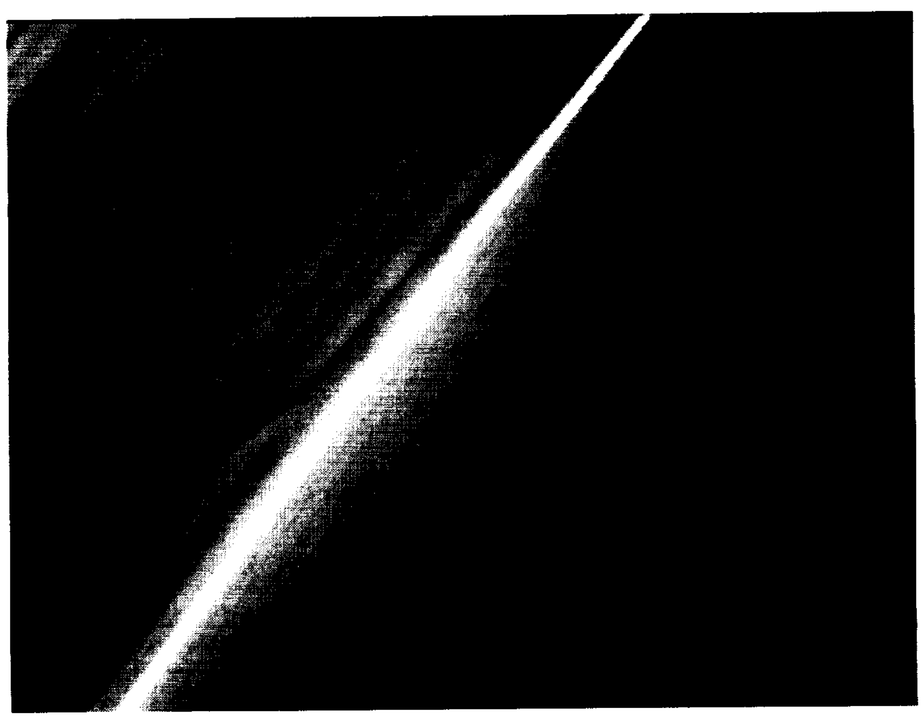

Figure 120.—Meltback interface.

initial 15 min of regrowth with a portion of the Czochralski grown rotational striations, the original meltback interface as a narrow white band, and the increasingly spaced interface demarcation lines.

Complemented by high-resolution electrical measurements (spreading resistance profiling) which yield information on localized dopant concentration changes, instantaneous growth rate changes can be correlated with dopant segregation behavior. This information can be used in the solution of the equations describing solidification processes in terms of heat transfer and fluid dynamics: First, the so-called Stefan problem in which solely the effects of the thermal gradients on the speed and shape of the crystal/melt interface are analyzed. Next, the combined effects of both the solute gradients and the temperature gradients are analyzed. In addition, the formation of morphological instabilities due to small departures from the theoretical limits of the energy and mass fluxes must also be examined, since they can lead to the formation of non-planar or even unstable oscillatory interfaces. Finally, the "rubber band effect", i.e. the degree of coupling of the growth system with the furnace, both at the onset and during directional solidification using these techniques must be analyzed, and explained.

Preliminary results on one of the crystals grown during mission USML–2 which included a translation arrest during a period of 90 min, i.e. one orbital period, clearly define the change over from steady-state growth conditions to stationary fluctuations, followed by a transient growth region upon resumption of growth. These results also indicate a very gradual change in the interface shape upon completion of the change of attitude maneuver. A three-dimensional reconstruction of this event is in progress.

Sponsor: NASA Microgravity Science and Applications Division

Industry Involvement: Computer Aided Process Engineering, Inc., Wellesley, MA

University Involvement: Massachusetts Institute of Technology

Biographical Sketch: Charles Baugher is a materials scientist and deputy division chief in the Microgravity Science and Applications Division of Space Sciences Laboratory. His recent research has been in the area of defining the low-level acceleration environment of the Space Shuttle during microgravity experimentation and in studying effects of that environment on materials processing. He has been published in the areas of electromagnetic propagation in plasmas, the interactions of plasmas with spacecraft, astronomical observations in the infrared, and the morphology of the Earth's magnetosphere.

Utilizing Controlled Vibrations in a Microgravity Environment to Understand and Promote Microstructural Homogeneity During Floating-Zone Crystal Growth

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***Special Notice:** This research task is being performed as a part of the cooperative agreement for microgravity research between MSFC, the Universities Space Research Association, and the University of Alabama, Huntsville. The principle investigator for the investigation is:*
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Solidification processing with the floating-zone method is an established technique for growing semiconductor crystals. Advantages include a self-contained melt which minimizes the introduction of impurities and thermal stresses. Unfortunately, inherent to processing is the development of detrimental thermocapillary flow. Consequently, crystal quality should improve during float-zone processing if convective flow within the liquid volume is minimized. The objective, therefore, of this proposed experimental and theoretical investigation is to utilize vibration driven surface streaming flows in an effort to negate the effects of thermocapillary convection. A schematic representation of the experimental apparatus is shown in figure 121. The processing parameters will be evaluated with the intent of optimizing microstructural homogeneity.

The ground-based experimental and theoretical work will concentrate on defining the role various processing parameters play in promoting microstructural uniformity during floating-zone crystal

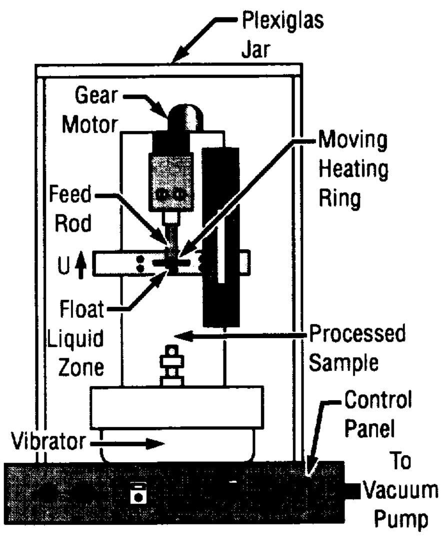

Figure 121.—Schematic representation of the experimental apparatus.

Figure 122.—Cross-sectional micrograph of a sodium nitrate-barium nitrate eutectic which has been float-zoned without vibration. Note non-uniformity between center and periphery.

Figure 123.—Cross-sectional micrograph of a sodium nitrate-barium nitrate eutectic which has been float-zoned with vibration. Note overall improvement in uniformity.

growth. In particular float-zone dimensions, aspect ratios, oscillation frequency, and amplitude will be evaluated with the intent of understanding how thermocapillary flow is negated. To this end, work has already been initiated by utilizing the transparent sodium nitrate-barium nitrate model system, figures 122 and 123; further insight regarding crystal homogeneity will be gained by processing sodium nitrate crystals which have been doped with silver nitrate. This ground-based work would then be extended to the microgravity environment of space where the effect of thermocapillary flow on crystal homogeneity may be studied in an optimized floating-zone.

Gravity driven flow which occurs during float-zone processing is minimized in a microgravity environment and thus permits thermocapillary flow to be singularly investigated. Here, utilizing incremented and calibrated vibration, the consequence of flow velocities on microstructure can be controlled and systematically investigated, not just acknowledged. The microgravity environment will minimize unit-gravity induced biases such as static shape distortion and buoyancy flow; furthermore, sedimentation of tracer particles will be minimized. Here then is an opportunity to evaluate crystal growth and homogeneity in association with a stable and dimensionally optimized floating-zone. The results of this study could well demonstrate a novel and inexpensive way of considerably improving crystal uniformity.

Shen, X.F.; Anilkumar, A.V.; Grugel, R.N.; Wang, T.G.:"Utilizing Vibration to Promote Microstructural Homogeneity During Floating-Zone Crystal Growth Processing." *Journal of Crystal Growth*, vol. 165, pp. 438–446, 1996.

Sponsor: Office of Life and Microgravity Sciences and Applications

Biographical Sketch: Charles Baugher is a materials scientist and deputy division chief in the Microgravity Science and Applications Division of Space Sciences Laboratory. His recent research has been in the area of defining the low-level acceleration environment of the Space Shuttle during microgravity experimentation and in studying effects of that environment on materials processing. He has been published in the areas of electromagnetic propagation in plasmas, the interactions of plasmas with spacecraft, astronomical observations in the infrared, and the morphology of the Earth's magnetosphere.

Novel Directional Solidification Processing of Hypermonotectic Alloys

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Special Notice: This research task is being performed as a part of the cooperative agreement for microgravity research between MSFC, the Universities Space Research Association, and the University of Alabama, Huntsville. The principle investigator for the investigation is: Richard N. Grugel/USRA 205–544–9165

The proposed investigation has several scientific objectives which will be realized by conducting a systematic experimental investigation in conjunction with a thorough modeling effort. The theoretical study will develop a semiquantitative predictive model relating microstructure to process parameters for the systems investigated experimentally. This will require close interaction with the experiment in order to determine more precisely the role of the various dynamic processes induced by ultrasound in these monotectic systems. Experimentally, ultrasound will be utilized to suspend and maintain separation of the liquid II (glycerol) droplets which precipitate from the bulk once the temperature drops below the miscibility gap boundary so that a uniformly aligned hypermonotectic composite might actually be produced by controlled directional solidification. This concept is demonstrated with a hypermonotectic, succinonitrile-glycerol mixture, figures 124 and 125.

The systematic, controlled directional solidification, experimental investigation will utilize a series of alloy compositions ranging from the monotectic reaction to well into the miscibility gap. Two sample sets will be investigated, one in conjunction with ultrasonics and one, otherwise identically processed, without. Metallographic examination will provide information regarding phase spacings, phase distributions, and volume fractions. The model will pay particular attention to the nature of the ultrasonic waves, including reflection and refraction of longitudinal waves and the two-liquid phase boundary, and on the importance of standing waves. Evaluation of the model and analysis of the data will provide valuable guidelines for optimizing a microgravity experiment.

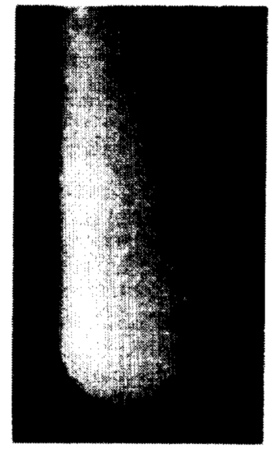

FIGURE 125.—Photograph showing a well-maintained dispersion of the liquid II phase in the presence of an applied ultrasonic field.

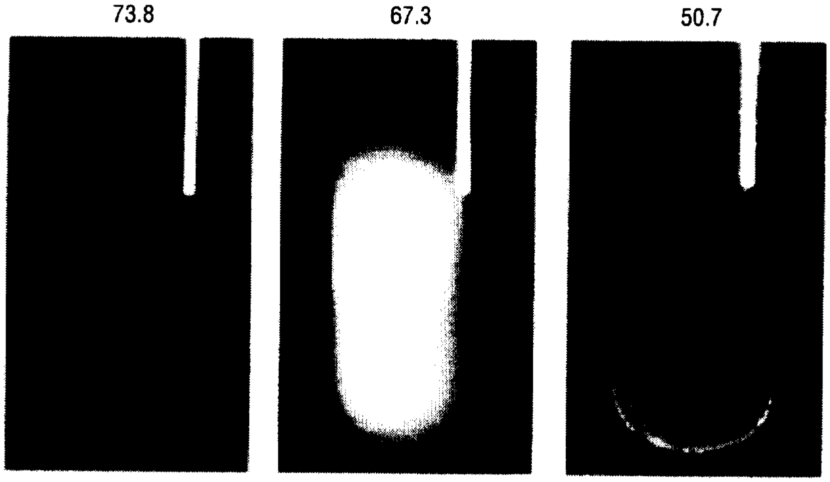

FIGURE 124.—Time sequence as a function of decreasing temperature showing precipitation and settling of liquid II (glycerol) from the bulk liquid.

Subsequent examination of the processed samples will promote our understanding of diffusion and coalescence processes, liquid-liquid interactions, wetting phenomena, and microstructural development. The liquid volume fraction ultrasonics can maintain dispersed versus the coalescing (settling) force imposed by gravity will be determined and then evaluated whether or not this could be improved upon in a microgravity environment. The value of this work will be a demonstration and mathematical characterization of a novel solidification processing technique. The knowledge acquired from investigating model alloys might then be applied to technologically relevant miscibility gap systems, e.g., superconducting Cu-Ba-Y, with the potential of producing novel composites having improved properties.

Sponsor: Office of Life and Microgravity Sciences and Applications

Biographical Sketch: Charles Baugher is a materials scientist and deputy division chief in the Microgravity Science and Applications Division of Space Sciences Laboratory. His recent research has been in the area of defining the low-level acceleration environment of the Space Shuttle during microgravity experimentation and in studying effects of that environment on materials processing. He has been published in the areas of electromagnetic propagation in plasmas, the interactions of plasmas with spacecraft, astronomical observations in the infrared, and the morphology of the Earth's magnetosphere.

A Demonstration Experiment to Study the Effects of Spacecraft Vibrations on Thermal Diffusion

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A fundamental and intrinsic objective of a microgravity experiment, especially a crystal growth or materials processing experiment, is to obtain diffusion limited growth conditions. Experiments pertaining to crystal growth from melts tend to be especially susceptible to the spacecraft acceleration environment, generally referred to as g-jitter, and great care has to be exercised in minimizing its deleterious effects. The objective of this investigation was to develop a simple scientific experiment that would provide a rigorous experimental basis for assessing the actual influence of jitter on thermal buoyancy driven convection. It employed very simple geometry, in a well understood circumstance, to allow materials science investigators to verify analytical and numerical models currently utilized for design and theoretical studies in a wide range of experiments. Its design, build, testing and integration was achieved in a record

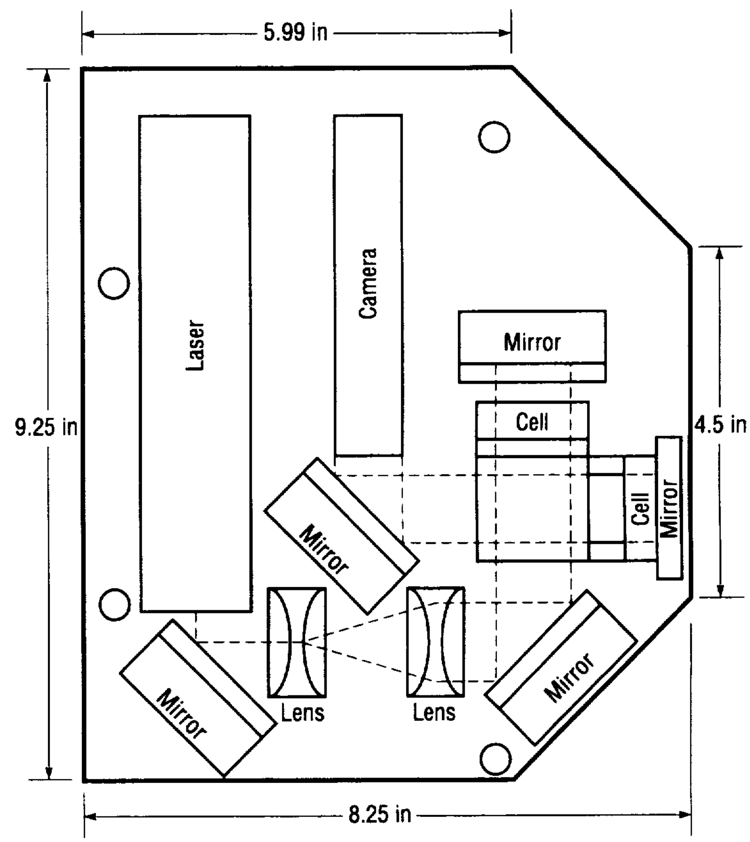

FIGURE 126.—Schematic representation of the Michelson Interferometric system showing component layout adapted to fit STABLE space constraints.

5 months duration using essentially off-the-shelf components and minimal costs.

A schematic diagram of the experiment called "Chuck" is shown in figure 126. As the figure shows, the entire unit is compact so that it could be integrated with the STABLE (suppression of transient events by levitation) vibration isolation platform that flew on the United States Microgravity Laboratory–2 (USML–2) mission in October 1995. The unit was designed to be modular and flexible so that not only different optical diagnostic configurations could be easily realized for studying different scientific phenomena, but also the unit could easily fit into the middeck/Space Station gloveboxes or the Canadian microgravity isolation mount (MIM). Figure 126 shows two cell locations, one of which is the experiment cell and the other is the optical path compensating cell used in the Michelson interferometer configuration. The test cell consisted of an optical quality glass cell (4 cm by 4 cm by 1 cm), pre-filled with 0.8 halocarbon oil, and outfitted with a uniform heat flux surface at the bottom of the cell (length 1.3 cm). At activation, power is applied to the heater. The progress and profile the thermal front is monitored by a combination of thermistors and the optical interferometric system and the temperatures, interferograms and acceleration data are recorded for future analysis. The experiment time line is about 15 min at a power level of 0.5 to 1 W followed by a sufficiently long cooling time (45 min) between runs. Due to the fairly quick system response, four different experiment runs were planned and executed; two runs without vibration isolation (hard mounted so that the experiment was subjected to the spacecraft acceleration environment) and two runs with active vibration isolation. Figure 127 shows a comparison of the interferometric fringe behavior from the experiment in space and on Earth. In the terrestrial experiment, Earth's gravity causes thermal buoyancy driven convection, seen in the figure as rising thermal plumes or blobs. This behavior is absent in the low-gravity experiment.

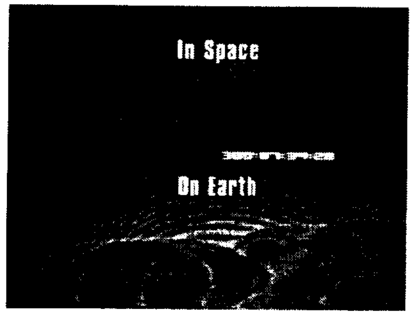

FIGURE 127.—Interferograms from "Chuck" operation in space and on Earth. Note the marked contrast between the two runs and the presence of convective plumes in the ground experiment.

"Chuck" was a unique experiment that was simple, modular and showed that a rugged flight science instrument could be built in a very short time with relatively minimal cost using essentially off-the-shelf components. It is a high-resolution interferometric system that can be used for optical diagnostics (to obtain qualitative and quantitative information) of different scientific phenomena. It contributed advanced design data on optics investigations (such as protein crystal growth) through the early solution of several engineering problems relating to the application of laser diodes and optics to small flight experiments.

[1]Ramachandran, N.; Baugher, C.R.; Rogers, J.; Peters, P.; Roark, W.; Pearcy, G.: "Thermal Diffusion Experiment 'Chuck'—Payload of STABLE." Proceedings of SPIE conference on Space Processing of Materials, Denver, CO, Aug. 4–9, 1996. Ed. N. Ramachandran, pp. 367–378.

[2]Edberg, D.; Boucher, R.; Schenck, D.; Nurre, G.; Whorton, M.; Kim, Y.; Alhorn, D.: "Results of the STABLE Vibration Isolation Flight Experiment." 19th Annual AAS Guidance and Control Conference, Brekenridge, CO, Feb. 7–11, 1996, AAS 96–071.

Sponsor: Center Director's Discretionary Fund.

University/Industry Involvement: Universities Space Research Association; Mevatec Corporation

Biographical Sketch: Charles Baugher is a materials scientist and deputy division chief in the Microgravity Science and Applications Division of Space Sciences Laboratory. His recent research has been in the area of defining the low-level acceleration environment of the Space Shuttle during microgravity experimentation and in studying effects of that environment on materials processing. He has been published in the areas of electromagnetic propagation in plasmas, the interactions of plasmas with spacecraft, astronomical observations in the infrared, and the morphology of the Earth's magnetosphere.

Particle Engulfment and Pushing at Solidifying Interfaces

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Obtaining uniform distribution of particles in the solid matrix during fabrication is an important issue in the manufacture of metal matrix composite materials. The main interactions in the introduction and incorporation of particles into the solid matrix especially when prepared by in-situ solidification are influenced by gravitational acceleration. The achievement of uniform distribution of particles in the matrix of these materials can only be achieved by understanding and controlling the particle interface interaction that determine when a particle is pushed or engulfed by the solidifying interface.

The Solidification Laboratory at The University of Alabama (Dr. Doru Stefanescu, principal investigator) in collaboration with co-investigators at MSFC's Space Sciences Laboratory are performing both experimental and theoretical work determining the critical velocity of engulfment of particles at a solidifying interface.

The objectives of the particle engulfment and pushing at solidifying interfaces, PEP, project are to gain a fundamental understanding of the physics of solidifying metal-ceramic particle systems, and to investigate the melt processing of metal matrix composites in the microgravity environment to obtain vital data for the processing of these important materials for terrestrial industry.

The experimental approach involves ground, aircraft low-gravity and orbital microgravity experiments that will compare data to comprehensive analytical and numerical models. Both metal and transparent matrices are to be used for the experiments. Although the metallic systems currently have the most important applications, transparent systems allow the detailed study of the solidifying interface/particle interactions which are important for a comprehensive understanding of the process.

The x-ray transmission microscope (XTM) developed for solidification studies—under a NASA advanced technology development program—has been utilized at the MSFC's Space Sciences Laboratory. The instrument allows the imaging in real-time of particle pushing and engulfing during solidification. Solid-liquid interfacial interaction with particles and voids were studied. Spherical zirconia spheres 30 to 60 μm are clearly resolved in aluminum samples 5 mm in diameter. The technique allows the monitoring of critical velocities for pushing and engulfment while monitoring the interfacial morphologies in-situ to test theory. Recent theory predicts the interfacial curvature response to approaching particles or voids can be significant for metallic systems. The XTM was also utilized to help select from candidate samples the metal/ceramic particle samples for flight experiments.

Transparent matrix samples of biphenyl matrix containing glass particles, and succinonitrile matrix containing spherical polystyrene particles are being studied to quantify how liquid convection ahead of the solidifying interface alters the particle behavior in the vicinity of the interface. Initial experiments were done on the NASA DC–9 parabolic aircraft. These experiments found that convection level and/or particle buoyancy significantly influences to critical velocity for particle engulfment. The critical velocity was found to increase, at the higher levels of natural convection, up to 40 percent. At the highest convection levels the particles failed to interact with the solidifying interface. A systematic study of current models showed that none could effectively quantify the observed convection effects on the critical velocity. These studies will be extended to near-convectionless conditions utilizing the middeck glovebox during the fourth United States Microgravity Laboratory Mission scheduled for launch in October 1997. The microgravity environment on orbit will allow the observation of particle pushing in steady-state conditions.

The initial Shuttle flight experiments for PEP metal matrix samples were done during the Life and Microgravity Sciences Spacelab mission in July 1996, utilizing the European advanced gradient heating furnace. The PEP, flight complement contained three samples. The first two with pure aluminum matrix and 500 μm ZrO_2 spherical particles. The third had Al-Ni eutectic alloy matrix and 500 μm ZrO_2 spherical particles. The thermal objectives of the experiment were successfully satisfied. The samples are to be delivered to the investigator team for analysis in fall 1996.

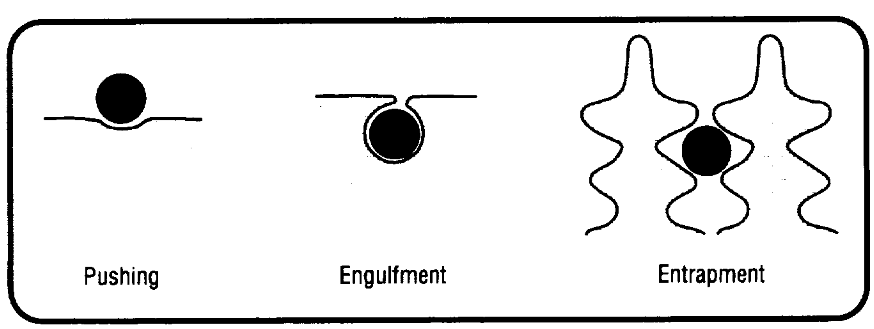

Figure 128.—Dynamics of particle-interface interaction.

Sen, S., Dhindaw, B.K.; Stefanescu, D.M.; and Curreri, P.A.: "Melt Convection Effects on the Critical Velocity of Particle Engulfment." Accepted for publication in *Journal of Crystal Growth*, Aug. 1996.

Sen, S., Dhindaw, B.K.; Stefanescu, D.M.; and Curreri, P.A.: "Melt Convection Effects on the Critical Velocity of Engulfment in the Biphenyl/Glass Particles System." Presented at the Eighth International Symposium on Experimental Methods for Microgravity Materials Science, Feb. 4–8, 1996, Anaheim, CA, 125 TMS Annual Meeting, to be published in proceedings.

Sen, S., Kaukler, W.; Curreri, P.; and Stefanescu, D. M.: "Dynamics of Solid/Liquid Interface Shape Evolution Near an Insoluble Particle." Submitted to Metallurgical Transactions, October 1996.

Sponsor: Office of Life and Microgravity Sciences and Applications

University Involvement: University of Alabama in Tuscaloosa

Biographical Sketch: Dr. Peter Curreri is a materials scientist in the Microgravity Science and Applications Division at MSFC's Space Sciences Laboratory. He serves as the United States Microgravity Payload mission scientist. His research focuses on solidification processes for metals, alloys and composite materials utilizing the unique properties of low and microgravity. Curreri earned his Ph.D. degree in materials and metallurgical engineering at the University of Florida. He has worked for NASA for 15 years.

Fundamental Studies of Solidification Using Real-Time X-Ray Microscopy

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Physical processes which occur at, or near, the solid-liquid interface during solidification or other phase transformations, partially determine important properties of solids. To date, interfacial morphologies and particle-interface interactions in the respective metallic, optically opaque systems have been deduced from post-process metallographic analyses of specimens. Thus, little information is obtained about the detailed dynamics of the processes.

We are developing a high-resolution x-ray microscope to view, in-situ and in real-time, interfacial processes in metallic systems during freezing or even during solid-solid transformations. The x-ray transmission microscope (XTM) operates in the hard x-ray range (10 to 100 keV) and achieves magnification through projection. We have obtained, using select aluminum alloys, in-situ records of the evolution of interface morphologies with characteristic lengths as small as 25 µm, interfacial solute accumulation (fig.129) and formation of droplets.

With metallic and semiconducting samples, the penetration of macroscopic layers requires photon energies in excess of 10 keV. This precludes the use of optical approaches for imaging. Only projection radiography can be practically employed in this energy range of over 10 keV. Projection radiography uses the divergence of the beam from a small source. The ultimate resolution is limited by the diameter of the source.

The major components of the system include a metal sample (thickness of order

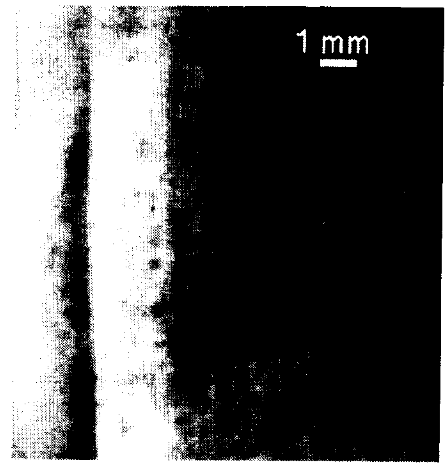

Figure 129.—Al-18 in solid/liquid interface growing at 12.4 µm/sec in a 45 °C/cm temperature gradient showing solute rejection to the liquid after the step increase of translation rate.

mm) which is contained in a specially designed, high-transmittance crucible and a high-temperature furnace on a translation stage imposes a temperature gradient onto the sample. The solid-liquid interface is positioned in close proximity to the focal spot of a microfocus x-ray source. The diverging x-ray beam permeates the sample and the resulting shadow falls on an x-ray image converter. The resulting visible image is converted to a digital image by a CCD camera and stored in a computer. This image is displayed on a high resolution monitor, either in real-time or after further processing (contrast enhancement, filtering, etc.).

At typical solidification rates, motion-induced blurring limits the exposure time to a few seconds. With state-of-the-art x-ray image intensifier/camera combinations, a magnification on the detector of some 20 times is the minimum required to obtain a spatial resolution of 10 µm. Such resolution is needed to see the dendritic structures formed in solidifying metals.

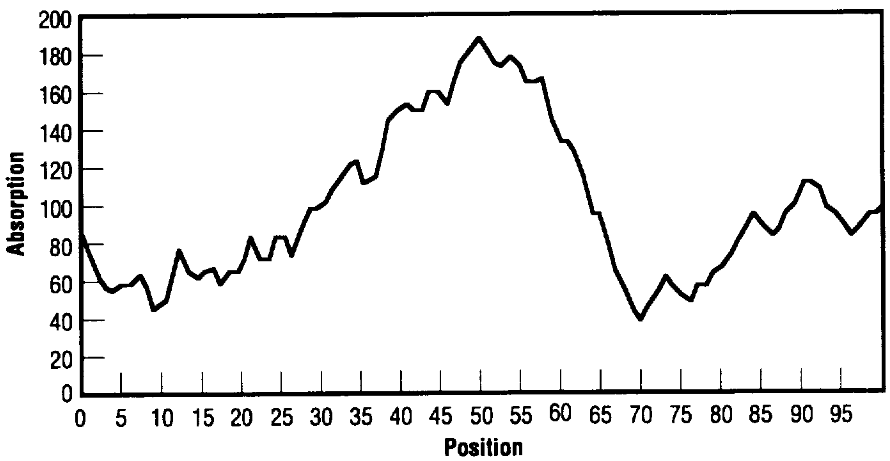

FIGURE 130.—Optical intensity (absorption) profile along the line in A) crossing the solute layer and interface. Solute gradient is clearly seen on the left part of the graph. Increasing in content represents increased absorption. The diffuse interface region is in the marked area. Note the solute layer is not uniform along the length of the interface.

Of course such observations require sufficient contrast (difference in absorptance) between features to be resolved and the retention of this contrast by the imaging devices (x-ray converter, image intensifier, camera, recording device). We found that employing higher magnifications than required by simple resolution arguments, provide an improved response in detecting low-contrast features. In monocomponent metallic systems, contrast between solid and melt is determined by the (electron cloud) density of the two phases resulting in less than 2 percent radiographic (image) contrast. In alloy systems, solute segregation can provide further contrast enhancement. The magnitude of contrast is proportional to the difference in atomic number of the components and their concentration. We therefore select the alloys based on x-ray contrast, and we employ the highest magnifications practicable.

How much of the original image contrast is retained depends on the dynamic range of the detector (imaging train) and the size of the features in the object. For small length scales, the contrast retained by the imaging train becomes much smaller than the original image contrast. This can only be (partly) compensated for if the dynamic range of the imaging train is high enough and if the lowest intensities of interest remain above the noise of the system.

We have been using a conventional x-ray image intensifier coupled to cooled (visible light) CCD camera of 12 to 16 bits dynamic range. The intensifier offers at best, a 10-bit dynamic range (1 part in 1,000). Evaluation of new CCD x-ray converter and camera technology was performed using radiation hardened CCD's as a direct conversion, hard x-ray detector. Comparisons between these and phosphor-coated CCD's were used to determine the best technologies to view the low-contrast details of solidification.

Research goals include studying solidification of metals and semiconductors and the dispersion of reinforcement particles in composites. Features we have already observed include dendrites and cells, the effects of voids and particles on the morphology during solidification of metal matrix composites, and solutal segregation profiles.

Curreri, P.A.; and Kaukler, W.: "Real-Time X-Ray Transmission Microscopy of Solidifying Al-In Alloys." Metallurgical Transactions 27A, no. 3, pp. 801–808, 1996.

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Curreri, P.A.; Kaukler, W.:"X-Ray Transmission Microscopy Study of the Dynamics of Solid/Liquid Interfacial Breakdown During Metal Alloy Solidification." Presented at the Eighth International Symposium on Experimental Methods for Microgravity Materials Science, February 4–8, 1996, Anaheim, CA, 125 TMS Annual Meeting, to be published in proceedings.

Kaukler, W.K.; Curreri, P.A.: "X-Ray Transmission Microscopy of Al-Pb Monotectic Alloys During Directional Solidification." Presented at the Eighth International Symposium on Experimental Methods for Microgravity Materials Science, February 4–8, 1996, Anaheim, CA, 125 TMS Annual Meeting, to be published in proceedings.

Kaukler, W.K.; Curreri, P.A.: "Advancement of X-Ray Microscopy Technology and Its Application to Metal Solidification Studies." Presented at the 1996 *SPIE* Technical Conference in Space Processing of Materials, August 4, 1996, and published as paper no. 5 in *Proceedings* vol. 2809, Ed. N. Ramachandran, pp. 34–44, 1996.

Sponsor: Office of Life and Microgravity Sciences and Applications

University Involvement: University of Alabama in Huntsville

Biographical Sketch: Dr. Peter Curreri is a materials scientist in the Microgravity Science and Applications Division at MSFC's Space Sciences Laboratory. He serves as the United States Microgravity Payload mission scientist. His research focuses on solidification processes for metals, alloys and composite materials utilizing the unique properties of low and microgravity. Curreri earned his Ph.D. degree in materials and metallurgical engineering at the University of Florida. He has worked for NASA for 15 years.

Solidification of II–VI Compounds in a Rotating Magnetic Field

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The primary aim of this work is to study the effects of a rotating magnetic field (RMF) on fluid flow and solidification of semiconductor compounds such as mercury cadmium telluride (HgCdTe) and cadmium telluride alloys. Control of the liquid boundary layer close to the solidifying interface has always been and continues to be of paramount interest to material scientists. The solid product is extremely susceptible to the behavior of such a layer and properties such as composition, defect concentration, precipitates and grain selection and twinning are dependent on the physical nature of the boundary layer. In Earth-based solidification, buoyancy driven convection and resultant fluid flows play a major role in establishing such a layer; indeed many of the flight projects involving solidification have had as their major objective the establishment of diffusion controlled solidification where the fluid flow becomes an insignificant contributor to compositional redistribution in the molten alloy.

The objective of the RMF is exactly the opposite. Fluid flow is encouraged and established by the interaction of the rotating magnetic field with the electrically conducting melt. The resulting flow cells prevent the formation of any kind of boundary layer and the material transport in the liquid can be controlled by the strength and frequency of the applied magnetic field. In practice, field strengths of the order of mT are required. Several advantages can be obtained from replacing the boundary layer. Transport of the alloy species through the melt is increased by using fluid flow rather than diffusion so that controlled solidification can be more rapid. The liquid-solid interface is more stable both from a temperature and a compositional standpoint. This stability prevents the oscillating temperatures which can give rise to the formation of inclusions. Indeed, in early work on a Soviet flight, a dramatic improvement in inclusion content was realized when the RMF was switched on midway through the flight.

Due to the nature of the process of solidifying alloys as compared to elements, it is necessary to solidify from a zone to make full use of the controlled stirring capability of the RMF. The zone enables complete replenishment of the solute component and thus permits the production of a uniform composition alloy. The types of solidification which will be studied are float zone, and the traveling solvent zone, or traveling heater method (THM). In this program, the float zone research will primarily be the responsibility of the University of Freiburg in Germany, while the THM work will be concentrated at MSFC. The alloy chosen for the MSFC study is the alloy of 80 percent HgTe and 20 percent CdTe, grown from a tellurium-rich zone. This alloy is strategically important as a sensor material, it is extremely difficult to grow with uniform properties, and it complements ongoing approved flight experiments for the United States Microgravity Payload missions (USMP–2 and USMP–4). Conventional THM work on Earth has been able to produce high, but not premium, quality HgCdTe material. Problems have included the incorporation of tellurium inclusions, the presence of low-angle grain boundaries, and the tendency for the composition to be non-uniform, particularly close to the edges of the wafer. All of these are deleterious to the production of large-scale arrays of detector devices. Control of the fluid flow close to the solidifying front will result in a degree of thermal and transport stability which will alleviate many of the difficulties associated with conventional THM.

Initial modeling of the process has shown that the interaction of the RMF with natural convection makes the interpretation of flow fields difficult to assess. It is thus important that microgravity experiments be undertaken to verify models. This we propose to do early in the program. Concurrent with this we shall grow THM HgCdTe both with and without the application of the RMF and fine tune the parameters. This work will be done concurrently and in close cooperation with modeling efforts to understand the role of the rotating magnetic field and the interaction of the field with the solvent zone both under terrestrial conditions and in a microgravity environment. From these results, we anticipate defining a flight experiment to verify the science of the technique.

Sponsor: Office of Life and Microgravity Sciences and Applications

University/Industry Involvement: University of Freiburg, Germany; Computer-Aided Process Engineering, Inc.

Biographical Sketch: Dr. Donald Gillies has been at MSFC working primarily on crystal growth and characterization of II-VI compounds. Prior to that, he spent 5 years at McDonnell Douglas Microelectronics Center in charge of liquid phase epitaxy production of detector grade mercury cadmium telluride.

Growth of Mercury Cadmium Telluride Single Crystals

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This flight investigation (experiment no. MPS77F069) was originally selected based on the response to NASA OA–77-3 Announcement of Opportunity. The content of the effort is based on an amended proposal submitted in response to Announcement of Opportunity OSTA–77-3 (formerly OA–77-3). Some of the initial work was done at McDonnell Douglas Research Laboratories under contract NAS8–33107. The investigation is consistent with the committee recommendations resulting from the "Review of the Microgravity Science and Applications Flight Programs" conducted January through March of 1987. The majority of the ground-based studies are being performed in the Space Sciences Laboratory at MSFC. In addition to crystal growth and characterization, this work has included thermophysical property determination, thermal modeling, phase diagram determination, fluid flow modeling, transient and diffusion analysis, and electronic property modeling. The flight portion of the investigation is being conducted using the advanced directional solidification furnace (AADSF) developed by MSFC and manifested for flights on the United States Microgravity Payload (USMP) series of missions. The first flight of the instrument took place in March 1994 on STS–62, and it is manifested to fly on USMP–4 in 1997. The ground-based portion of the experiment consisted of growing crystals in several different configurations of heat pipe furnaces, AADSF, and a similar furnace incorporated in a superconducting magnet capable of operating up to 5T.[2]

The major objective of this research is to establish the limitations imposed by gravity during growth on the quality of bulk solid crystals having large separation between their liquidus and solidus temperatures. The important goal is to explore the possible advantages of growth in the absence of gravity. Such crystals are extremely difficult to grow on Earth due to large density variations in their melts which give rise to fluid flows that result in large compositional variations.

The alloy system being investigated is $Hg_{1-z}Cd_x$ Te with x-values appropriate for infrared detector applications in the 8 to 14 m region. Both melt and Te-solvent growth methods as well as growth in magnetic fields are being pursued. The study consists of flight experimentation and ground-based experimental and theoretical work needed to establish material properties and optimum experimental parameters for the ongoing flight experiment and to assist material evaluation. $Hg_{1-z}Cd_x$ Te is representative of several alloys which have electrical and optical properties that can be compositionally tuned to meet a wide range of technological applications in the areas of sensors and lasers with applications to optical computing and communications as well as the national defense. The investigation includes both Bridgman-Stockbarger and solvent growth methods, as well as growth in a magnetic field. The alloys are prepared by reacting pure, elemental constituents in evacuated, sealed, fused-silica ampoules. The crystals are gown in a multizone furnace. The hot zone is heated above the liquidus temperature of the given alloy and the cold zone is maintained at lower temperatures to provide temperature gradient sufficient to prevent constitutional supercooling. Crystal growth is accomplished by slowly moving the ampoule from the hot zone to the cold zone of the furnace.

Detailed microstructural and compositional analysis has been completed for the approximately 16 cm long $Hg_{0.8}Cd_{0.2}Te$ alloy crystal that was successfully grown over a period of 11 days during the USMP–2 mission. Equivalent analysis was done on a series of ground-control crystals. The space grown crystal was significantly different from crystals grown under similar conditions on the ground.[3] One clear difference was that there was no hydrostatic force pushing the material against the ampoule wall during the solidification as is the case on Earth. During the mission the orbiter was maneuvered into several different attitudes with the results that the residual acceleration vector caused by drag in on the orbiter and the distance of the ADSF from the center of gravity of the orbiter was aligned differently with respect to the growth axis of the solidifying material for distinct parts of the mission. Significant differences were observed during three long, but uninterrupted, periods at constant attitude. Compositional variations along the crystal circumference indicated residual fluid flows for the least favorable vector orientations. Identifiable regions exist in which a transverse vector has pushed the material against the ampoule wall and allowed it to readily contract away from the opposite wall. Such surfaces showed etch pits produced by preferential evaporation at defect sites. X-ray scattering showed that the regions pulled away from the wall tended to be less strained or of higher quality material that the opposite surface, and considerably better than the Earth-grown material. Composition determination on the surface of the material demonstrated significant difference, dependent on the direction of the residual acceleration vector. These are clear indications of three-dimensional fluid flow. A significant portion of the boule was grown with a component of the vector aligned in a direction from liquid to solid. Synchroton x-ray studies of this material showed it to be single crystal and of much less defect density that found in ground-based growths.

[1]Lehoczky, S.L.; Szofran, F.R.; Gillies, D.C.: "Growth of Solid Solution Single Crystals." Second United States Microgravity Payload: One Year Report, ed. by P.A. Curreri and D.E. McCauley, NASA Technical Memorandum 4737.

[2]Watring, D.A.; Lehoczky, S.L.: "Magnet Hydrodynamic Damping of Convection during Verical Bridgman-Stockberger Growth of HgCdTe." *Journal of Crystal Growth*, in press, 1996.

[3]Gillies, D.C.; Lehoczky, S.L.; Szofran, F.R.; Watring, D.A.; Alexander, H.A.: "Effect of Residual Accelerations During Growth of Mercury Cadmium Telluride (MCT) on the USMP-2 Mission." *Journal of Crystal Growth*, in press, 1996.

Sponsor: Microgravity Science and Applications Division

Biographical Sketch: Dr. Sandor Lehoczky is the chief of the Microgravity Science and Applications Division at MSFC.

Crystal Growth of Selected II–VI Semiconducting Alloys by Directional Solidification

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This research study is investigating the effects of a microgravity environment during the crystal growth of selected II–VI semiconducting alloys on their compositional, metallurgical, electrical and optical properties. The ongoing work includes both Bridgman-Stockbarger and solvent growth methods, as well as growth in a magnetic field. The materials investigated are II–VI $Hg_{1-x}CdTe$, $Hg_{1-x}Zn_xTe$, and $Hg_{1-x}Zn_xSe$ ($0<x<1$), with particular emphasis on x-values appropriate for infrared detection and imaging in the 5- to 30-μm wavelength region. Wide separation between the liquidus and solidus of the phase diagrams[1] (fig. 131) with consequent segregation during solidification and problems associated with the high volatility of one of the components (Hg), make the preparation of homogeneous, high-quality, bulk crystals of the alloys nearly an impossible task in a gravitational environment.

The three-fold objectives of the ongoing investigation are as follows:

- To determine the relative contributions of gravitationally driven fluid flows to the compositional redistribution observed during the unidirectional crystal growth of selected semiconducting solid solution alloys having large separation between the liquidus and solidus of the constitutional phase diagram;
- To ascertain the potential role of irregular fluid flows and hydrostatic pressure effects in generation of extended crystal defects and second-phase inclusions in the crystals; and
- To obtain a limited amount of "high-quality" materials needed for bulk crystal property characterizations and for the fabrication of various device structures

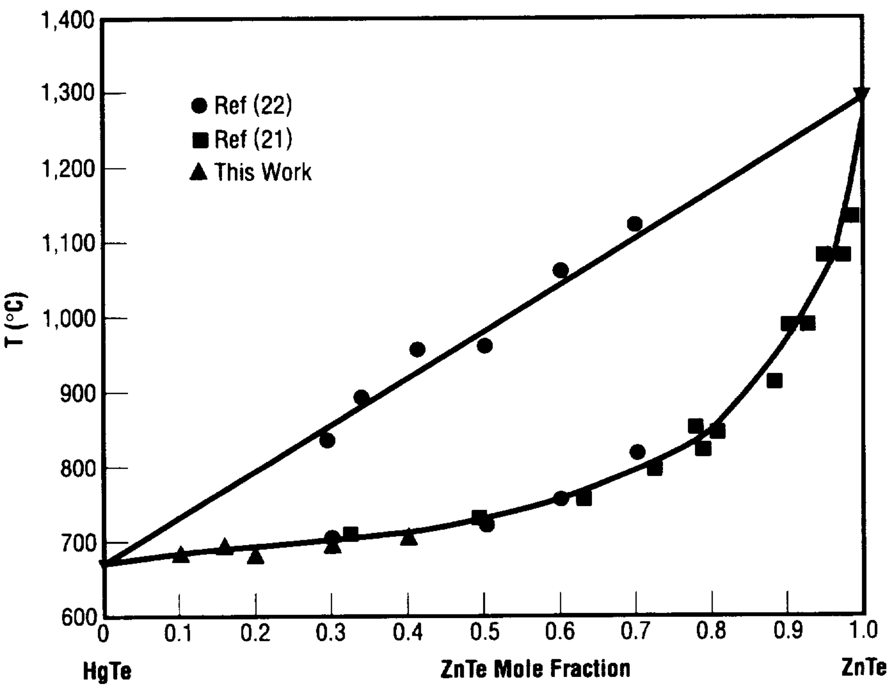

Figure 131.—Pseudobinary phase diagram of HgTe-ZnTe.

needed to establish ultimate material performance limits.

The flight portion of the study was to be accomplished by performing growth experiments using the crystal growth furnace (CGF) manifested to fly on various Spacelab missions. The investigation complements the experiments being done on the crystal growth of $Hg_{1-x}Cd_xTe$ using the advanced automatic directional solidification furnace (AADSF) flight instrument. The main emphasis of the study involves the $Hg_{1-x}Zn_xTe$ and $Hg_{1-x}Zn_xSe$ alloys. The combination of the two studies provides the basis for the evaluation of the influence of alloy property variations on the relative importance of various gravity- and nongravity-related effects. Several alloy properties including the effective diffusion coefficient, segregation coefficient, thermal conductivity,[2] viscogity microhardness, etc., are known to vary substantially with composition and from alloy system to alloy system. For example, the "effective" mass diffusion coefficients deduced from directional solidification compositional redistribution data differ by about a factor of 10, from that of $Hg_{1-x}Cd_xTe$ being the largest and $Hg_{1-x}Zn_xTe$ being the smallest. These variations will cause nongravity-related effects to be more significant in some cases than in others.

A series of HgZnTe crystal ingots has been grown from pseudobinary melts by Bridgman-Stockbarger type directional solidification using the CGF ground control experiment laboratory (GCEL) furnace, as well as MSFC heat pipe furnaces. Several ZnTe crystals were also grown using a Te-solvent zone growth method. Various thermal boundary conditions and growth rates were employed and several of the ingots were rapidly quenched during the steady-state portion of growth to establish correlation between thermal conditions and melt/solid interface shapes. These experiments also indicated that the ingots can be successfully quenched and back melted to allow a rapid return to steady-state growth. The fitting of the measured crystal compositional distributions to appropriate theoretical models was used to obtain an estimate of the effective HgTe-ZnTe liquid diffusion coefficient. To assist the modeling of the pertinent heat and mass transport processes, selected portions of the pseudobinary phase diagram,[1] thermal diffusivity[2] and melt viscosity[3] have been measured. A microscopic theoretical model for the calculation of point defect energies, charge-carrier concentrations, Fermi energy, and conduction-electron mobility as functions of x, temperature, and both ionized and neutral defect densities has been developed and some of the pertinent materials properties were measured. Theoretical models have also been developed for the axial and radial alloy segregation as functions of alloy composition, growth rate, thermal gradient and growth interface curvature. The calculated results agreed well with experimental data and indicated that the axial alloy composition is limited by diffusion-like behavior and the radial segregation by fluid flow effects. Further numerical modeling including the detailed sample, experiment container and furnace system is in progress to further assess the role of gravity in the overall solidification process.

A ground preprocessed and quenched sample was successfully back-melted and partially regrown in the CGF instrument during the first United States Microgravity Laboratory (USML–1) mission. The meltback interface was within 0.5 mm of the desired value. Because of the loss of power to the CGF, the experiment was prematurely terminated after approximately 39 hr into the planned 150-hr growth period. About 5.7 mm of sample had been grown at that point. Surface photomicrographs of the sample clearly showed significant topographical differences between the space- and ground-grown portions. Compositional measurements along the sample axis indicated that the desired steady-state growth for the axial composition was reached at about 3 mm into the growth because of the quenched in melt composition for steady-state growth. An x-ray diffraction and SEM survey of the sample showed that both the ground- and flight-portions of the ingot contained only a few grains, i.e., were nearly single crystals, and the crystallographic orientation was maintained following back-melting and space growth. The interface shape, radial compositional variations, and the quenched-in dendretic structures of the flight sample all have shown an asymmetric behavior. The compositional data strongly suggest that the most likely cause was unanticipated transverse residual accelerations.

A new seeded method has been developed recently for the growth of HgZnTe crystal ingots from pseudobinary melt by the Bridgman-Stockbarger type directional solidification for the second United States Microgravity Laboratory (USML–2) mission. A physical vapor transport method developed by MSFC was used to grow 2-cm ZnTe seed crystals in the fused silica ampoules. Then a stack of precast pseudobinary alloys of varying compositions were loaded in the remaining ampoules. The alloy compositional variation in the stack was chosen to correspond to the expected melt composition variation along the growth axis for steady-state diffusion-controlled growth conditions (fig. 132). Composition analysis on the grown crystals confirm that steady-state growth was achieved from the beginning of the growth process. A series of $Hg_{0.84}Zn_{0.16}Te$ and $Hg_{0.88}Zn_{0.12}Te$ crystals were then grown using the CGF ground control experiment laboratory (GCEL) furnace, as well as in heat-pipe furnaces. Several crystals were also grown under the influence of a 5-T axial magnetic field and 0.5-T transverse magnetic field.[4] Detailed compositional and microstructural characterization of the samples indicated that the alloy stacks could be successfully back-melted within 0.5 mm of the seed interface to assure that growth begins under nearly steady-state growth conditions. The applied magnetic fields had a significant influence on radial alloy segregation and growth interface constitutional supercooling breakdown demonstrating the importance of gravity-induced fluid-flow effects.

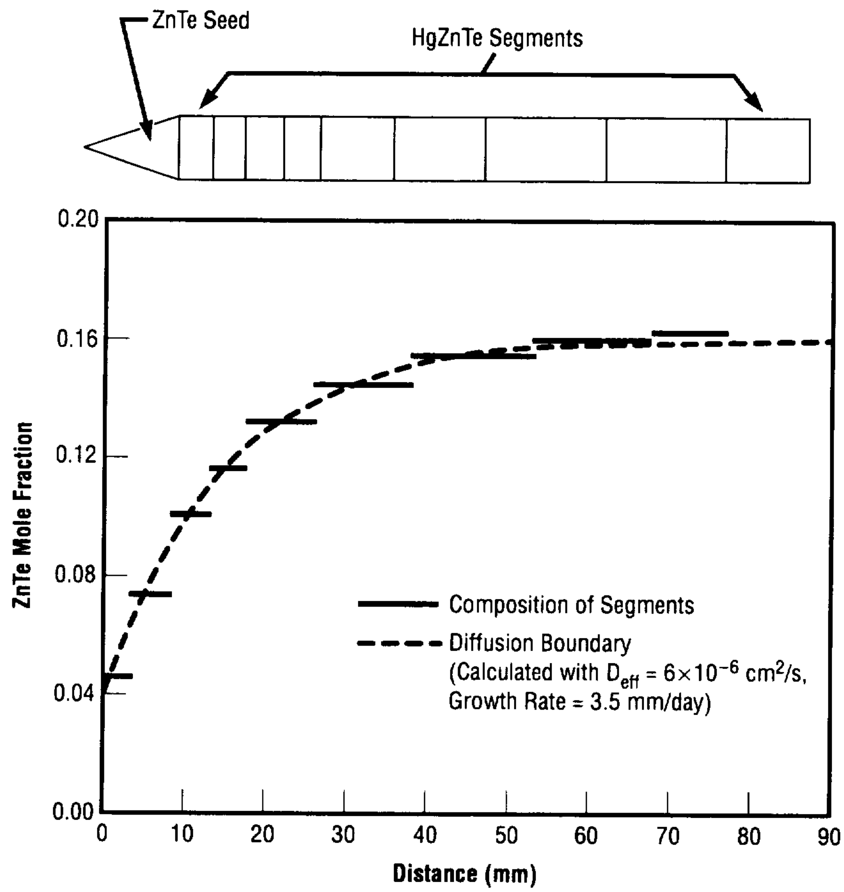

Figure 132.—Sample configuration and compositional distribution in HgZnTe segments used for seeded growth experiments.

Two $Hg_{0.88}Zn_{0.12}Te$ seeded ampoules were chosen for processing in the CGF during the USML–2 mission. The results from a similar experiment that was inadvertently terminated during the previous USML–1 mission strongly indicated that residual accelerations transverse to the growth axis are detrimental for achieving the primary experiment objectives. Thus a Shuttle flight attitude that minimizes such accelerations was requested for the USML–2 mission. Just prior to launch the attitude was disallowed because of programmatic constraints and a decision was made not to perform the flight portion of the experiment under unfavorable growth conditions.

Su, C.-H.; Sha, Y.-G.; Mazuruk, K.; Lehoczky, S. L.: "Phase Diagram, of HgTe-ZnTe Pseudobinary and Density, Heat Capacity and Enthalpy of Mixing of $Hg_{1-x}Zn_x$ Te Pseudobinary Melts." *Journal of Applied Physics*, 80,1, 137, 1996.

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$Hg_{0.84}Zn_{0.16}Te$ Pseudobinary Melt." *Journal of Applied Physics*, 79, 12, 9080, 1996.

Sha, Y.-G.; Su, C.-H.; Lehoczky, S.L.: "Growth of HgZnTe by Directional Solidification in a Magnetic Field." *Journal of Crystal Growth*, in press, 1996.

Sponsor: Microgravity Science and Application Division

University Involvement: Dr. Rosalia N. Scripa, University of Alabama at Birmingham; Dr. Yi-Gao Sha, Universities Space Research Association

Biographical Sketch: Dr. Sandor Lehoczky is chief of the Microgravity Science and Applications Division of the Space Sciences Laboratory of MSFC.

Measurement of the Optical and Radiative Properties of High-Temperature Liquid Materials by Fourier Transform Infrared Spectroscopy

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Basic to the understanding of high-temperature materials in the liquid state is first measurement of the optical and radiative properties. Unfortunately, very little spectral emissivity data are available for high-temperature liquid and solid materials in the wavelength range 2 to 20 μm. These data are virtually nonexistent when the case of undercooled materials is considered. The use of fourier transform infrared (FTIR) spectroscopy to investigate the radiative and optical properties of high-temperature liquids is proposed.

The first objective of this program is to fully develop the use of FTIR spectroscopy for the purpose of determining, at a high rate of speed, the normal and total hemispherical emissivities. Spectral emissivities would be measured in the 2- to 20-μm wavelength range for high-temperature liquid and undercooled materials. Due to the nature of the approach, the spectral emissivities can be determined quickly over the complete wavelength range. The measurements would then be conducted over a wide temperature range, including the deeply undercooled state. The second objective of this research would be to apply this technique to materials that are of current interest to the MSAD program; in particular, where there is a strong need in the numerous furnace programs and containerless programs which include electromagnetic, electrostatic and acoustic levitators as well as the 105-Meter Drop Tube Facility at MSFC. A third objective would be to provide optical and radiative property data for nucleation and solidification theories.

The overall approach is to use the FTIR spectrometer to measure the intensity of light emitted by a high-temperature liquid sample. Due to the intrinsic nature of FTIR techniques, the light intensity can be recorded over a wide range of wavelengths (2 to 20 μm) in a rapid manner, on the order of 100 spectrums per second. Spectral emissivity values for any given wavelength would be found by comparing the spectrum for a liquid sample to a spectrum recorded using the same optical path, from a standard. The standard would be a blackbody source such as a solid sphere of tungsten with a precise blackbody hole located in it. Additionally, laser polarimetric techniques which have been developed for emissivity measurements on liquids, would provide additional verification of calibration of the FTIR. Absolute specimen temperature measurements would be obtained with a aid of a singlecolor pyrometer operating at a wavelength where an independent measure of the spectral emissivity has already been determined with the aid of the laser polarimetric method. Once an FTIR spectrum is obtained, the normal spectral emissivity over the 2- to 20-μm range is derived. The spectral hemispherical emissivity (SHE) would then be derived in one of two ways.

Research in the FTIR program over the past year has been in the design and development of the FTIR system and adaptation for the specific purpose of measuring the high-temperature optical properties of undercooled metals. A complex innovative optical system has been designed and developed. In addition, a modified electromagnetic levitation system has also been designed and is nearing completion. Immediate plans are to begin measurement of the optical properties of standard samples and blackbodies to be used as calibration sources. Next the research will concentrate on the optical properties of undercooled high-purity elements, such as zirconium and niobium.

Sponsor: Office of Life and Microgravity Sciences and Applications, NASA Headquarters

Industry Involvement: Containerless Research, Inc.

Biographical Sketch: Dr. Michael B. Robinson came to Marshall Space Flight Center in September 1976, and currently is a member of the Crystal Growth and Solidification Physics Branch in the Space Sciences Laboratory. He currently serves as project scientist for the MSFC 105-Meter Drop Tube, for the modular electromagnetic levitator, and the German TEMPUS space flight electromagnetic levitator, scheduled to fly aboard the Space Shuttle on the International Microgravity Laboratory–2 mission. In addition, Robinson is currently co-investigator on two flight programs, one involving the study of the effect of microgravity on the nucleation distribution of pure metals, and the other involving directional solidification under microgravity conditions and influences of magnetic fields. He also serves as co-investigator on a ground-based research program involving undercooling, nucleation, and solidification studies. Robinson received his M.S. in physics from the University of Alabama in Huntsville and his Ph.D. in materials science from Vanderbilt in May 1988.

A Study of the Undercooling Behavior of Immiscible Metal Alloys: The Absence of Crucible-Induced Wetting and Nucleation

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In many metal binary systems, there exists a region where the two phases in the liquid state will not mix; i.e., they are immiscible. In processing these binary systems for commercial or scientific applications, decomposition of the homogenized liquid into two separate liquid phases will occur during cooling. Because of density differences between the two liquid phases, processing of these systems in a gravitational field will result in a layered structure with the lighter phase at the top, the heavier phase on the bottom. Such difficulties have plagued the pursuit of commercially important materials such as Ag-Ni and Al-Pb for electrical contact and self-lubricating bearing uses, respectively.

Attempts have been made to process composite, immiscible systems having uniform metallurgical structures of either aligned rod-like structures, or uniform, finely dispersed second phase within the majority phase matrix. Because of the larger particle interface-to-volume ratio in a finely dispersed alloy, the latter structure would potentially be more viable for commercial application.

Microgravity materials processing has the possibility of producing fine, homogeneously dispersed immiscible alloys. The low-gravity environment of a drop tube or space experiment could greatly reduce sedimentation and convection and thus reduce or eliminate separation during cooling through the two-liquid portion of the phase diagram. However, space flight experiments to date have produced disappointing results in that massive segregation still occurs during solidification in crucible contained experiments. It appears that separation of the liquid phases is due to mechanisms other than sedimentation alone. Research activities have since focused on the evaluation of these different mechanisms which would cause separation in either an Earth or a low-gravity environment.

To achieve the above studies, the environment provided by the MSFC 105-Meter Drop Tube Facility has been utilized. These conditions are ideally suited to prevent the sedimentation effects and the crucible-induced wetting and nucleation phenomena. Research in a truly containerless, low-gravity environment should provide much information to the question of whether preferential wetting of the free surface occurs and more importantly whether it can be controlled. Over the past year effort has been centered on initial studies of a number of immiscible systems. From these initial studies, three representative systems, those of Ni-Cr, Ga-V, and Ti-Ce have been selected for more in-depth study. Initial processing and analysis of samples from these three systems indicate a wide range in the separation behavior after processing. In addition there is a range in undercooling behavior depending on sample composition, environment pressure, and amount of overheat. The next year studies will continue with the intent of concentrating on the selected representative systems.

Sponsor: Office of Life and Microgravity Sciences and Applications, NASA Headquarters

University Involvement: The University of Alabama in Huntsville

Biographical Sketch: Dr. Michael B. Robinson came to Marshall Space Flight Center in September 1976, and currently is a member of the Crystal Growth and Solidification Physics Branch in the Space Sciences Laboratory. He currently serves as project scientist for the MSFC 105-Meter Drop Tube, for the modular electromagnetic levitator, and the German TEMPUS space flight electromagnetic levitator, scheduled to fly aboard the Space Shuttle on the International Microgravity Laboratory–2 mission. In addition, Robinson is currently co-investigator on two flight programs, one involving the study of the effect of microgravity on the nucleation distribution of pure metals, and the other involving directional solidification under microgravity conditions and influences of magnetic fields. He also serves as co-investigator on a ground-based research program involving undercooling, nucleation, and solidification studies. Robinson received his M.S. in physics from the University of Alabama in Huntsville and his Ph.D. in materials science from Vanderbilt University in May 1988.

MSFC 105-Meter Drop Tube Undercooling and Nucleation Studies

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In order to improve present metals and alloys through space processing, it is necessary to first understand the effect of low-gravity processing on the structure and properties of the material. The effect of low gravity coupled with containerless processing is being studied using the MSFC 105-Meter Drop Tube Facility. This environment, achieved in both the drop tube and during a containerless space flight, is conducive to large degrees of undercooling before solidification of the metal occurs. Therefore this facility provides an ideal environment for undercooling and nucleation studies of undercooled metals.

In the past year, effort has been directed to supporting six flight and ground-based investigations. Approximately 600 research samples and a much larger number of test samples were processed in the drop tube in support or preparation for these investigations. The supported investigations and a brief description of the science objectives are listed below:

- Dr. Kelton of the Washington University: A study of the effect of low-gravity, containerless processing on the formation and properties of quasi-crystalline materials.
- Dr. Flemings of the Massachusetts Institute of Technology: An attempt to measure the viscosity and surface tension of undercooled metals samples by recording the shape and rate of the spreading front from a splat quenched sample.
- Dr. Johnson of Cal. Tech.: A study of the thermophyscial properties (heat capacity, surface tension, viscosity) of metallic glass forming materials.
- Dr. Bayuzick of Vanderbilt University: A measurement of the distribution of nucleation temperatures of undercooled metals and alloys.
- Dr. Grugel of University Space Research Associates: A study of the effect of undercooling on hypomontectic alloy systems.
- Dr. Robinson of MSFC: A study of the separation and undercooling phoneme in immiscible metal systems through low-gravity, containerless processing.

In addition to supporting the above named research efforts, the drop tube facility is actively supporting a study of the effect of welding in space on space suit materials in support of MSFC's Materials and Processes Laboratory.

Sponsor: Office of Life and Microgravity Sciences and Applications, NASA Headquarters

Biographical Sketch: Dr. Michael B. Robinson came to Marshall Space Flight Center in September 1976, and currently is a member of the Crystal Growth and Solidification Physics Branch in the Space Sciences Laboratory. He currently serves as project scientist for the MSFC 105-meter drop tube, for the modular electromagnetic levitator, and the German TEMPUS space flight electromagnetic levitator, scheduled to fly aboard the Space Shuttle on the International Microgravity Laboratory–2 mission. In addition, Robinson is currently co-investigator on two flight programs, one involving the study of the effect of microgravity on the nucleation distribution of pure metals, and the other involving directional solidification under microgravity conditions and influences of magnetic fields. He also serves as co-investigator on a ground-based research program involving undercooling, nucleation, and solidification studies. Robinson received his M.S. in physics from the University of Alabama in Huntsville and his Ph.D. in materials science from Vanderbilt University in May 1988.

Bridgman Crystal Growth in Static Magnetic Fields

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The objectives of this study are:

- To experimentally test the validity of the modeling predictions applicable to the magnetic damping of convective flows in conductive melts as this applies to the directional solidification and floating zone growth of solid solution semiconducting materials; and
- To assess the effectiveness of steady magnetic fields in reducing the fluid flows occurring in these materials during space processing that result from density gradients (driven by the residual steady-state acceleration or g-jitter), or surface tension gradients (Marangoni flow).

During the past year, experimental work has continued on Bridgman and floating-zone growth experiments and numerical modelling of the Bridgman experiments. Ingots of gallium-doped germanium and germanium-silicon alloys ≤5 percent silicon) been grown by the Bridgman method while the floating-zone experiments were done with silicon and silicon-germanium alloys (≥95 percent silicon). Some of these experiments were carried out jointly with colleagues from the Crystallographic Institute (KI), Freiburg University in Germany.

The immediate goal of the gallium-doped germanium experiments was to determine the magnetic field intensity necessary to achieve diffusion-controlled growth conditions. This refers to the fact that there are primarily two mass transport mechanisms taking place in the molten material ahead of the solid-liquid growth interface. These include convection driven by thermally induced density differences and diffusion of the gallium dopant within the molten germanium. At zero field, the convection is sufficiently vigorous to completely mix the melt, that is, there is no detectable diffusion contribution to the mass transport. In a non-zero magnetic field, the convection is reduced because the liquid is highly electrically conductive. Thus, applying a high enough magnetic field should reduce the convective flow velocity to the point that diffusion is the predominant mass transport mechanism. The field at which this occurs will be dependent on the diameter of the melt and the thermal field in the melt. For the configuration which was used, both experimental evidence and numerical simulations suggest that a field of 3 Tesla is sufficient to reduce the convective transport to less than the diffusive transport. A comparison of the experimental data and a diffusion-controlled model is shown in figure 133.

The collaborative experiments with KI included silicon float zone growth and additional Bridgman growth using a KI mono-ellipsoid mirror furnace installed in a 5-Tesla magnet in the MSFC Space Sciences Laboratory. The Bridgman experiments were especially interesting in the mirror furnace because, unlike the furnaces normally used at MSFC, the sample can be observed during growth. Fluid motions that were unexpected were observed and some expected motions were much higher in intensity than anticipated. In summary, static magnetic fields are useful to reduce convection in semiconductor melts. The three growth schemes employed, floating zone and Bridgman growth in two configurations, have been shown to be complementary. Each one provides a part of the information that will be needed to understand more thoroughly the role of gravity in the solidification of semiconductor materials. Work on doped Ge is essentially complete and attention is being intensified on the Ge-Si alloy system.

[1]Rolin, T. D. and Szofran, F. R.: "Determination of the Electrical Conductivity of Liquid Ge0.95Si0.05." Journal of Crystal Growth, vol. 153, pp. 6–10, 1995.

Sponsor: Office of Life and Microgravity Science and Applications, Microgravity Science and Applications Division

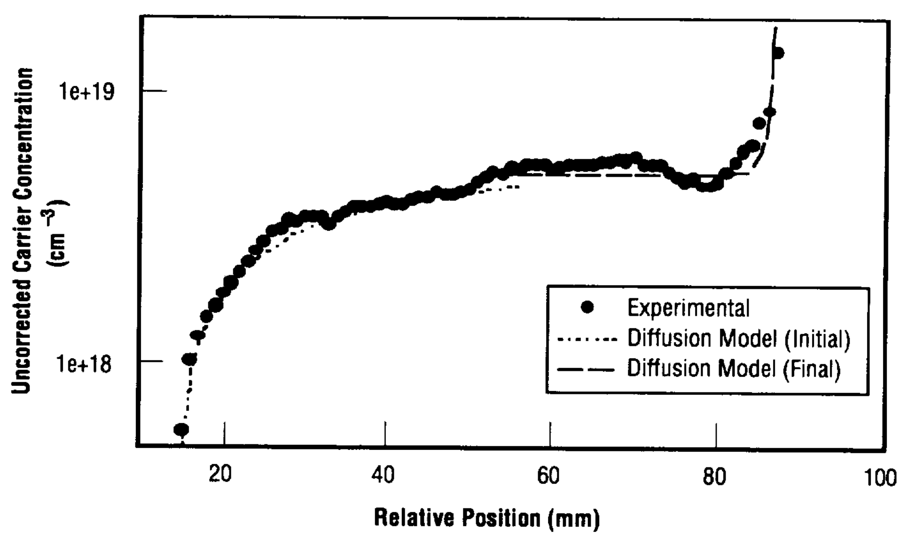

FIGURE 133.—Axial Ga distribution in a Ge:Ga sample grown at 8-μm/sec in a 5-Tesla field.

University/Industry Involvement: Crystallographic Institute of the University of Freiburg, Germany; Co-investigator Dr. Shariar Motakef, CAPE, Inc.

Biographical Sketch: Dr. Frank R. Szofran is a senior scientist in the Space Sciences Laboratory responsible for studying the effects of magnetic fields on semiconductor crystal growth with emphasis on the application of this method to microgravity experiments. In 1996 he spent two months at the University of Freiburg at the invitation of Prof. K.W. Benz, the director of the Crystallographic Institute. Szofran has a Ph.D. in solid state physics from Brown University (1973) and a B.S. in physics from Washington University in St. Louis, 1966.

Containerless Processing of YBa2Cu3O7–d Superconductors

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The production of bulk YBa2Cu3O7–d (YBCO) and other high-Tc superconductors that maintain high-current-carrying capabilities has been hindered by weak connectivity along grain boundaries, reactions at elevated temperatures with the container materials, incongruent melting behavior, and phase instabilities.

Containerless processing provides a partial solution to these difficulties. Crucible contamination is eliminated, allowing access to the high-temperature portions of the phase diagram. In addition, containerless processing affords the possibility to deeply undercool melts leading to unique solidification paths and microstructures. This degree of undercooling should lead to enhanced physical properties, in particular, improved critical currents (Jc).

Containerless processing was performed using pure YBCO powders and small spheres in a drop tube, as well as an aero-acoustic levitation device. The drop tube (fig. 134) consists of a graphite element

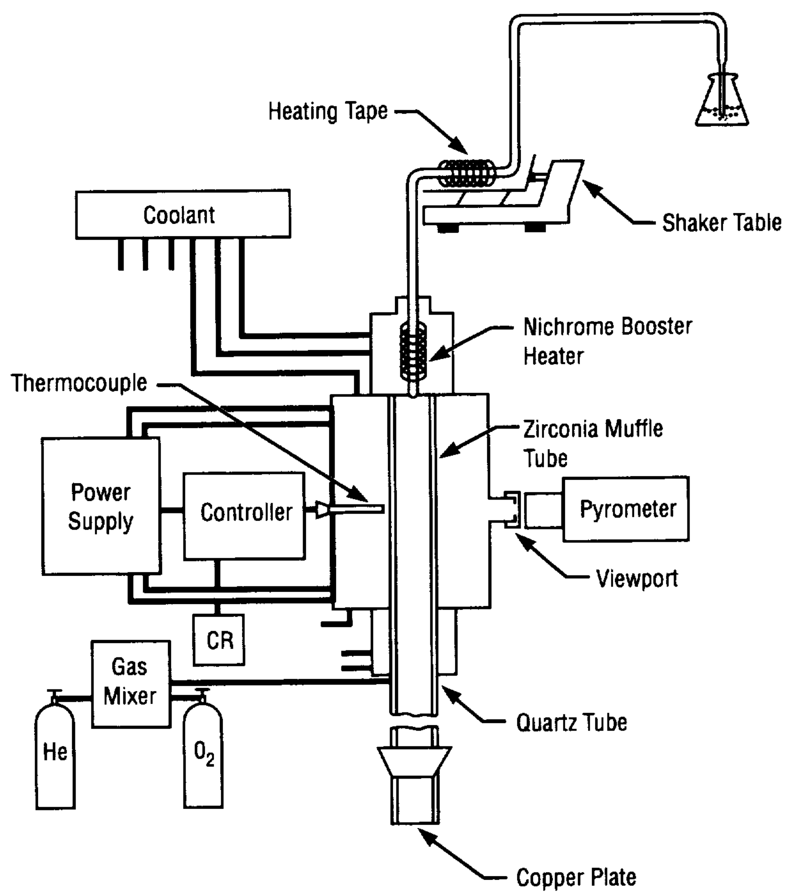

FIGURE 134.—Schematic of the drop tupe.

muffle furnace, a zirconia muffle tube, oxygen atmosphere control and associated electronics. The levitation device was a single dry air jet coupled to a three-axis acoustic positioner. In this device, the small spheres were heated using a CO_2 laser. Two video cameras recorded the experiments and monitored transient thermal events. During the experiment, the samples were annealed (kindled) for several minutes at 1,270 K and then heated quickly to about 2,070 K. They were then cooled rapidly (300 to 400 K/sec). A pronounced recalescence (increase of heat) was observed in some samples upon cooling. After solidification, those spheres that showed pronounced recalescence were annealed in oxygen at 1,210 K for 14 hr and then cooled slowly to 690 K and held for 40 hr to induce the tetragonal-to-orthorhombic transformation and the superconducting state. SQUID magnetometer measurements were performed to calculate intragranular critical current densities. X-ray diffraction and microstructural analysis were also carried out on preannealed and postannealed samples. The microstructures developed in the samples were primarily single-phase tetragonal YBCO and YBCO with several other related phases. In both cases, a dendritic structure appears in clusters. The formation of tetragonal YBCO indicates that the liquid was undercooled to below the peritectic temperature for this phase. Upon annealing in oxygen, the samples became single-phase orthorhombic YBCO with randomly oriented grains of 10 to 20 mm in size. The outer surface of the sample shows a 70-mm layer with columnar structure. The magnetic data indicate an intragranular Jc of 4×103 A/cm^2 at 50 KOe and 5 K, using the Bean critical state model (fig. 135). If the actual grain size is used (at 20 mm) in the calculation, the Jc values would be two orders of magnitude higher. The samples processed in the drop tube show similar behavior, and structural and physical properties. Both the structure and properties of processed YBCO depend on the degree of undercooling, and deeply undercooled samples show excellent critical current densities in high magnetic fields.

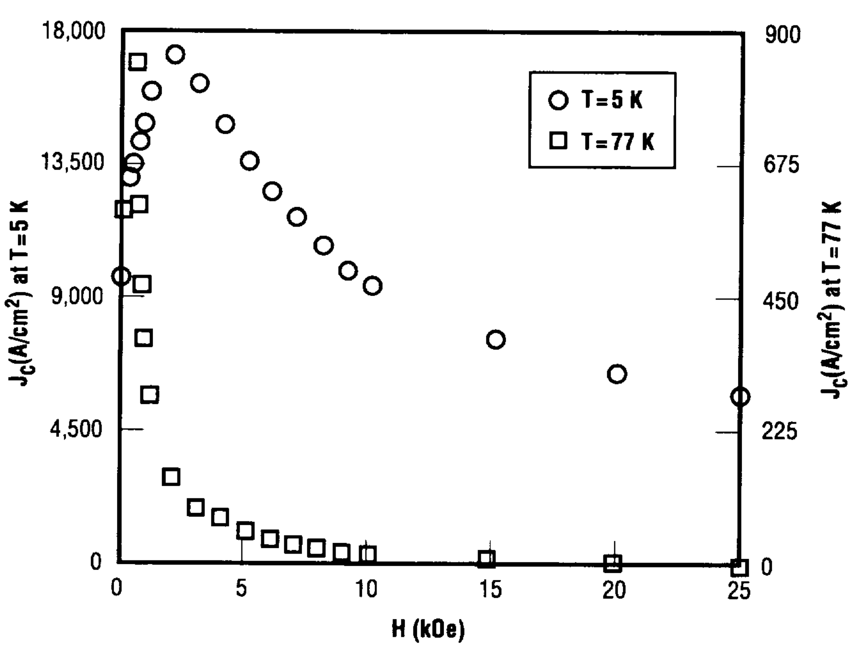

FIGURE 135.—Magnetic intragranular critical current density versus applied magnetic field at 77K and 5K.

Containerless processing of oxide superconductors can lead therefore to deep undercooling prior to solidification and result in enhanced superconducting properties.

Associated work was also carried out in optimizing the processing parameters of pure phase YBCO and Bi-based superconductors. The preheat treatment appears to be a very important parameter in achieving this objective. The synthesis of pure phases in the Bi-based system also involves effects due to oxygen partial pressure, time and temperature. The optimization of this processing is a key step toward the successful continuation of superconducting materials development and eventual application. In conclusion, the objectives of processing oxide superconductors by containerless methods and optimizing their preparation have been attained and have led to enhanced Jc under magnetic fields. The significant improvement in Jc would result in a major step toward the use of such materials in the Materials Processing in Space Program and in other NASA-specific ground and space applications such as shielding, magnetic levitation and magnetic bearing development.

Olive, J.R.; Hofmeister, W.H.; Bayuzick, R.J.; Carro, G.; McHugh, J.P.; Hopkins, R.H.; Vlasse, M.; Weber, J.K.R.; Nordine, P.C.; and McElfresh, M.: "Formation of Tetragonal YBa2Cu3O7–d From an Undercooled Melt." *Journal of Material Research*, 9, 1, 1994.

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Sponsor: Office of Life and Microgravity Sciences and Applications

University Involvement: Vanderbilt University

Biographical Sketch: Dr. Vlasse is a materials scientist in the Microgravity Sciences and Applications Division at MSFC's Space Sciences Laboratory. He conducts research in the area of oxide superconductors and their applications, as well as in crystal growth of organic and macromolecular materials. Vlasse earned a Ph.D. in crystallography from the University of Pittsburgh and a D.Sc. degree in materials science from the University of Bordeaux.

Crystal Growth by Physical Vapor Transport

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Physical vapor transport (PVT) offers several advantages (e.g., lower process temperature, improved purity and stoichiometry) over other techniques of bulk crystal growth. The quality of the crystals may, however, be downgraded by the presence of convection in the growth system. Another source of crystal imperfections may be interactions (sticking) of the crystal with the walls of the growth capsule. Our research program addresses these topics.

Growth of crystals by "contactless" PVT (without contact with the side walls of the growth ampoule) depends on such factors as the geometry of the ampoule and furnace, their configuration, temperature field, thermal and thermochemical properties of the materials (crystal, ampoule), composition of the vapor phase, type of medium outside the ampoule, and others. The technique of "contactless" PVT in compact geometry (the diameter of the crystal is close to that of the ampoule) has been used in the past. However, the literature reports on the subject are primarily experimental, and no comprehensive treatment of the method exists. The technique could be very useful for a prospective experiment(s) performed under microgravity conditions: elimination of crystal defects generated by crystal-wall interactions would improve the crystal quality and facilitate (or even enable) identification of gravity-related effects. The project consists of the following tasks:

- Theoretical and experimental determination of the mass transport properties of the Pb (Se, Te) (lead selenide-telluride) and (Cd, Zn) Te (cadmium-zinc telluride) model materials;
- Numerical fluid-dynamic modeling of the growth system; and
- Crystal growth experiments.

Since the initiation of the project (May 1995), thermochemical analysis of PVT of Pb (Se, Te) has been done; experimental verification of the model is under way. The technique for determining residual gases in sealed ampoules (important for a meaningful description of the actual growth conditions) has been developed. Purification procedures for the source materials (removal of oxygen) have been determined theoretically and verified experimentally. Two furnaces suitable for visual monitoring of the growth process have been fabricated. Numerical modeling of the thermal field in the system has been initiated.

To investigate the convective effects in PVT, a suitable growth system for terrestial and microgravity experiments is necessary. Such a system should enable a meaningful comparison of the theoretical predictions of convective effects with experimental results. That requires the geometry that would be feasible for a realistic modeling of the fluid flow and crystal growth in the ampoule. The main technical problem here is how to maintain a flat crystal-vapor (c-v) interface for the duration of the experiment. The shape of the interface is a complex function of the system parameters, particularly the geometry, temperature field, thermal and thermochemical properties of the materials, and the growth rate. With the aid of numerical modeling, different ampoule designs, materials, and other process conditions will be tested and their effect on the shape of the c-v interface will be anticipated. The theoretical predictions will be verified experimentally.

Another important task of the project is to develop a growth system which will provide a means for identifying convective flows during growth. This will be accomplished by using an appropriate doped binary and/or ternary source materials and investigating the distribution of the minority component(s) in the grown crystal.

Our research program is aimed at a better understanding of the role of convection and its significance for crystal growth from the vapor. The results of this work will provide the basis for designing a related microgravity experiment on convective phenomena in vapor growth systems. The results of the work may be also beneficial for industrial applications of the PVT technique.

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Palosz, W.: "Removal of Oxygen From Electronic Materials by Vapor Phase Processes." *Journal of Crystal Growth*, in press.

Sponsor: Office of Life and Microgravity Sciences and Applications.

University/Industry Involvment: Fisk University, Nashville, TN; University of Durham, Durham, UK; Albert-Ludwigs Universitat, Freiburg, Germany; FhG, Institut für Physikalische Messtechnik, Freiburg, Germany. Universities Space Research Association (USRA), CFD Research, Inc., Huntsville, AL; Brimrose Corporation, Baltimore, MD.

Biographical Sketch: Dr. Martin Volz is a research scientist in the Space Sciences Laboratory, and is currently working in the area of semiconductor crystal growth and characterization.

Diode-Laser Holographic Imaging System Applied to the Study of Fluids in Microgravity

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The objective of the proposed study is to create a compact holographic system that will fit inside a Shuttle locker. Holography is an important research method because it records an image of the entire volume of a test cell at a given instant in time. When a hologram is constructed, it records the wave front coming from the test cell. Then when the hologram is reconstructed the same wave front is reproduced. The reconstructed wave front can be analyzed by the same optical techniques that could have been used on the original test cell.

This capability is important in many areas of research, such as solution crystal growth, fluid physics, and particle phenomena. For example, quantitative studies of the growth of transparent dispersions require diameter measurements from numerous microscopic droplets at a given instant of time in order to produce statistically significant results. Typically the droplets will be undergoing changes in position or size as the experiment progresses. Accurate measurement of the entire population of droplets is impossible by normal techniques. However, by recording a hologram of the experiment the entire test cell volume is stored. The entire test cell from the reconstructed hologram can be investigated by microscopy to measure all of the droplets.

The primary objective of the proposed research is the development of a compact, state-of-the-art, modular holographic imaging system, based on laser-diode technology which will incorporate micro-optics in order to record full three-dimensional images of the test cell. The apparatus is designed to be compatible with a variety of test cell modules. The device could find applications in ground-based laboratories, as well as reduced gravity environments, such as the Space Shuttle, the KC–135 aircraft and sounding rockets. The goal of the design effort is to develop and test a compact, state-of-the-art, modular holographic imaging system. No such integrated apparatus is presently available.

A second objective of the research described in this proposal is to develop a compact apparatus designed for such low-gravity fluid physics studies. This fluids module will be designed to plug in to the imaging system, and will be used in order to verify the functionality of the imaging system. The module will be designed to have several fluid handling functions: producing well-defined dispersions having user-specified characteristics, deploying numerous small droplets of selected volumes, and delivering selected volumes of fluid.

An initial breadboard system has been constructed to test the capabilities of the diode laser to construct holograms. In-line holograms of static 200-µm-diameter glass beads suspended in water and of calibration test patterns have been made. Side-band holograms of melting ice in water (fig. 136) have also been made. The capabilities of the initial system are being evaluated. The

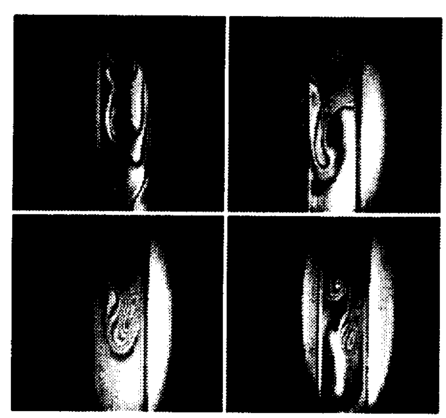

Figure 136.—Double exposure holograms of ice melting in water.

holographic system was flown on the KC–135 flight in May 1995 has been established. A fluids processing module was developed for the KC–135 flight with heating and mixing capabilities.

A miniaturized holographic system will be designed based on current optics technology. An optics breadboard table that is the same size as a Shuttle locker will be used to construct the holographic system on. Miniaturized optical components will be used to construct the system. Once a holographic system is constructed it will be tested and refined. A variety of experiments will be performed in the system to demonstrate its capabilities. Also a microgravity fluids module will be designed and developed. The system will be tested for various modes of fluids processing, such as dispersion generation, fluid delivery, and heating. The fluids module will also be added to the holographic system to help define its capabilities. The microgravity fluids module and the holographic system will be combined and tested on the KC–135.

Sponsor: Center Director's Discretionary Fund

Biographical Sketch: William Witherow currently holds the position of AST, Basic Properties of Materials, at MSFC. He designs and fabricates optical data acquisition systems for various experiments. The areas of experiments include protein crystal growth, immiscible fluids studies, crystal growth, multicolor holography, phase-shifting interferometry, optical measurements of alloy solidification in a micro-g environment, and nonlinear optics measurements. His current work also includes image analysis, image digitization, and he also serves as the project scientist for the observable protein crystal growth facility. He holds a B.S. in engineering physics, 1977, from the University of Tennessee, Knoxville; and an M.S. in physics, 1981, from the University of Alabama in Huntsville.

Phase Shifting Interferometric Analysis of Protein Crystal Growth Boundaries and Convective Flows

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The objective of the proposed study is to obtain experimental evidence of several characteristics of a crystallizing protein solution and model their effects on the crystal growth process. The characteristics to be studied include: the presence of concentration gradients during the crystal growth, the extent of the boundary layer from the crystal face, and the effect of buoyancy driven convection on the growth. Whether such convection is able to produce flows capable of disturbing the attachment of macromolecules onto the crystal surface is still a matter of controversy among scientists in the field. Phase shifting interferometry (PSI) can provide significant insight to this issue. PSI will produce a visual confirmation of the concentration profile at the boundary layer and concentration values within the depletion region. PSI has the potential to offer a direct visualization of convective flows within proteinic crystallizing solutions. The importance of this matter is enhanced by the accepted fact within the field that the suppression of these convective effects is the only proven consequence of establishing a low gravity environment for protein crystals. On a recent Shuttle flight (USML–1), Dr. Larry de Lucas observed that the nucleation rates seemed lower and that the crystals were still in a growing regime at the end of the mission. The investigation of convective flows in relation to gravity as a parameter for protein crystallization is therefore of importance.

Protein crystals are grown to determine the three-dimensional structure of proteins. By utilizing x-ray or neutron diffraction, the collected information allows the direct identification of active sites of the macromolecule, its conformation, and sequence of the amino acids. Sections of very large assemblies of proteins such as structural proteins or viruses can also be crystallized. Crystallization is therefore the starting point of any study aiming at the development of new drugs and the understanding of viral diseases. Crystallization techniques for proteins are now well known, but a biophysical understanding of the growth mechanisms is underdeveloped. This aspect of protein research needs to be expanded as the proteins being studied are more complex and their purification more costly.

Microgravity grown crystals of several proteins were found to be larger or diffracted with higher resolution than ones previously grown on the ground. These results tend to demonstrate that a reduction of gravity affects the interfacial growth mechanisms which are directly dependent upon the mass transport regime. Convection is known to play a significant role in the growth kinetics of inorganic crystals but its importance is still debated in relation to the crystallization of biological macromolecules. There is little doubt about the existence of convective flows in proteinic solutions, but the flow rates they generate close to the crystal/solution interface and their effect on growth kinetics have not been quantified experimentally. The technique of PSI will allow us to determine these values and provide direct comparison between solutal flows in crystallizing solutions under various levels of gravity. An examination of the flows in the fluid and its correlation with crystal growth will strongly depict the role of microgravity in protein crystal growth.

Mach-Zehnder and Michelson-Morley interferometry will be used to examine growing protein crystals. Phase shifting will be accomplished using an electro-optic phase modulator or a piezo-electric mirror. PSI can provide a resolution of at least 1/100 of a wavelength. Phase maps generated by the PSI will provide a

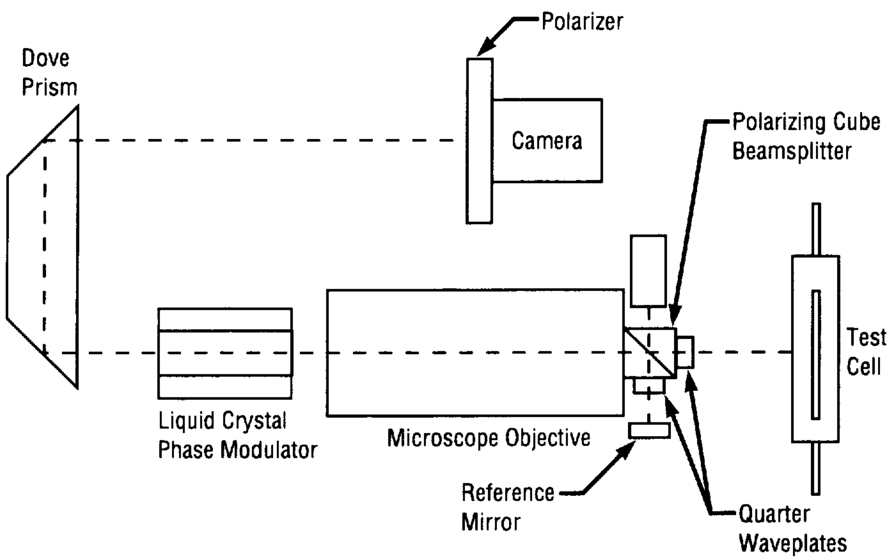

FIGURE 137.—Schematic of phase shifting interferometer.

correlation between crystal growth and convective flow in the growth fluid. Inorganic crystals and protein crystals have been grown. The optical system (fig. 137) is a phase shifting Michelson-Morley interferometer. The phase-shifting algorithm chosen to collect data uses five $\pi/2$ phase shifts. By using $\pi/2$ phase shifts, the PSI algorithm becomes insensitive to phase shift errors. A computer program has been developed that controls the phase shifter, collects the interference data, and calculates the phase map. Initial experiments used sodium chlorate crystals to test the PSI. Strong concentration gradients are formed around sodium chlorate crystals when they grow. The next experiments will grow lysozyme protein crystals. The PSI system is also being developed into a flight system to be flown on the Russian Mir station next year. After the Mir experiments, ground-based protein crystal growth will be compared with the same type of crystals grown in micro-g. Variations of the PSI system and software developed at MSFC/NASA are being used by groups at the University of California at Riverside, CA, and at the De Montfort University in England.

Sponsor: Office of Life and Microgravity Science and Applications

Biographical Sketch: William Witherow currently holds the position of AST, Basic Properties of Materials, at MSFC. He designs and fabricates optical data acquisition systems for various experiments. The areas of experiments include protein crystal growth, immiscible fluids studies, crystal growth, multicolor holography, phase-shifting interferometry, optical measurements of alloy solidification in a micro-g environment, and nonlinear optics measurements. His current work also includes image analysis, image digitization, and he also serves as the project scientist for the observable protein crystal growth facility. He holds a B.S. in engineering physics, 1977, from the University of Tennessee, Knoxville; and an M.S. in physics, 1981, from the University of Alabama in Huntsville.

Mechanics of Granular Materials

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Unlike materials such as metals, polymers, concrete, rocks, etc., which derive their strength and deformation characteristics mainly from strong cohesive forces of chemical cementation, the constitutive relations of uncemented granular materials, eg. strength, modulus behavior, dilatancy, localization of deformations, shear band formation and instability behavior are, to a large extent, derived from interparticle friction resulting from normal forces acting on particles and particle groups.

Particle bonding by weak electrostatic and short- or long-term Coulomb forces may also influence, to a small extent, the constitutive behavior of granular materials. However, their behavior is mainly governed by interparticle friction which, in turn, under very low effective stress levels is highly dependent on gravitational body forces. Erosional processes, which among other effects, cause an irreversible loss of a very significant amount of fertile soil in the midwestern United States; dust storms and off-road locomotion are illustrative examples.

The force-deformation behavior of granular materials is fabric or internal structure dependent, highly nonlinear, dilatant and nonconservative. The gravity-induced stresses in laboratory specimens on Earth are nearly of the same order of magnitude as the externally applied tractions, thus limiting the size of the specimens. On the other hand, the same laboratory specimens must be sufficiently large to replicate the behavior of large geologic deposits in-situ, or the behavior of large masses of industrial or agricultural products during storage, handling and transportation.

During critical, unstable states, such as the liquefaction of saturated loose sands under earthquake or wave loading, landslides due to pore water pressure buildup, or the collapse of sensitive clays, gravity acts as a "follower load," causing these events to take place essentially instantaneously and making the sequence of such phenomena impossible to observe and study as they occur on Earth, either in the laboratory or in the field.

In granular materials, gravity-driven particle convection induces material inhomogeneities and anisotropies during testing, especially under low-confining pressures, which alters the initial fabric of the test specimens and hence their constitutive relations. Accordingly, from an engineering point of view, uncertainties of unknown magnitude are introduced into the laboratory tests performed to emulate the actual field behavior of large masses.

Under moderate to high stress levels, the influence of gravity on the behavior of test specimens may not be pronounced and, therefore, the test results in a terrestrial (1-g) environment may be sufficiently conclusive for engineering purposes. However, testing of granular materials under very low stress levels can only be performed in a microgravity environment in order to yield meaningful results. It should be emphasized again that the the laboratory specimen which would, on one hand, best resemble a magnified version of the elemental cube in a continuum mechanics sense, should, on the other hand, be representative, in a statistical sense, of the particle fabric of the real mass.

The gravity induced stresses within a specimen transform the experimental setup into a very complex boundary value problem, in which the constitutive properties and stability issues cannot be resolved by inverse identification techniques due to the highly nonlinear nature of the constitutive behavior. For the same reasons, one cannot determine the constitutive relations of granular materials at very low effective stress levels by extrapolating results from centrifuge tests performed at very high stress levels.

Because of the above considerations, NASA has supported the development of a microgravity experiment called mechanics of granular materials (MGM), figure 138. This experiment entails the performance of a test series of nine displacement-controlled triaxial compression tests on right cylindrical specimens 75 mm in diameter by 150-mm long, consisting of Ottawa F–75 banding sand, a natural quartz sand (silicon dioxide). Because Ottawa sand is widely used as a standard material in soil mechanics experiments on Earth, results from tests on the same material in a microgravity environment will allow direct comparisons with experimental results already obtained on Earth.

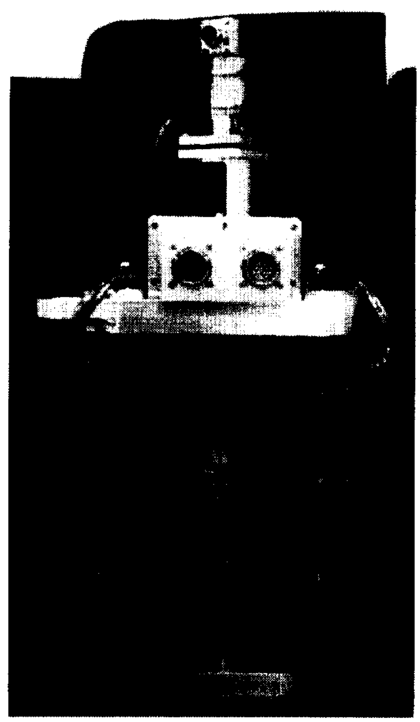

FIGURE 138.—Mechanics of granular materials test cell.

The sand has been tumbled, degreased, washed, and dried. It has been screened to sizes of 0.1 to 0.3 mm (with no grains below 0.074 mm present—the demarcation size between coarse and fine granular materials), removing all silt and clay-sized particles. The soil specimens are contained in a latex sheath that is 0.3-mm thick and inprinted with a grid pattern so cameras can record relative changes in shape and position. On the top and bottom of each specimen are placed special platens. These are made of polished tungsten carbide steel to provide the necessary hardness and low coeffient of friction between the platens and the soil specimen.

Each specimen is placed in a test cell shaped like an equilateral prism consisting of a Lexan jacket sandwitched between metal end plates connected by guide rods. Within the Lexan jacket the cell is filled with water which is pressurized to keep the specimen stable under confinement during launch, and during re-entry in its postfailure configuration. An electric stepper motor on top of the test cell drives a gear assembly that moves the top platen, which is centered over the soil specimen by the guide rods along the longitudinal direction of the specimen. A load cell measures the resistance to deformation of the specimen during the prescribed displacement of the top platen.

Three fluid lines connect the test cell to the MGM hydraulic system. During the first mission the specimen is completely dry. One line is connected to the specimen and allows the air to escape from the specimen as it compresses. The second line supplies water to the jacket to confine the specimen and the third line measures the jacket water pressure. During the other missions, the specimens are completely saturated and the water is not allowed to escape from the specimen as it compresses. In other words, the tests are undrained tests. In this configuration, the air line is replaced by a water line. The fluid pressure on the test cells is enacted and controlled by two hydraulic accumulators which also measure pressure.

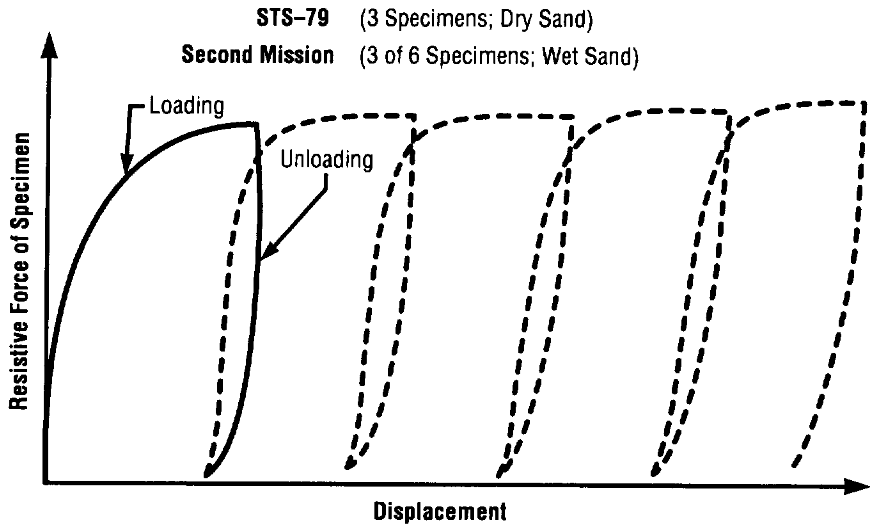

FIGURE 139.—Typical compression-unloading sequence.

During each test, the test cell is held on a rigid test/observation pad mounted between an array of three CCD cameras and banks of small light-emitting diodes. Each camera is pointed at a different side of the prismatic Lexan jacket to provide full coverage of the specimen. The MGM video control system electronically obtains the images and transmits the signals to a portable video recorder. The stepper motor, accumulators, and cameras are controlled by the payload general support computer (PGSC), a laptop computer operated by the flight crew during the mission.

The first series of MGM tests, consisting of three dry specimens tested under drained conditions were performed during the STS–79 Shuttle–Mir mission, aboard the Space Shuttle Atlantis in September 1996. All tests were performed successfully, each under a different confining pressure, e.g. the first test was performed under a confining pressure of 0.007 lb/in^2; the second under 0.075 lb/in^2 and the third test under a confining pressure of 0.189 lb/in^2. All specimens were subjected to 5 compression-unloading cycles (fig. 139), resulting in a 25-percent longitudinal strain. Upon the completion of each test, the confining pressure was increased to 13 lb/in^2 to keep the deformed specimen stable and the test cell was stowed according to procedures. Figure 140 was taken on Atlantis showing Mission Specialist Carl Walz observing an MGM specimen during testing.

FIGURE 140.—Mission Specialist Carl Walz with MGM specimen during testing on STS–79.

Upon the completion of Shuttle mission STS–79, and the return of the Atlantis to Earth, the three MGM test cells were unstowed and flown to MSFC. There they underwent profilometer measurements at the MSFC Space Sciences Laboratory, using an MTI CCD 72, black and white detector, connected to a "frame grabber." Longitudinal profiles were obtained from the specimens at 5-degree rotation intervals. During the same time, holograms were also obtained using a HeNe-6328 A laser. To perform these activities, the specimens had to be removed from their test cells and be subjected to the same confining pressure of 13 lb/in^2 by drawing the air from the interconnected pores of their interior through a vacuum pump. The specimens are now kept at the MSFC MGM Laboratory and are scheduled to be flown to the University of Colorado, Boulder, for epoxy impregnation and thin sectioning to observe and analyze their interior fabric in their compressed and deformed configuration. The thin sections will be returned to MSFC from UCB for postmission analyses and theoretical studies.

The joint effort between UCB and MSFC will be reported in three postflight reports, scheduled for October 1996, March 1997 and September 1997, respectively.

The current plans for the subsequent two test series of the MGM experiment are now scheduled for STS–86 to take place in August 1997. In both test series, The specimens will be fully saturated with water and will be undrained during testing. In the first of these two test series the specimens will be subjected again in five compression-unloading cycles (fig. 139), whereas in the second series the loading will be cyclic, which will simulate earthquake loading. Figure 141 shows this type of loading.

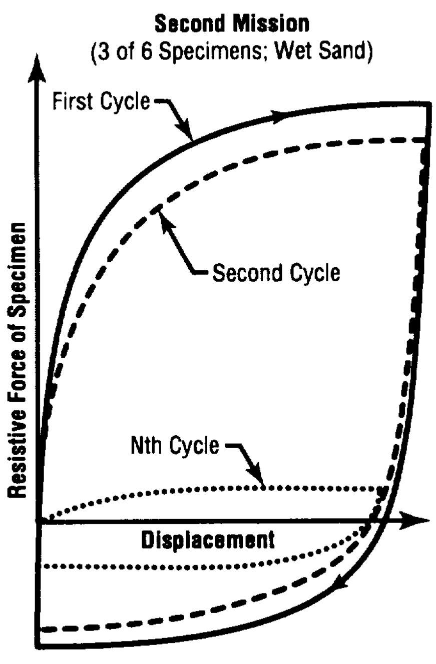

FIGURE 141.—Cyclic specimen loading sequence.

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Sponsor: Office Of Life And Microgravity Sciences and Applications

University/Industry Involvement: University of Colorado at Boulder, Dept. of Civil, Architectural and Environmental Engineering; Laboratory for Atmospheric Space Physics (LASP); Sandia National Laboratories, Albuquerque, N. M.

Biographical Sketch: Dr. Nicholas Costes is a civil engineer in the Microgravity Science and Applications Division, Space Sciences Lab, specializing in fluid and geomechanics. He holds a Ph.D. in soil mechanics from North Carolina State University. He is the principal investigator on the Mechanics of Granular materials Microgravity experiment. Costes was a co-investigator on many Apollo mission lunar geology experiments and was a member of the Lunar Roving Vehicle design team.

Integrated Optics in Films of Organic and Polymeric Materials

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In recent years, a great deal of interest has been directed toward the use of organic materials in the development of high-efficiency optoelectronic and photonic devices. There is a myriad of possibilities among organics which allow flexibility in the design of unique structures with a variety of functional groups. The use of nonlinear optical (NLO) organic materials as thin film waveguides allows full exploitation of their desirable qualities by permitting long-interaction lengths and large susceptibilities allowing modest power input. Organics have many features that make them desirable for use in optical devices such as high-second and third-order nonlinearities, flexibility of molecular design, and damage resistance to optical radiation. However, their use in devices has been hindered by processing difficulties for crystals and thin films.

Here, we report research and technology progress relevant to photonic applications of phthalocyanines (Pc) and the potential role of microgravity on processing these materials. It is of interest to note how materials with second- and third-order nonlinear optical behavior may be improved in a diffusion-limited environment and ways in which convection may be detrimental to these materials. In this report, we focus our discussion on third-order materials for all-optical switching.

Materials processing techniques of general interest are solution-based and physical vapor transport (PVT), both having proven gravitational acceleration dependence. Two promising classes of organic compounds for optical thin films and waveguides are polydiacetylenes, which are conjugated zig-zag polymers, and phthalocyanines, which

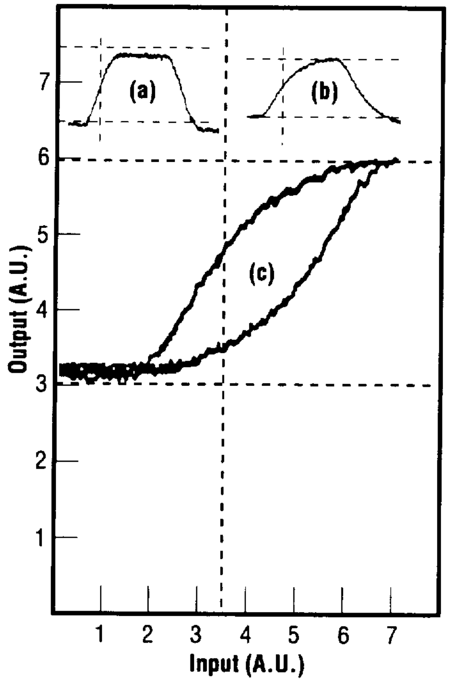

Figure 142.—The bistability loop of a 833 nm metal-free phthalocyanine film using a chopped CW He-Ne laser at 632.8 nm: a) the input pulse; b) the transmitted pulse; c) hysteresis switching constructed from (b).

are large ring-structured porphyrins. Epitaxial growth on ordered organic and inorganic substrates under various processing conditions have been useful for preparing highly oriented polydiacetylene (PDA) and phthalocyanine films. The degree of significance relating processing conditions to uniformity in thickness, degree of orientation, and optical properties for a specific processing technique is the general focus of work in this area. It is a goal of some researchers to produce good quality anisotropic films, therefore, an important yet understudied requirement should be to assess the role of gravity during processing. This may be particularly true for the vapor deposition of Pc's in view of the results of microgravity experiments by 3M Corporation involving the preparation of thin films of copper Pc (CuPc). Microgravity grown CuPc had several desirable features which indicate that the growth of organic films in low-g may result in better quality films for optical and electrical applications. Important aspects of any study involving fluids, as in vapor transport, are driving mechanisms for heat transfer with natural convection and diffusion processes which determine flow profiles and temperature distributions. In terms of processing by PVT, phthalocyanines are excellent nonlinear optical materials with the promise of significantly improved NLO properties through order and film quality enhancements possible by microgravity processing. Although fibers have dramatically increased node to node network speeds, electronic switching will limit network speeds to about 50 Gb/sec. Already, it is apparent that terabit-rate speeds will soon be needed to accommodate the 10- to 15-percent/month growth rate of the Internet and the increasing demand for bandwidth intensive data such as digital video.

Primarily, the study of this work focuses on important technologies, particularly involving thin films, relevant to organic and polymeric materials for improving applicability to optical circuitry and devices and to assess the contribution of convection on film quality in unit and microgravity environments. All-optical switching using nonlinear optical materials can relieve the escalating problem of bandwidth limitations imposed by electronics. Several important limitations need to be overcome such as the need for high-χ^3 materials with fast response and minimum absorption (both linear and nonlinear), development of compact laser sources, and reduction of the switching energy.

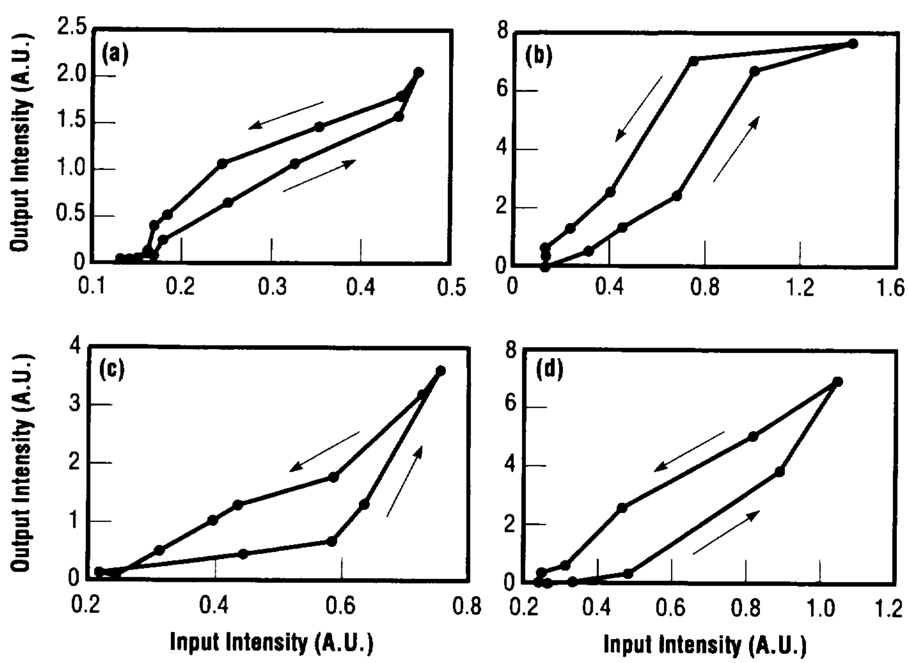

Figure 143.—The bistability loop for different time spans of a metal-free phthalocyanine film of thickness 232.5 nm using a CW He-Ne laser. Time spans between successive points are: a) 3.84 sec; b) 10 sec; c) 342 sec; d) 1800 sec. (a) shows the least prominent bistability loop, while (b), (c), and (d) show a minimal effect of the time span between points.

Investigation of the bistability of metal-free Pc films of 833-nm thickness used a chopped He-Ne 632.8-nm laser beam at frequencies ranging from 100 to 750 Hz. The film was positioned on a micrometer stage, at the lens focus, and transversely translated in and out of the beam alternately to record intensity input (fig. 142 (a)) and film transmittance (fig. 142 (b)). A digitizing oscilloscope recorded the input and the transmitted pulse. The nonsymmetrical shape of the transmitted pulses indicated the presence of intrinsic bistability in metal-free phthalocyanine. Figure 142 (c) depicts typical bistable switching, constructed from the transmitted pulse. The switching power of ~0.33 mW per pulse in combination with a pulse duration of 1.37-ms recovery time yields a very low switching energy of ~0.45 nJ. Observation of bistability was repetitive in the same film using a CW He-Ne laser as shown in figure 143b for different time spans between successive points. Source and substrate temperatures were maintained at 300 °C and 5 °C, respectively, while vapor vacuum deposition, in this case, occurred at 10^{-6} torr onto quartz disks.

One result of this work is the determination, theoretically, that buoyancy driven convection occurs at low pressures (determination at 10^{-2} mm) in an ideal gas in a thermal gradient from source to sink. Subsequent experiment supports the theory. A further result of this work is the discovery of intrinsic optical bistability in metal-free phthalocyanine films which enables the possibility of the development of logic gate technology on the basis of these materials. Bistability in these films is due to changes in the level of absorption and refractive index caused by thermal excitation. This nonlinear effect could improve dramatically in highly oriented microgravity processed films.[2]

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[2]Abdeldayem, H.A.; Frazier, D.O.; Penn, B.G.; Witherow, W.K.; Banks, C.; Shields, A.; Hicks, R.: "Intrinsic Optical Bistability in Vapor Deposited Films of Metal-Free Phthalocyanines." *Optics Communications*, in press, 1996.

Sponsor: Center Director's Discretionary Fund (CDDF); Office of Life and Microgravity Science and Applications (OLMSA)

University/Industry Involvement: Hossin A. Abdeldayem, Universities Space Research Association; Optron Systems, Inc., Bedford, MA

Biographical Sketch: Donald O. Frazier is a senior scientist for physical chemistry at MSFC. Frazier earned his Ph.D at Rutgers University. He develops research programs which focus on microgravity processing for fundamental and applications sciences. He also serves as project scientist for ground-based and flight programs, and establishes educational outreach relevant to ongoing projects. In addition, he promotes technology transfer relevant to research programs.

Polydiacetylene Thin Films for Photonic Applications

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The goal of this work is to access the role of fluid flow on the formation and properties of polydiacetylene thin films for photonic applications such as nonlinear waveguiding and all-optical switching. Researchers at MSFC have been investigating polydiacetylenes (PDA), as well as other organic and polymeric nonlinear optical (NLO) materials, for the past several years. As a result of this research, a simple, novel technique for the photo-deposition from solution of thin amorphous films (on the order of a micrometer) of a polydiacetylene (PDAMNA) derived from 2-methyl-4-nitroaniline has been developed (U.S. Patent No. 5,451,433). During the course of this process, radiative heating by UV light produces thermal gradients in the solution; also, variations in the chemical composition of the solution caused by photo-polymerization causes solutal gradients. These density gradients, under the influence of Earth's gravity, induce natural convection in the system. This convection affects heat and mass transport to and from the growing film, and thereby affects the microstructure, morphology, and properties of the film. Preliminary numerical simulations of the fluid flow indicate that convection is present in the system even under conditions often thought to be gravitationally stable.[1]

One area in which experimental results have established that convection plays a role is defect formation: films grown in 1-g contain small (submicron) solid particles embedded throughout. These particles can scatter light and thereby lower the optical quality of the films. The particles consist of precipitated polymer which forms in the bulk solution, and get transported by convection to the surface of the growing film where they become embedded. In some cases the particles may actually nucleate on the film surface itself. By varying the orientation of the growth chamber with respect to gravity to minimize convection, the concentration of particles in the films can be reduced but not eliminated (fig. 144).

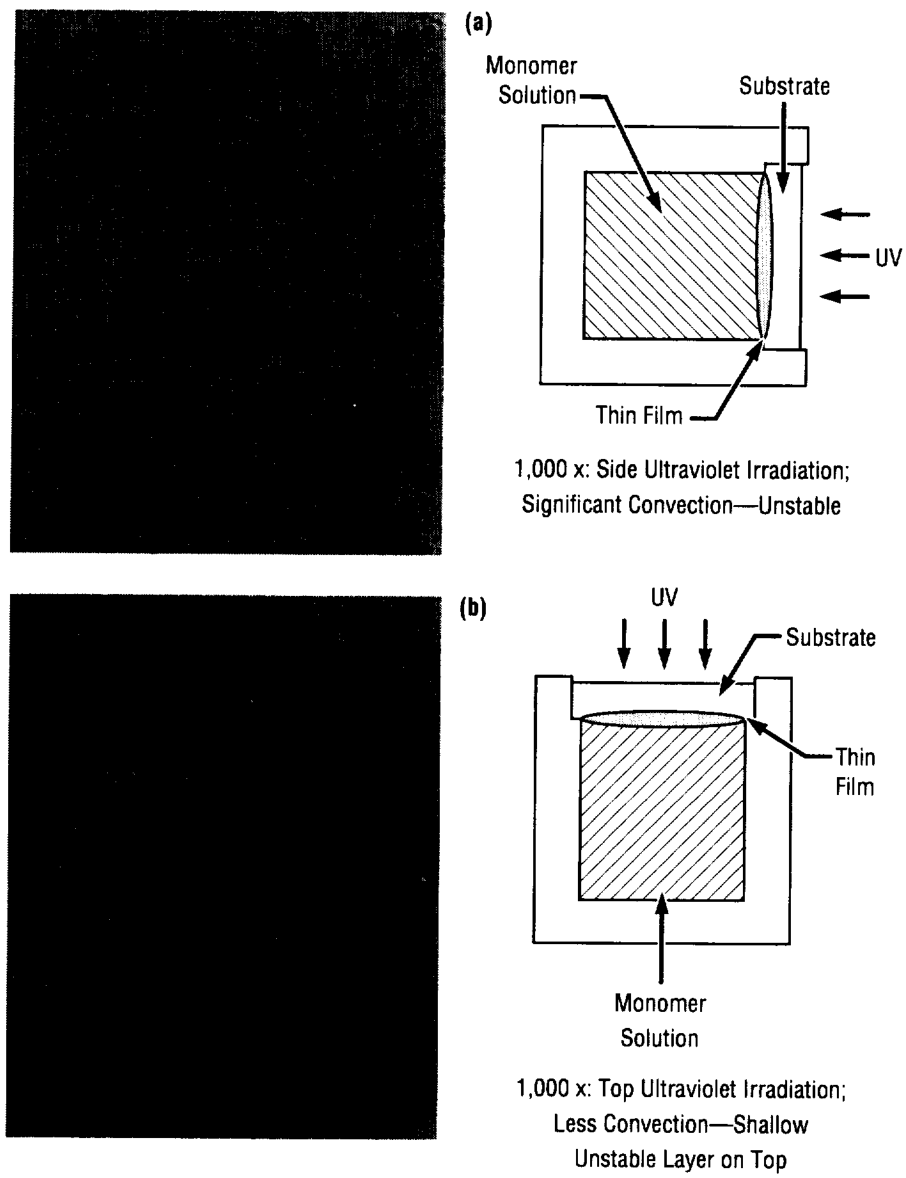

FIGURE 144.—PDAMNA films grown in two different orientations: a) films grown with the chamber horizontal; b) films grown with the chamber vertical.

Last September an experiment (PTFG–CONCAP IV–03) was flown aboard Endeavor (STS–69) in which films were grown in the reduced convection environment of microgravity. While results varied among samples, the best space-grown films clearly exhibited fewer defects than the best ground-based films (fig. 145). This demonstrates that reducing convection can result in higher quality polydiacetylene films.

Not only can convection affect the transport of particles which are formed in the solution, it can also transport colloidal particles which are purposely introduced into the system to alter the optical properties. For example, small metal nanoparticles incorporated into a nonlinear host polymer can be used to enhance the nonlinearity and also reduce undesirable effects such as two-photon absorption, which causes loss. Researchers at MSFC have successfully prepared gold colloids in organic solvents, which, in turn, provides a means for getting the particles into polymer hosts.[2] PDAMNA films containing gold nanoparticles are readily obtained using photodepositon from such organic gold colloids. The resulting films, however, suffer from gradients in the metal concentration which most likely result from convection. In order to achieve the desired optical properties, uniform concentration of the metal colloid is neccessary. Processing in a diffusion-controlled environment could thus be quite beneficial.

Preliminary studies conducted at MSFC of the rate law for polydiacetylene film photodeposition indicate that the rate of film growth depends linearly on UV radiation intensity and, interestingly, on the square root of monomer concentration.[3] Also, it is known that the rate increases with higher temperature. Because convection affects the temperature and concentration profiles along the surface of the growing film, the rate of film growth will likewise be affected. Variations in the growth rate along the surface can lead to uneven film growth; this is manifested in the thickness and surface roughness of the films.

In addition to affecting the formation and/or distribution of bulk particles in polydiacetylene films photodeposited from solution, convection may also affect the molecular orientation. Recently, researchers

CONCAP IV-3 PTFG Cell 9

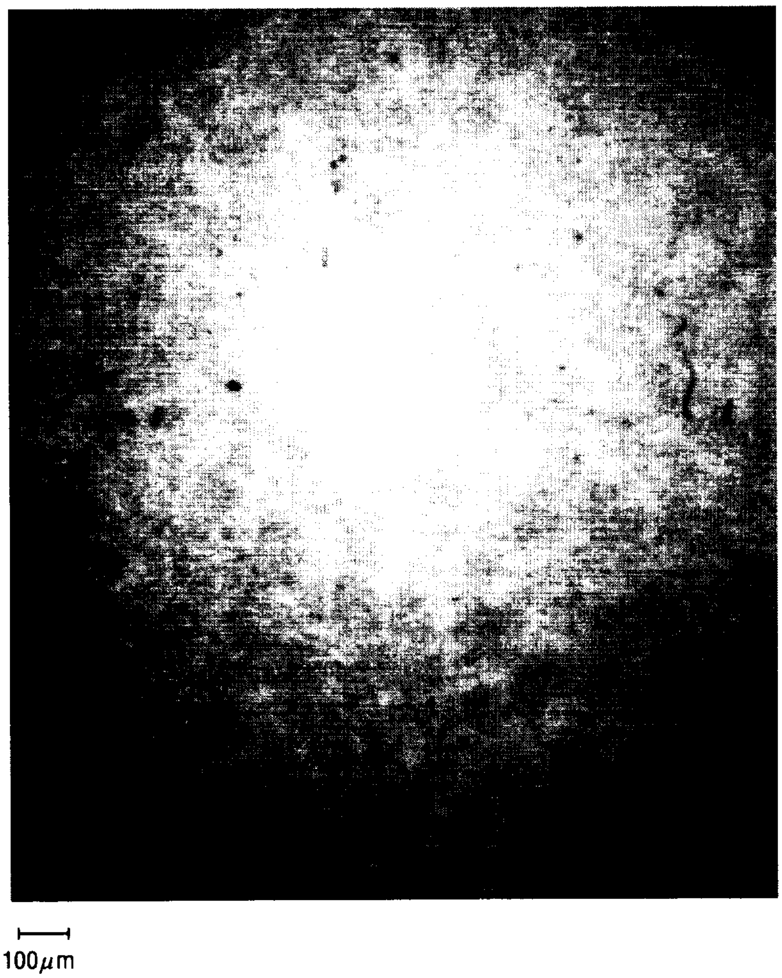

Figure 145.—PDAMNA films grown in space. The best space-grown films clearly exhibit fewer particles than the best ground-based films.

discovered that these films exhibit partial alignment of the polymer chains normal to the substrate surface. This is important because ordered films are desired for many applications. Convection may be detrimental to obtaining well-ordered films. It has been observed that in 1-g films grown for short durations of time are more highly ordered than those grown for longer durations. This could be a result of convection; the turbulent and chaotic molecular motions that take place during convection could cause the polymer chains to become entangled and matted around each other as they grow longer. The use of moieties chemically incorporated into the polydiacetylene structure is being investigated to aid in inducing self-alignment of the polymer chains.[4] At Rice University, a student researcher is performing synthetic modifications to PDAMNA which appear to exhibit the desired behavior.

[1]Frazier, D.O; Hung, R.J.; Paley, M.S.; Long, Y.T.: *Journal of Crystal Growth*, in press, 1996.

[2]Brust, M.; Walker, M.; Bethell, D.; Schiffrin, D.J.; Whyman, R.: *Journal of Chemistry Society Chemical Communications*, 801, 1994.

[3]Paley, M.S.; Armstrong, S.; Witherow, W.K.; Frazier, D.O.: Chemistry of Materials, 8(4), 912, 1996.

[4]McArdle, C.B.: Ed., Side Chain Liquid Crystal Polymers. Publication: Chapman and Hall, NY, 1989.

Sponsor: Office of Life and Microgravity Science and Applications

University/Industry Involvement: Mark S. Paley, principal investigator, Universities Space Research Association (USRA); Optron Systems, Inc., Bedford, MA

Biographical Sketch: Donald O. Frazier is a senior scientist for physical chemistry at MSFC. Frazier earned his Ph.D at Rutgers University. He develops research programs which focus on microgravity processing for fundamental and applications sciences. He also serves as project scientist for ground-based and flight programs, and establishes educational outreach relevant to ongoing projects. In addition, he promotes technology transfer relevant to research programs.

Protein Crystallization Apparatus for Microgravity

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The major objectives of this research are aimed at the design, construction, and operation of an improved microgravity protein crystal growth hardware and facility.

Previously, in response to the first NASA biotechnology NRA, we proposed to develop and construct a facility based protein crystal growth concept. This was undertaken largely because of the many important examples of quality improvements gained from growth in the diffusion-limited environment in space. The concept was based on the adaptation for microgravity of a commonly used disposable crystallization tray thereby improving sample logistics and handling, as well as greatly increasing the potential coinvestigator group and science return. The proposal proceeded in two phases, in the first stage a hand-held concept was to be developed and tested in microgravity to test the principal/concept. If successful, we further proposed to construct a facility for the mass production of protein crystals for application in the structure determination. Access to the facility is open to scientist from industry, academia and government laboratories. The principal aims of the research are:

- Establish a protein crystal growth facility which would provide greatly increased experiment and coinvestigator capacity in order to increase the odds of obtaining crystals of improved quality for application in this atomic structure determination, consequently increasing the overall science return from each mission;
- Investigate the disposable interface concept in development of microgravity hardware for reduced cost and improvements in logistics and handling; and
- Utilize the facility to delineate factors contributing to the effect of microgravity on the growth and quality of protein crystals.

Improvements in the quality protein crystals can be the limiting step in the determination of the atomic structure. A detailed knowledge of the atomic three-dimensional structure of protein molecules is key to a fundamental understanding of biochemistry and is of tremendous application in structure-based drug design. Further, examination of crystals grown in microgravity provides important scientific data which illuminates the mechanisms involved in the growth of high-quality crystals in the microgravity environment.

During the course of this investigation hardware design and construction has proceeded rapidly through hand-held versions to complete facility hardware. A large flight coinvestigator group has been established and the hardware has been manifested and flown succesfully on several Shuttle missions (table 10). Additionally, special dialysis counter-diffusion hardware has been designed, constructed and is now currently active on Mir. The accomplishments from both the hardware development and the results from the flight experiments have been outstanding. Over the course of 3 flights of the protein crystallization apparatus for microgravity (PCAM) facility hardware in 1995, over 1,600 individual vapor equilibration experiments were flown, exceeding the total number flown in under the Microgravity Science and Applications Division (MSAD) program since the inception of the protein crystal growth program in 1985. It should be noted that the PCAM hardware pioneered the development and deployment of disposable interface in flight hardware which has resulted in greatly reduced costs, as well as numerous additional advantages. Highlights of the PCAM and diffusion-controlled crystallization apparatus for microgravity (DCAM) experiments include crystals of human antithrombin III (Dr. Mark Wardell, Washington University) which were of greatly improved quality. These crystals have allowed for the completion of the atomic model of this important protein. Improved crystals have also been grown of neurophysin/vaspressin complex, liver augmenter, (Dr. B.C. Wang, Dr. John Rose, University of Georgia) raf kinase, (Drs. J.P. Wery and David Clawson, Eli Lilly) and the nucleosome core particle (Dr. Gerry Bunick and Joel Harp, Oak Ridge National Laboratory). Several publications describing the improvements gained from microgravity are in preparation. 1996 marked the first long-duration experiment for DCAM. Crystals produced from DCAM returned from STS–79 after a 6-month stay on Mir were recently distributed to the guest investigator group. Notable accomplishments include numerous large, spectacular crystals of the nucleosome core particle which were the largest grown to date (Dr. Gerry Bunick and Joel Harp, Oak Ridge National Laboratory) and the largest crystal ever produced of T7 RNA polymerase (Dr. B.C. Wang, Dr. John Rose, University of Georgia). A summary for the

Table 10.—*Flight hardware characteristics.*

Mission	Hardware	# Sample Chambers	# Investigators	# Proteins
STS–62	HH-PCAM	96	1	4
STS–63	6 PCAM	378	7 (5 groups)	9
STS–67	6 PCAM	378	11 (8 groups)	9
STS–73	12 PCAM	756	13 (8 groups)	12
	8 Short PCAM	168	1	
	81 DCAM	81	3	3
STS–76	162 DCAM	162	8 (7 groups)	9
STS–79	162 DCAM	162	9 (7 groups)	11

flight experiments conducted to date are synoposized in table 10. Several publications describing the effects and improvements gained in microgravity are in preparation.

Carter, D.: "PCAM and DCAM, Summary of Flight Results 1994–96." Protein Crystal Growth Workshop, Panama City, FL, May 1996.

Carter, D.: "PCAM and DCAM, Summary of Flight Results 1995–96." Gordon Research Conference, New Hampshire, June 1996.

Carter, D.: "PCAM and DCAM Hardware and Facility," International Microgravity Protein Crystal Growth Workshop, University of California, Riverside, 1996.

Sponsor: Microgravity Science and Applications Division, NASA Headquarters

University/Industry Involvement: Eli Lilly and Company; Monsanto/Searle; DuPont Merk; Oak Ridge National Laboratory; Washington University School of Medicine, St. Louis; University of Louvain, Belgium; University of Georgia; University of Pittsburgh; Virginia Commonwealth University; University of Saskatchewan, Canada; University of Colorado; University of Groningen, The Netherlands; Justus-Liebig University, Giessen, Germany; University of Helsinki, Finland; Max-Delbruck-Centrum für Molekulare Medizin PG Kristallographie, Berlin, Germany; Institut de Biologie Structurale Jean Pierre Ebel, Grenoble, France; Rosenstiel Basic Medical Sciences Research Center at Brandeis University, Maryland.

Biographical Sketch: Dr. Dan Carter is the senior scientist for biophysics at Marshall and is director of the Laboratory for Structural Biology. His accomplishments include the crystallization and atomic structure determination of several important proteins including serum plasma albumin. His research has been published in scientific journals, featured on the cover of *Science*, and he has been selected for NASA Inventor of the Year awards. His current research interests in structural biology include important HIV proteins, improvements in drug efficacy and delivery through rational drug design, and blood replacement products. Carter received his Ph.D. in x-ray crystallography from the University of Pittsburgh in 1984.

Microgravity Liquid Containment Vessel

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Numerous protein crystal growth experiments performed in microgravity have been degraded due to the existence of air bubbles within the liquid solutions. Other materials processing and fluid experiments flown on Space Shuttle missions have encountered similar problems. The origins of most of these bubbles were generally unknown, except where leakage was an obvious cause.

To study this problem, a variety of liquid-handling experiments were developed by Dale Kornfeld at MSFC and Dr. Basil Antar at the University of Tennessee Space Institute and flown aboard the NASA KC–135 aircraft during the last 3 years with a specific purpose of understanding the conditions that lead to incipience and growth of unwanted bubbles during liquid-handling operations in microgravity. These procedures included the filling of various empty containers with liquid, liquid jet-impingement on a vessel wall, stirring of a partially-filled container, geysering in a liquid pool, and several others, all using liquids with different surface tensions. Each

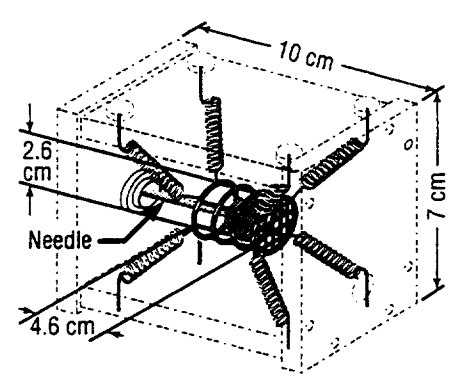

Figure 146.—Drawing of a typical "cage" tested during many parabolas on the NASA KC–135 aircraft.

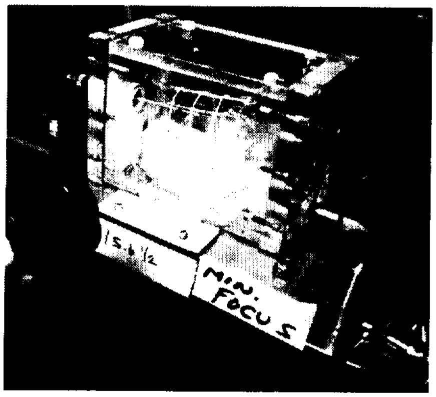

FIGURE 147.—A test photo of one of the cages being filled during a low-G parabola.

liquid injection or agitation was recorded using high-speed movie film and was performed during an aircraft parabola providing ~20 sec of low-g ($\sim 10^{-3}$). Approximately 40 parabolas could be flown in one day. Postflight analysis of the film revealed that in almost all cases the bubbles formed were either folded into the liquid bulk during breakup of the gas/liquid interface, or they originated from trapped gas voids at the corners of the vessel, or from wall defects as liquid spread along a wall.

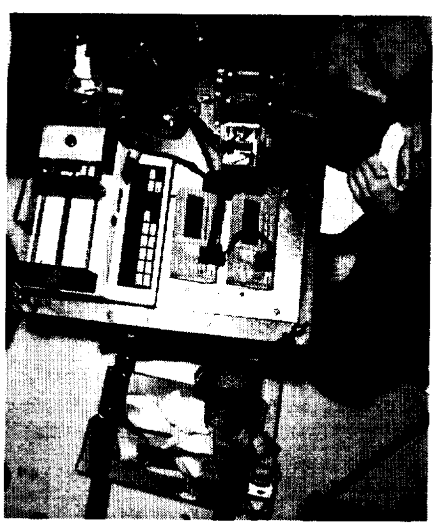

FIGURE 148.—A photo of test work as flown aboard the NASA KC–135 aircraft.

Results from these flights led the investigators to invent a novel design for a low-gravity liquid containment vessel which will minimize bubble formation while being filled. The primary feature of this vessel is the absence of walls and corners; the new vessel consisting only of an open-weave mesh. Solid walls are not necessary for liquid containment in microgravity, since the surface tension force becomes the most dominant force. The air-liquid interface, pinned by the mesh, in effect becomes the wall. This type vessel, actually a three-dimensional "cage," whose shape and volume are defined by a thin mesh is fully adequate for containing liquid volumes while in microgravity. Both plastic and wire mesh cages of various sizes, with gaps from 1/8- to 1/2-in between each mesh strand, have been tested during low-G parabolas and were found to easily contain liquid indefinitely at 10^{-2} G or lower, and to even contain liquid during transients of $\sim 10^{-1}$ G.

In addition to bubble minimization, numerous other benefits over solid-wall containers are suggested, i.e., investigators will have easy access to all parts of a fluid volume while in microgravity for sample withdrawal or injection; equilibration of vapor pressures when the cage is inside a larger containment box, etc. A cage-container would be useful for solution crystal growth experiments in general, and protein crystal growth experiments, in particular.

Antar, B.N.; Kornfeld, D.M.: "Bubble Generation During Low-Gravity Fluid Handling Procedures." AIAA Paper no. AIAA-95-0878, January, 1995.

Kornfeld, D.M.; Antar, B.N.: "Bubble-Free Containers for Liquids in Microgravity." *NASA Tech Briefs*, vol.19, no.12, p.91, December 1995.

Antar, B.N.; Kornfeld, D.M.: "Gas/Liquid Flows During Low-Gravity Fluid Handling Procedures." AIAA Paper no. AIAA-96-0502, January, 1996.

Sponsor: Biotechnology Project Office

Biographical Sketch: Dale M. Kornfeld is a chemical engineer, AST Aerospace Polymeric Materials, in the Space Sciences Laboratory. Kornfeld currently is lead scientist and engineer on the low-gravity bubble generation experiment, flown 15 times on a NASA KC–135 low-gravity aircraft. He has served as a mission scientist team member on three Marshall-managed Spacelab missions and has received numerous awards, including a NASA Inventor of the Year award in 1984.

Space Aerogel

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On April 3, 1996, the first space samples of aerogels were produced by NASA in low-Earth orbit on the Starfire Rocket. Aerogel is the lightest solid known—only three times the density of air. A gel is an amorphous solid formed from a liquid with defined gellation conditions for temperature and concentration. As the only known transparent insulator, aerogel is a supercritically dried gel with all its liquid removed—sometimes garnering the name "frozen smoke." A block the size of a human weighs less than a pound. An inch thickness can shield a hand from the heat of a blowtorch. A sugar-cube-sized portion of the material has the internal surface area of a basketball court.

The formation of these gels has attracted space research, owing to the strong influence of gravity on how a gel is formed. "Practically all biochemical processes which occur in living beings are proceeding in medium with a sol-gel balance of all components. If fragments of gel phase depend on gravity, it can be an additional way for gravity to influence living beings, including humans."[1] In fact, "gel formation can display very high gravitational dependence... The structure of gel matrices obtained on Earth and in orbital conditions has been found to be different... space processing of gels could be quite advantageous... microgravity conditions can allow gels with a more uniform or prescribed structure."[2]

Aerogel is transparent because its microstructure is very small compared to the wavelength of light. However, as currently processed on Earth, all but the clearest aerogels scatter some light at the blue end of the spectrum giving them a slightly hazy appearance. The scattering can be thought of as arising from the large holes or pores that have a lower index of refraction than the average of the aerogel, i. e., index of refraction 1.00 versus 1.02. Thus research on aerogel preparation to improve its clarity currently is focused on minimizing the number and size of the large pore population in the aerogel.

When characterized for porosity (nitrogen adsorption and desorption), the space aerogel showed a four-fold reduction in pore sizes in the 17- to 3,000-Å range, compared to otherwise identical ground controls. Since the light scattering varies with pore size to the sixth power, a calculated reduction in opacity of 4,000 times is derived. The difference in porosity may arise from lack of sedimentation during the early stages of space gellation, in which large gel particles entrap or occlude solvent into a mosaic rather than a more close-packed structure. The comparison between ground and space samples becomes more striking when pore volume is considered, since more than a decade and a half of ground research typically produces pore volumes in the range of 5 to 7 cm^3/g (inverse density), but the space aerogel has a benchmark value of 1.07 to 1.6 cm^3/g. For pure solid silica (0.5 cm^3/g) with no pores, the space aerogel is remarkably close to the values expected from a 30 to 50 percent solid, compared to the typical 5 to 10 percent solid material encountered on the ground. The next generation aerogel experiment will be optimized for longer, more quiescent conditions in the Shuttle middeck.

According to the "Technology to Watch" section of *Fortune Magazine* (1992), the overall market for the aerogel industry worldwide is projected to include more than 800 potential product lines ranging from surfboards to space satellite components.

Research Milestones:

- June 1995, KC–135 Low-Gravity Production of Low-Density Silica Flocs (results published in *Microgravity Science and Technology*, 1995).
- April 1996, microgravity Starfire rocket flight successfully forms 32 samples of aerogel.
- June 1996, publication of "Ground-Based Studies on Aerogel Transparency." *Journal of Materials Research*, 1996.
- September 1996, received first porosity data from rocket flight; results being analyzed, but indicate 4 to 5 times improved pore size control in the space-processed aerogel.

[1]Leontjev, V., et al.: Micro-g Science Symposium, Moscow, May 13–17, p. 274, 1991.
[2]Bogatyreva, et al.: Sixth ESA Conference ESA-SP-333, vol. 1, 1992.

Sponsor: Center Director's Discretionary Fund

University/Industry Involvement: Lawrence Berkeley National Labs; Aerojet; Universities Space Research Association (USRA)

Biographical Sketches: Dr. David Noever is a research scientist in the Space Sciences Laboratory at Marshall. He has held this position since 1991. His association with Marshall began in 1988 as an USRA visiting scientist. Noever currently initiates and designs microgravity experiments in materials processing, with particular emphasis on aerogel production. Noever received his B.S. degree in chemical engineering from Princeton University, Princeton, N.J. in 1984. He graduated summa cum laude; was a Phi Beta Kappa; and a Chevron Scholar. He earned his Ph.D. in theoretical physics at Oxford University, Oxford, U.K., in 1988. While there he was a Rhodes Scholar and earned a Silver Medal at the Royal Society of Arts, London, U.K.

A Protein Crystal Growth Studies Cell (Year 3 of 3)

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This proposal is to develop growth cells, a fluids preparation system, and practical means for long-term storage of protein solutions for a protein crystal growth studies system. The project was initiated in FY95, and this represents the third year of this effort.

Two concerns have driven the growth cell design effort. The first was recognition that higher performance interferometry systems would enable us to achieve all of our experimental goals with smaller crystals. The second was that smaller growth cells would consume considerably less solution. Small-volume cell design has now gone through two iterations, with the first being a plain cell and the second being a cell enclosed in a water jacket. Prototype small volume glass cells (0.3 mm by 10 mm by 30 mm) have proven to be extremely suitable in use in an optical face growth rate measuring system in this laboratory.

Solution temperature control will be developed along two lines. The first will be to stick with the now-developed method of surrounding the growth cell with a heater working against a surrounding cooling system. Growth cell temperature control to within ±0.025 °C has been demonstrated with this system. However, this method is bulky, and adequate optical access to the growth cell may introduce thermal gradients across the growth cell at the optical access ports, the regions of least thermal control, and uncertainties about the actual temperature. These difficulties have led us to investigate a growth cell with a surrounding water jacket, with temperature control supplied by a remotely located circulating bath. This reduces the overall bulk of the growth cell, while enabling us to "dump" the waste heat elsewhere. This system is exactly analogous to the most commonly employed temperature-control methods in the laboratory. The primary disadvantage is the reliance on a circulating fluid, which may be a safety problem for μg applications. Regardless, this is the favored system, and we have now started assembly of a prototype circulator bath of ~200- to 300-ml volume. Minimizing the bath volume is desirable from the standpoint of reducing the cooling (power consumption) required. However, this also reduces the thermal mass which serves to dampen oscillations in the temperature.

The fluidics system has been reconfigured to improve its compatibility with the protein crystal growth cell. The redesigned system has two pairs of solution delivery syringes. Each pair is capable of independantly preparing a solution, with the components being drawn from one of eight stock reservoirs. By going to this type of design, we are able to separately prepare the buffer and protein solutions, and mix them immediately prior to injection into the growth cell. The second syringe in each pair is used to allow the solution to be passed back and forth. Tests with a concentrated polyethyleneglycol and dye solution have shown that mixing can be achieved by this technique in the laboratory.

A working assembly of the syringe system, and current operations include debugging/improving the hardware and controlling software. Specifically, this means optimizing the solution withdrawal routines, standardizing the lengths of the solution lines, improving the control wiring layouts, and improving the software user interface and modularity to make it easier to add additional features as needed. Concurrent with this, assembly is underway of a phase shift interferometer and face growth rate systems (to which the fluidics system will be connected) in order to:

- Conduct data collection runs which can be compared to existing data; and
- Begin collection of reference ground-based interferometry results for comparison with planned glovebox interferometer experiments.

This will constitute assembly of a working system which will be totally controlled through a computer keyboard. Methods of remotely positioning the growth cell, while the system is interfaced to a video camera for data acquisition, will be patterned upon those currently employed in a growth-rate apparatus in this laboratory. This work will be done concurrently with, and as a part of, the interfacing of the fluidics system to the growth cell.

Two sets of long-term storage stability measurements have been made using the proteins lysozyme and ovostatin. Storage conditions were at 20, 4, and −20 °C, both as a solution and as a lyophilized powder. The storage period was 3 months, and the materials were assayed for crystallizability every 2 weeks over this period. As expected, the least stable storage conditions were solutions at 20 °C. While lysozyme was expected to show exceptional stability, ovostatin was expected to be very sensitive to the storage conditions. Surprisingly, ovostatin showed a high degree of stability, as determined by crystallizability, both in solution and lyophilized at 4 °C, and the protein kept its crystallizability considerably longer than expected at 20 °C. We are now defining crystallization conditions for four new test proteins, lactate dehydrogenase, α-amylase, ovalbumin, and ovotransferrin, for use in storage (and other crystal growth) experiments over the next year. It should be pointed out that the lactate dehydrogenase being was obtained over 3 years ago, and stored as a suspension in 3.2 Molar ammonium sulfate solution at 4 °C. This material is still pure by electrophoretic measurements and still crystallizes.

This system will provide the basis for a dedicated protein crystal growth studies system suitable for use in both microgravity and on Earth. Through use of such a system, it is anticipated that the factors which govern protein crystal growth, and the resultant x-ray diffraction quality of the crystals will be obtained. Higher diffraction resolution crystals means a better understanding of the structure-function relationship in the proteins being studied, which, in turn will lead to faster/more facile design of drugs, for example, targeted to that specific protein.

A versatile, real-time, and user-friendly system for studying protein crystal growth is now under final assembly in this laboratory. This system will enable researchers to collect growth data by a variety of methods, with the parameters for each experiment being determinable immediately prior to execution, based upon the previous data. A design philosophy of this system is that it should be of practical utility for corresponding ground-based PCG studies. The overall design analysis goals are the ability to measure face growth rates, solution concentration gradients, and interfacial growth features in either quiescent or defined flow velocity solutions.

Sponsor: Office of Life and Microgravity Science and Applications

Biographical Sketch: Marc Pusey currently holds the position of AST materials specialist in the Biophysics Branch of NASA/MSFC. He obtained his Ph.D in biochemistry at the University of Miami, Florida, and did his postdoctoral research at the University of Minnesota. Dr. Pusey currently conducts experiments into all aspects of the protein crystal growth process, including the interaction of the protein with the surrounding solvent, how the monomeric materials aggregate to form nuclei, the measurement of crystal growth rates, and the effects of aggregation on the crystal growth process.

Earth System Science

Interannual Variability in Tropical Radiation and Water Vapor

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More than any other factor, the presence of water defines the unique characteristics of climate on planet Earth. Evaporation from the ocean/land surface and trapping of upwelling longwave radiation by atmospheric water vapor are processes that moderate climate at the surface. At present it is uncertain how variability in the global hydrologic cycle, whether natural or anthropogenic, will modify climate in the future. As part of NASA's Mission To Planet Earth (MTPE) research program, we are using a combination of infrared satellite measurements and numerical models to study short-term climate variations and the role that water plays in these. In particular the phenomena known as El Niño is a frequent but aperiodic readjustment of tropical climate that provides us a natural "laboratory" in which to study the dynamics of water in climate. An El Niño event together with a subsequent readjustment phase known as La Nina, may take two to three years to complete. This time span is short enough to be monitored by individual satellite sensors measuring temperature, moisture, and upwelling radiation from the planet.

The key issue that we have focused on in the past year is the impact of El Niño-related water vapor changes on outgoing longwave clear-sky radiation (LWCS) during the period 1987 through 1989. The fundamental statistic of interest is the change in LWCS with change in sea-surface temperature (SST) averaged over the tropical oceans (30 degrees north to south). Fortunately, three independent data bases of LWCS were available during this period. Because maximum excursions in area-mean LWCS are of the order 3.0 Wm^{-2}, or about 1 percent of the climatological LWCS value, it is important to understand the effects of biases and random errors. Intercomparing these three data bases has enabled us to greatly enhance our confidence in our result.

Figure 149 shows a time series for each of three LWCS data sets: the Earth Radiation Budget Satellite (ERBS); University of Maryland's high-resolution infrared sounder (UMD HIRS); and TIROS operational vertical sounder (TOVS Path A). Also shown is the tropical average SST from National Oceanic and Atmospheric Association's (NOAA) Climate Analysis Center. These time series are composed of monthly mean departures, or anomalies, from their respective 3-year monthly climatology. Also shown is a calculation of LWCS anomalies we would expect if there were no variability in atmospheric water vapor. Each data set shows a general tendency for the Earth/atmosphere system to emit more LWCS as tropical ocean SST's increase during the onset of El Niño in 1987. A decrease in LWCS is seen in 1988/1989 as SST's decrease during La Nina. However, the amplitudes of this response are seen to differ. Through our analysis of the measurement strategies we have found that the ERBS sensor has too little dynamic range, due mostly to difficulties in properly distinguishing partly cloudy scenes from those that are clear but have abundant water vapor present. We also suspect that each of the three methods is subject to some error arising from the inability to screen very thin high ice clouds when looking almost vertically. Sensitivity studies indicate that biases arising from this effect are only several tenths Wm^{-2}.

If we calculate the slope of the quantity (LWCS anomaly/SST anomaly), or ΔLWCS/ΔSST from the data in figure 149, we obtain: ERBS (1.67 $Wm^{-2}K^{-1}$), UMD (2.93 $Wm^{-2}K^{-1}$), and TOVS Path A (2.77 $Wm^{-2}K^{-1}$). These slopes are

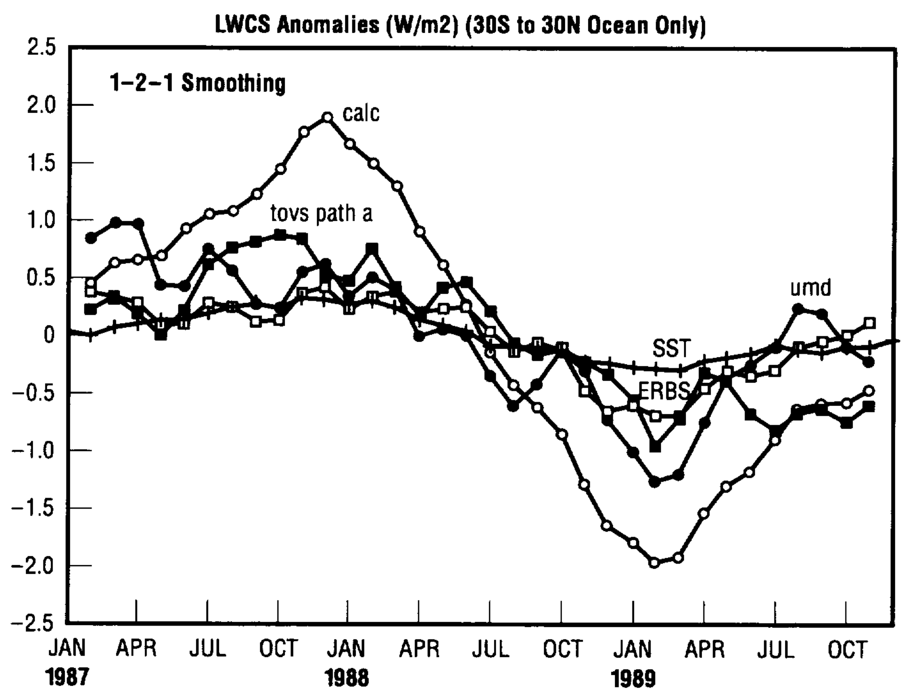

Figure 149.—L2WCS estimates from three satellite-based algorithms (ERBS, TOVS, Path A, UMD HIRS) and a radiative model calculation (calc).

important because of what they tell us about changes in greenhouse trapping of LWCS by changes in atmospheric water vapor and temperature induced by El Niño/La Nina. If the greenhouse trapping, or ratio of LWCS measured by satellite at the top-of-atmosphere to the LWCS emitted by the ocean surface were constant during this period, we would expect the slope ΔLWCS/ΔSST to be about 3.9 $Wm^{-2}K^{-1}$. Each of our estimates of the actual ΔLWCS/ΔSST is substantially smaller. This suggests that during warm SST periods, more LWCS radiation is being trapped by increased water vapor. Sensitivity analyses indicate that ERBS is about 1.5 $Wm^{-2}K^{-1}$ too small, while UMD and TOVS Path A are of the order 10 percent too small. Even with these adjustments our conclusion still holds: During El Nino, changes in atmospheric water vapor and thermal structure act to retard LWCS cooling of the tropical oceanic regions.

Our current efforts are directed to two areas. First, we are conducting radiative modeling studies to separate atmospheric temperature effects from water vapor effects. Our initial results suggest that temperature changes enhance radiative losses to space during El Niño, while water vapor is the agent that retards radiative loss. Our other area of focus is to determine the extent to which water vapor changes during El Niño and La Nina, when averaged over the tropical oceans, are the result of moisture transport by winds from the tropical land areas. This other mechanism for moisture supply would be in-situ ocean surface evaporation.

This ongoing research is supported under the office of MTPE and constitutes an important inquiry into how the hydrologic cycle is involved in climate variability. The three data sets used are forerunners of more precise measurements to be undertaken by the Earth-observing component of MTPE. We anticipate that in the near term these results will be of use in validating climate models which use the 1987/1989 period as a test case. We have performed some of these type studies in house with the GENESIS climate model. We also expect the results of this study to phase well with the Tropical Rainfall Measuring Mission (TRMM). Since tropical precipitation releases energy to heat the tropics and drive planetary wind fields, our studies will provide some insight as to how this heat is rejected back to space and exported to higher latitudes to maintain the global heat balance.

Robertson, F.R.; Fitzjarrald, D.; Braswell, W.D.: "Anomalies in Radiation, Heat and Water Budgets as Diagnosed from Pre-EOS Data Sets: Insights on Tropical Climate Sensitivity." 1996 NOAA Climate Diagnostics Workshop, Huntsville, AL, October 27–November 1, 1996.

Sponsor: Office of Mission to Planet Earth

University Involvement: University of Maryland

Biographical Sketch: Dr. Franklin Robertson (Ph.D. Purdue University, 1981) leads the Climate Diagnostics and Modeling Group in studying water and its influence on the atmosphere and climate dynamics. He serves as the lead MSFC investigator on a joint EOS interdisciplinary investigation "The Global Water Cycle: Extension Across the Earth Sciences," conducted jointly with Pennsylvania State University. Robertson has also contributed to the formulation of science strategies for a NASA space-borne lidar to measure atmospheric wind measurements critical to studies of the global energy and water cycle.

Marine Boundary-Layer Clouds and Their Representation in a Climate Model

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The marine boundary layer is the bottom 500 to 2,000 m of the atmosphere over oceans. Because of the availability of heat and moisture, clouds often form in this shallow and turbulent layer for a long lasting period, and cover extensive areas. Their existence has important influences on Earth's climate for the following reasons. First, these clouds are highly reflective for solar radiation compared to their underlying ocean surfaces, so they drastically reduce the amount of solar radiation absorbed by the Earth. In the meantime, the emitted infrared radiation from these clouds to space are not much different from that from the ocean surfaces, since the cloud-top absolute temperatures are not significantly lower than those of the surfaces due to the low altitude of the clouds. As a result, these clouds reduce the total radiation energy received by the surfaces, which suggests that they tend to provide an overall cooling effect to the planet. In addition, these clouds are intimately involved in regulating moisture fluxes from the oceans, which are the major moisture source for the atmosphere. Thus, marine boundary layer clouds are important components of the climate and should be realistically represented in a climate model. However, this representation remains one of most difficult and unsolved problems, since the computer models cannot explicitly resolve the phenomena with the scales less than their grid length (several hundred kilometers) due to the limited computer power. More importantly, our knowledge of the physical processes operating in the clouds are far from complete, which makes impossible a realistic representation of the clouds in the current climate models. In this research, we have focused on the following issues.

Understanding the Interaction Between Shallow Cumulus and Stratiform Clouds

Observations from the recent field experiment, Atlantic stratocumulus transition experiment (ASTEX) showed that cumulus and stratocumulus clouds often coexist over large areas of the Atlantic Ocean. Thus, it is important to understand how the cloud system maintains. We used a two-dimensional numerical model that can explicitly resolve turbulent eddies in the boundary layer for this study. The model results indicate a strong mass detrainment from the cumulus to stratiform clouds, suggesting the importance of cumulus clouds in maintaining the stratiform clouds. It has been found from budget analysis that although the cumulus updrafts occupy only 1 percent of the domain, it contributes significantly to the turbulent fluxes. In addition, the horizontal transport of liquid water from cumulus updrafts to stratiform clouds is significant compared with the vertical turbulent transport in the stratiform clouds region. These results suggest that one needs to explicitly include the contribution from cumulus convection in the representation of large area of marine boundary-layer clouds.

Effects of the Microphysics on the Cloud Optical Properties

It has long been recognized that an increase in cloud condensation nuclei (CCN) concentration number leads to an increase in the cloud albedo provided the liquid water content does not change, which is so-called Twomey effect. The assumption for this hypothesis is that there is no interaction between CCN change and cloud dynamics, which may be termed as noninteractive condition. However, when CCN number increases, the absorption of thin clouds increases, which will tend to reduce cloud liquid water by cutting off the moisture supply from below. This results in negative feedback from the cloud absorption to the albedo, which may be termed an interactive condition. To evaluate the feedback, we used the same two-dimensional model to simulate diurnal variation of marine boundary layer clouds with two different cloud droplet numbers, $50/cm^3$ and $150/cm^3$. The model calculation reveals that when CCN number increases, the simulated albedo increases. However, since liquid water content decreases resulting from the increase of the solar absorption, the cloud albedo does not increase as much as it would if no interaction between CCN and the cloud dynamics is allowed. The relative decrease due to the absorption feedback is between 0 and 20 percent, with the maximum decrease just after noon local time. The daily average decrease is about 5 percent. Current research is focusing on the following questions:

- Is it likely that a realistic increase in CCN number eliminates all the clouds?
- Is the decrease in the cloud albedo due to the cloud absorption important to the climate change problem?

These questions will be addressed using detailed models of atmospheric processes, and comparing results with observations and theory. Results will be used to improve the parameterization of these processes in global climate models.

Wang, S.: "Defining Marine Boundary-Layer Clouds With a Prognostic Scheme." *Monthly Weather Review*, vol. 124, pp. 1617–1833, 1996.

Wang, S.: "A Prognostic Approach of Parameterizing Marine Boundary-Layer Clouds." Abstracts in AGU fall meeting, December 15–20, San Francisco, CA 1996.

Sponsor: Office of Mission to Planet Earth; Atmospheric Radiation and Dynamics Program

University/Industry Involvement: Dr. Shouping Wang, Universities Space Research Association

Biographical Sketch: Dr. Franklin Robertson, (Ph.D., Purdue University, 1981), leads the Climate Diagnostics and Modeling Group in studying water and its influence on the atmosphere and climate dynamics. He is involved in validating clouds and their representation in climate models. Robertson serves as the lead MSFC investigator on a joint EOS interdisciplinary investigation "The Global Water Cycle: Extension Across the Earth Sciences," conducted jointly with Pennsylvania State University.

Remote Sensing of Urban Land Use and Effects on Climate

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The urban heat island effect exists as a "dome" of elevated temperatures that presides over cities, primarily in summertime, in contrast to their rural surroundings. The occurrence of urban heat islands reflects the human-induced contrasts between rural and urban areas caused by alteration or replacement of the "natural" environment (e.g., trees) surrounding the city with generally nonevaporating and nonporous materials, such as pavements and buildings. This results in reduced evapotranspiration and more rapid runoff of rain water, as well as a general increase in temperatures over urban areas as opposed to their rural counterparts. Urban heat islands have caused changes in precipitation and temperatures over cities that are at least similar to, if not greater than, those predicted to develop over the next 100 years by global change models. Although the urban heat island has been well established for very large cities, such as New York City or Mexico City, there are little data to support the development of this phenomenon over small- to medium-sized cities of between 100,000 to 300,000 population and located in humid, temperate climatic regimes. Additionally, low-resolution satellite data used in past studies have not adequately captured the extreme heterogeneity of the urban landscape, which in part drives the development of the urban heat island. This research project, therefore, has sought to obtain a better understanding of the causes of the urban heat island across the heterogeneous urban landscape, and for a city of medium population size, through examining high-resolution airborne remote sensing data obtained over the Huntsville, AL metropolitan area.

Day and night airborne thermal infrared image data were collected at 5- and 10-m spatial resolutions over Huntsville on September 7, 1994, using the NASA Advanced Thermal and Land Applications Sensor (ATLAS). The ATLAS is a 15-channel scanner with 9 visible and middle and near-reflective infrared bands between 0.45 to 4.20 μm, and 6 thermal infrared bands in the 8.20 to 12.2 μm range. ATLAS data were acquired during the daytime between approximately 11 A.M. to 2 P.M. local time to capture the time of greatest solar incidence upon the urban surface around solar noon, and then again between about 9 p.m. to midnight to capture the time when the urban heat island phenomenon is most pronounced. These data were used to measure and model the state and changes in thermal responses from specific urban land cover types typical of the Huntsville metropolitan area to better measure and model how dynamics of city surface drive or force development of the urban heat island. Additionally, these data have been used to spatially model heating and cooling patterns as a means for visualizing how thermal responses are distributed across the Huntsville urban landscape.

Progress during the past year has focused on deriving a visualization model of heating and cooling patterns for the Huntsville area. Figure 150 represents ATLAS 10-m pixel spatial resolution data for daytime that have been draped on top of digital elevation model (DEM) data for a portion of the study area. Prominent features are Huntsville and Green Mountains on the right side of the image, Jones Valley located in the center of the image which is comprised of pasture land for grazing cattle, the low hills bordering Jones Valley on the left, and an urbanized area on the far left side of the image. This three-dimensional perspective is useful for developing a better perspective of daytime thermal energy (i.e., heating and cooling) patterns across the urban landscape and also for modeling the effects of slope and aspect on thermal energy responses. High thermal responses (or areas exhibiting higher temperatures) are represented in white with decreasing thermal responses shown in gray to black tones. Mountainous areas on the right side of the image exhibit relatively low thermal responses because of the extensive vegetation cover present (i.e., trees). Pasture land in Jones Valley expresses higher thermal energy responses because of factors related to the type of vegetation present (i.e., grass), the amount of area open to the sky for solar heating, and other factors. Considerably higher thermal energy responses are exhibited by

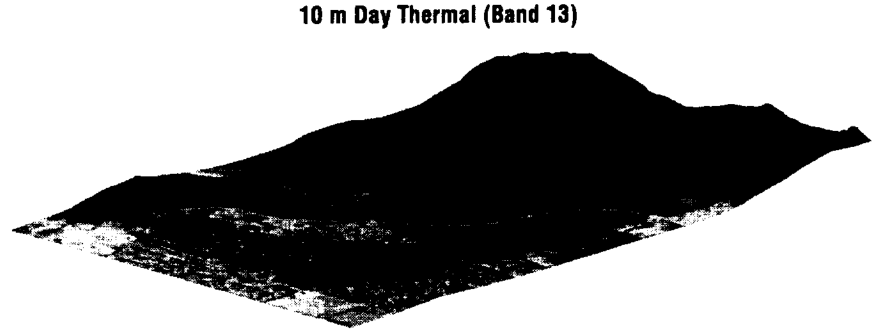

FIGURE 150.—Three-dimensional model of daytime ATLAS 10 m thermal remote sensing data draped on top of digital elevation model (DEM) data for a portion of the Huntsville metropolitan area.

the residential and urbanized areas bordering Jones Valley on the far left and center-facing side of the image. Figure 151 represents the same area as observed using nighttime ATLAS 10-m data. The mountains on the far right side of Jones Valley have relatively high thermal energy responses due to the effects of late afternoon solar incidence on the west-facing slopes. Some ground fog is evident as a haze creeping into the coves in Jones Valley adjacent to the mountains on the right side of the image. Pasture land in Jones Valley exhibits relatively low thermal responses because of the effects of the high availability of moisture in the form of dew and because of cold air drainage coming into the valley from the mountains, as well as other factors. The residential and urbanized area on the left and center-facing sides of the image are high in thermal energy responses at night because pavement, buildings and other impervious surfaces store heat during the day and begin to release this stored thermal energy after sunset.

As a result of the findings from this project, a research proposal submitted in response to NRA–95–MTPE–03, "Opportunities to Participate in NASA Mission to Planet Earth and Earth Observing System Science and Education Programs," has been funded to support a project entitled "A Remote Sensing-Based Study of Past and Future Land Use Change Impacts on Climate and Air Quality of the Atlanta, Georgia Metropolitan Region." This new research effort seeks to provide scientific understanding of the importance of urbanization as a forcing-function in local and regional climatic processed by analyzing how the rapid growth in the Atlanta metropolitan area over the last 25 years has impacted the climate and air quality of the region. Additionally, using information from the Atlanta Regional Commission on proposed growth of Atlanta in the next 20 years, this research will model how the proposed growth of the Atlanta metropolitan area will potentially affect the climate and air quality of the region.

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Lo, C.P.; Quattrochi, D.A.; Luvall, J.C.: "Detection Of Urban Heat Island Development Using High-Spatial Resolution Thermal Infrared Remote Sensing." *Proceedings*, vol. 1, Remote Sensing and Photogrammetry. American Society for Photogrammetry and Remote Sensing/American Congress on Surveying and Mapping Annual Convention and Exposition, April 22–25, Baltimore, MD, pp. 138–147, 1996.

Sponsor: MSFC Center Director's Discretionary Fund

University/Industry Involvement: Dr. Chor-Pang Lo from the Department of Geography at the University of Georgia has been a direct collaborator in this research as a NASA summer faculty fellow at MSFC during 1994 and 1995.

Biographical Sketches: Dr. Dale Quattrochi is a geographer/research scientist within the Earth System Science Division, Global Hydrology and Climate Center of the MSFC Space Sciences Laboratory. His research focuses on analysis of land surface energy exchanges and their effect on climate and hydrologic processes using remote sensing data.

Dr. Jeffrey Luvall is a forest ecologist/research scientist within the MSFC's Space Sciences Laboratory's, Earth System Science Division, Global Hydrology and Climate Center. His research focus is also directed toward examining land surface energy fluxes and their effects on local and regional climate, and hydrology using remote sensing.

10 m Night Thermal (Band 13)

Figure 151.—Three-dimensional model of nighttime ATLAS 10 m thermal remote sensing data draped on top of digital elevation model (DEM) data for a portion of the Huntsville metropolitan area.

The Use of the Thermal Response Number to Characterize Land Surface Energy Flux

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On a global scale, initial research by climate modelers identified the importance of including the linkages between different kinds of land surfaces and the atmosphere as factors influencing global patterns of rainfall, temperature, and atmospheric circulation.[5] Yet, these linkages have not been fully characterized in global models of atmospheric processes and climate change.[1] General circulation models (GCM's) suffer from a lack of detail about how different surfaces respond thermally, and hence, affect local climatic processes. Hewitson[2] states "GCM's are currently unable to reliably predict the regional climate change resulting from global warming, and it is at the regional scale that predictions are required for understanding human and environmental responses." These models could be improved by using thermal infrared measurements to quantify the biophysical response of the surface in relation to environmental energy fluxes (radiative, latent, conductive, and convective). Information at larger spatial resolution is also needed by the global modelers for improving their predictive capabilities, since the heterogeneity in surface types makes it difficult to characterize averages over the smaller spatial resolution used in global climate models.

The purpose of this study is to characterize the landscape in terms of a functional classification using the thermal response numbers (TRN) for the incorporation into the PSU/NCAR Penn State University/ National Center for Atmospheric Research MM5 model for mesoscale water vapor transport and convective activity.

One approach to characterizing the landscape is to take the U.S. Geological Survey landcover data and incorporate it into the Regional Atmospheric Modeling System (RAMS.)[4] This approach uses a structural classification based on landcover type instead of a functional classification to assess the impact of landcover in the RAMS output. The major problem with this approach is that the partitioning of the surface energy fluxes is spatially variable within and between each landcover class due to changes in soil moisture and vegetation canopy differences.[3] A method is needed that can classify land surfaces by their functional characteristics which are important in the linkages between the atmosphere and land surfaces. An example is the surface energy budget which can be quantified over space and time. One such classifier has been developed by Luvall and Holbo[3] and is called the thermal response number (TRN).

A change in surface temperature can be used as an aggregate expression of both surface properties (canopy structure and biomass, age, and physiological condition) and environmental energy fluxes. A change in surface temperature will be measured by the GOES–8 over a 30- to 60-min time period during cloud-free conditions. Usually a separation of about 30 min results in a measurable change in surface temperature caused by the change in incoming solar radiation. Surface net radiation is used as the value that integrates the effects of the non-radiative fluxes and the rate of change in surface temperature as the value that reveals how those nonradiative fluxes are reacting to radiant energy inputs. Their ratio can be used to define a surface property defined by Luvall and Holbo[3] as a TRN.

The thermal response number is readily calculable as a diagnostic from MM5/ RAMS model output and will be compared to the observed values generated from GOES. Analysis of the TRN spatial patterns and temporal evolution during periods that are dominated by nonprecipitating convective clouds will show how the draw down of soil moisture by surface evapotranspiration is handled by the numerical model and the effect of landcover on surface evapotranspiration.

The first year's efforts have been focused on obtaining the tools and data needed for the project.

- Land use/land cover maps have been obtained for the TVA region and have been added as a GIS layer as the structural classification of surface types.
- USGS (U.S. Geological Survey) digital elevation models (DEM) at 1:250,000 scale have been obtained for the TVA region. Integration into the GIS has begun.
- Switched from RAMS to PSU/NCAR Penn State University/National Center for Atmospheric Research) MM5 for mesoscale modeling. MM5 source code has been obtained and is compiled and running on MSFC's Crays.
- MM5 source code has been modified to assimilate GOES–8 data and is now being tested.

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[3]Luvall, J.C.; Holbo, H.R.: "Measurements of Short-Term Thermal Responses of Coniferous Forest Canopies Using Thermal Scanner Data." *Remote Sensing of Environment*, vol. 27, pp. 1–10, 1989.

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Sponsor: Center Director's Discretionary Fund

Biographical Sketch: Dr. Jeffrey Luvall has been with NASA since 1985 and is currently at NASA's Global Hydrology and Climate Center. He has worked extensively with surface energy budget modeling using remotely sensed data. He is using the thermal response number (TRN) to quantify surface energy flux characteristics from urban areas. The use of the TRN allows the functional classification of land surfaces in modeling surface/atmospheric interaction and feedback mechanisms for use in global climate models using remotely sensed data from aircraft and satellite platforms. He has developed a portable ground-based atmospheric monitoring system (PGAMS) in conjunction with Dr. Steve Schiller, South Dakota State University, for the correction of atmospheric radiance effects on remotely sensed data. The PGAMS is currently being used in developing atmospheric radiance corrections algorithms for the future Landsat-7 data.

Assessment of Biomass Burning on the Hydrologic Cycle of the Amazon

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Research into estimating total column atmospheric water vapor from infrared sensors onboard satellites has been a focus of research at MSFC for a number of years. Water vapor plays an important role in climate processes. It is a major element of the hydrologic cycle and provides the mechanism for energy exchange among many of the Earth system components. Recently, the Global Hydrology and Climate Center (GHCC) was contacted by researchers, Dr. Tracy DeLiberty and John Callahan, from the University of Delaware about joint research into quantifying the role that biomass burning is playing on the hydrologic cycle of the Amazon. The physical split window (PSW) technique will be used to estimate total precipitable water (i.e., total column water vapor) in the Amazon and surrounding areas. The technique was developed by MSFC's Dr. Gary Jedlovec.

The focus of this research is to examine the moisture budget in the Amazon using data from a variety of sources (e.g., satellite, model, and conventional surface and upper-air data), to determine the time-space variability of components of the hydrologic cycle, and to examine regional implications versus localized differences in forested versus deforested areas. Recent modeling and site-specific observational efforts have suggested that the effects of land cover change from biomass burning and deforestation may play a major role in the climate and hydrologic cycle. One of the most active regions of biomass burning and deforestation is located in South America, yet very little is known concerning the environmental implications of these activities in the Amazon Basin.

Two particular months, June and October (months prior to and following the peak biomass burning and deforestation activities in the Amazon) are under current investigation during 1988 and 1995. Rainfall rates,

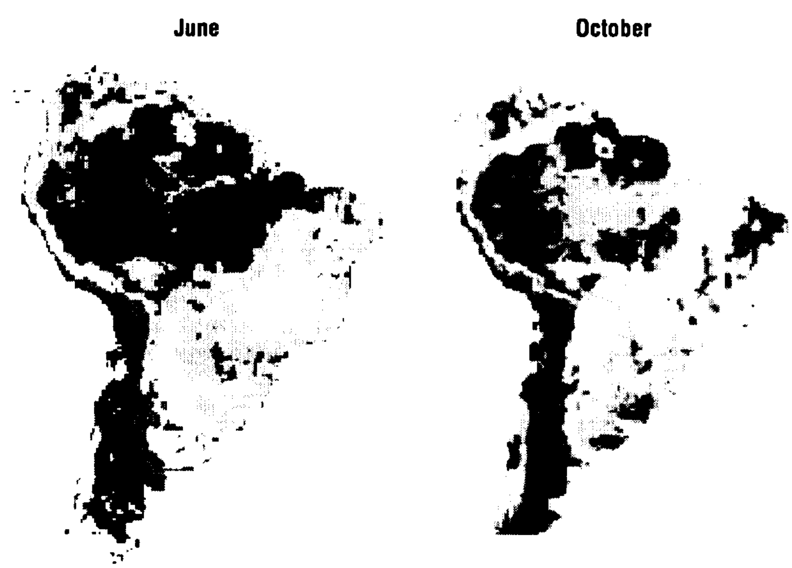

FIGURE 152.—Five-year climatology of Normalized Vegetation Index (NDVI) from AVHRR.

total precipitable water, and land surface temperature changes are being calculated from Geostationary Operational Environmental Satellite (GOES–7), Visible Infrared Spin Scan Radiometer (VISSR), Atmospheric Sounder (VAS), and GOES–8 Imager, while the vegetation state is characterized from the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) vegetation index. Conventional data (e.g., raingage and hydrologic data) is being used to verify and supplement satellite-derived parameters of the hydrologic cycle. The study will provide a regional view of the moisture cycle, document the variability across the region, investigate the enhanced capabilities of GOES–8 versus GOES–7, and evaluate the possible hydrological signatures associated with deforestation activities. This research began as part of Dr. DeLiberty's National Research Council Associate Programs at the University of Wisconsin, and she continues collaboration with researchers at the Center for Meteorological Satellite Studies. The aim is to extend the period of study to include several years to perform a trend analysis of the hydrologic cycle of the Amazon spanning a decade.

Specifically relating to the hydrologic component total precipitable water, researchers at the University of Delaware hope to enhance the PSW by improving the cloud filtering algorithm and incorporating the vegetation index which would vary spatially and temporally to provide a better estimate of surface emissivity.

Initial results from the examination of 1988 and 1995 will hopefully be submitted for publication early this winter.

Previous work of Dr. DeLiberty has entailed examination of the moisture budget, specifically with precipitation and soil moisture, in the Southern Great Plains. The GHCC scientists involved have focused on the evaluation of precipitable water algorithms and of infrared sensor capabilities.

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Sponsor: Office of Mission to Planet Earth

University/Industry Involvement:
University of Delaware, Geography Department

Biographical Sketch: Anthony Guillory is an atmospheric scientist in the Earth System Science Division at MSFC's Global Hydrology and Climate Center. He conducts scientific research using measurements from satellites, aircraft, and ground-based systems to study the Earth's hydrologic cycle. Guillory earned his M.S. degree in meteorology from the Florida State University in 1991 and has worked for NASA for 5 years.

High-Resolution Infrared Atmospheric Remote Sensing and Applications

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Unique high-spatial resolution measurements of the Earth are made with the airborne Multispectral Atmospheric Mapping Sensor (MAMS) in support of NASA's Mission to Planet Earth Program. The MAMS is a multispectral scanner that flies on board an ER2 high-altitude aircraft and measures reflected radiation from the Earth's surface and clouds in eight visible-near-infrared channels and thermal emission from the surface, clouds, and atmospheric constituents (primarily water vapor) in four infrared bands. The airborne scanner is used to make unique measurements of the atmospheric hydrologic cycle. The scanner views a 37-km-wide scene of the Earth from the ER2 altitude of about 20 km. Each MAMS footprint (individual field-of-view) has a horizontal resolution of 100 m at nadir. Since the ER2 travels at about 208-m/sec, a swath of MAMS data 37 by 740 km is collected every hour. The nominal duration of an ER2 flight is 6 hr (maximum of about 7 hr). The instrument is managed by MSFC and maintained by NASA's Ames Research Center.

A number of geophysical parameters important in studying the Earth's hydrologic cycle can be derived from the MAMS data. The resolution of each product varies with the desired parameter. Table 11 lists the parameters that can be derived from MAMS. Precipitable water and skin temperatures (land or sea surface) are derived with a physical split window algorithm.[1, 3, 5] The accuracy of precipitable water ranges between 2 to 5 mm (root mean square error) based on the MAMS calibration, quality of the first guess, the desired spatial resolution, and the sounding environment (poor performance occurs where temperature inversions exist). Sea surface temperature is retrieved quite accurately and not subject to the temperature inversion problem. Varying surface emissivity over land influences the quality of the land surface temperature retrieval. The Normalized Difference Vegetation Index (NDVI) is calculated from the ratio of visible to near-infrared channels as with LANDSAT and SPOT satellites. The absolute accuracy of NDVI depends on the channel gains and the pre-/post-flight calibration of the visible channels.[2] Upper-level humidity is retrieved with an empirical method.[4] Accuracy of the humidity field varies with MAMS calibration and the quality of locally generated retrieval coefficients. Clouds can be detected quite well with the multispectral channels of MAMS (even thin cirrus). The accuracy of cloud-top temperature and height assignment varies with MAMS absolute calibration and cloud emissivity. Absolute calibration degrades at cold temperatures and therefore cloud top information is the least accurate for the tallest (coldest) clouds.

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Table 11.—*MAMS-derived parameters and their accuracy.*

Parameter	Resolution	Coverage	Accuracy
Total Precipitable Water	250–1,000 m	Over Entire Image	2–5 mm rms
Land Surface Temperature	100–300 m	Over Entire Image	0.1–1.0 K (Relative) 0.5–6.0 K (Absolute)
Sea Surface Temperature	100–300 m	Over Entire Image	0.1 K (Relative) 0.1–1.0 K (Absolute)
Normalize Difference Vegetation Index (NDVI)	100–300 m	Over Entire Image	5% (Relative) 5–30% (Absolute)
Upper-level Humidity (In Weighting Function Layer)	100–300 m	Over Entire Image	1–2% (Relative) 5–10% (Absolute)
Clouds			
– Detection	100–200 m	Over Entire Image	99% Efficiency
– Mean Top Temperature	100–200 m	Where Cloud Present	0.5 K (Relative) 0.5–6.0 K (Absolute)
– Mean Height (Pressure)	100–200 m	Where Cloud Present	50 mb (Relative) 50–200 mb (Absolute)

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[5]Suggs, R.J.; Jedlovec, G.J.: "Evaluation of a Split Window Technique for the Retrieval of Geophysical Parameters From GOES." In preparation for *Journal of Applied Meteorology*, 1996.

Sponsor: Office of Mission to Planet Earth

Biographical Sketch: Dr. Gary Jedlovec is an atmospheric scientist in the Earth System Science Division at MSFC's Global Hydrology and Climate Center. He conducts scientific research using measurements from satellites, aircraft, and ground-based systems in order to study the Earth's hydrologic cycle. Dr. Jedlovec earned his Ph.D. degree in meteorology from the University of Wisconsin–Madison in 1987 and has worked for NASA for 11 years.

Testing Global Warming Theory With Satellite Passive Microwave Observations

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Satellite passive microwave data contain valuable information on the workings of Earth's climate system. Specifically, temperature and water vapor data are being utilized to better understand how the climate system responds to natural forcings so that better estimates of global warming can be made. These satellite data are having increasing impacts in the science and policymaking communities through new climate diagnostic studies and an 18-year record of global temperatures.

The microwave sounding units (MSU) on the National Oceanic and Atmospheric Administration's TIROS-N series of polar-orbiting satellites are supporting the only global temperature monitoring effort in existence. An 18-year record (1979 to present) of global lower tropospheric and lower stratospheric temperatures continues to be updated on a monthly basis (fig. 153). Careful intercalibration of a total of eight separate satellites' instruments was necessary to achieve a data record having sufficient precision to calculate long-term trends in global temperatures. This record has been independently validated with radiosonde (weather balloon) data which has revealed excellent agreement. This validation has now been extended through 1994. Several types of temperature data sets have been developed and made available to the global research community, and have formed the basis for numerous published research studies. For example, the seasonal and geographical distribution of lower stratospheric cooling has been linked to total ozone mapping spectrometer (TOMS) trends in total column ozone, thus providing independent validation of global ozone depletion. The development of the method, first published by R. Spencer of NASA and J.R. Christy of the University of Alabama in Huntsville in 1979, was recognized in January 1996 with the American Meteorological Society's (AMS) Special Award. This award was the first given by the AMS for the development of a satellite method for monitoring climate fluctuations.

The global temperature record is often cited by skeptics of global warming because it has not yet indicated a warming trend since 1979. Because the surface thermometer data have indicated a small global warming trend for the same period, several groups are now actively involved in understanding why the two data sets do not agree. Based upon our recent research, it appears that the satellite measurements, which represent a deep layer of the atmosphere, are indicating that temperature fluctuations can change with height in the atmosphere. As a result, decadal trends of surface thermometer data probably can not be expected to agree with the satellite trends to better than about 0.1 to 0.2 °C per decade. This is contrary to expectations of many climate researchers, though there has not been any observational basis for that expectation, only theoretical. Because computerized general circulation models (GCM's) suggest that any warming will increase in magnitude with height, combined with the known tendency for surface temperature data to be susceptible to localized effects, we believe the satellite data will be increasingly relied upon for first signs of global warming due to its larger signal-to-noise ratio. Indeed, new analytical techniques we are utilizing to retrieve temperature trends as a function of height are suggesting that the global upper troposphere has warmed substantially in the last 18 years. But, combined with the lower tropospheric cooling trend indicated in the same data, it now appears that the climate system is more complex in its behavior than was previously appreciated. This should not be too surprising, though, since moist convective processes (clouds and rainfall) that transport excess surface heat to high in the troposphere, are not well represented in GCM's.

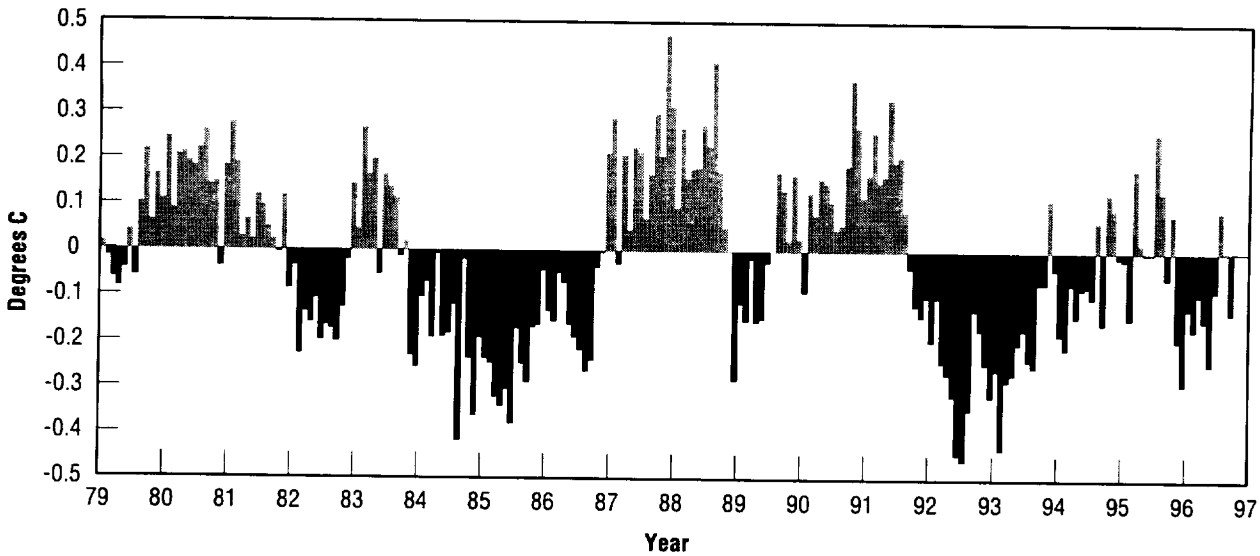

Figure 153.—Global lower tropospheric temperatures (1979 through 1996).

With the approaching implementation of the United Nations framework convention on climate change (FCCC), the satellite temperatures will likely be central in the argument against hasty action to curb emissions of carbon dioxide, the leading contributor to the enhanced greenhouse effect. Because protocols implemented under the FCCC treaty could have huge economic consequences, the satellite temperature monitoring effort is having a direct impact on the economies of the United States and the world.

Central to global warming theory is the existence of "positive water vapor feedback." This is a process wherein the small amount of warming initiated by increasing levels of carbon dioxide in our atmosphere is amplified by increasing levels of water vapor (the Earth's main greenhouse gas) that is expected to occur in response to the initial warming. This sets up a positive feedback loop which results in water vapor feedback being responsible for most of the warming in future projections of global warming. While this feedback is likely to be positive in the turbulent boundary layer, it is much less certain whether it exists at all in the free troposphere above the boundary layer. We are utilizing new observations from the water vapor sounder (SSM/T–2) instruments that flew on the defense meteorological satellite program's (DMSP) F11 and F12 satellites. We have assembled the only complete record of SSM/T–2 data since 1993, and have focused on the relationship between sea surface warming and free tropospheric humidity in the tropics. During the 1993 to 95 period, a warming occurred as the Earth emerged from the cooling effects of the 1991 eruption of the Mt. Pinatubo volcano. During this warming we found no evidence of positive water vapor feedback in the tropical free troposphere. However, this might not necessarily represent the climate system's response to increasing levels of man-made greenhouse gases, and so additional years of data will be required to determine whether water vapor feedback varies between different types of climate fluctuations. An interesting spinoff of the water vapor work has been the discovery that the tropical free troposphere is, for the most part, extremely dry (Spencer and Braswell, 1996). We find peaks in the daily frequency distribution of tropical gridpoint relative humidity between 5 and 10 percent. This new finding will have important implications for how GCM's control humidity, since small fluctuations in humidity at such dry levels can have huge impacts on outgoing longwave radiation, the type of radiation central to global warming theory.

The satellite passive microwave observations of deep-layer atmospheric temperature and water vapor will continue to have a large impact on our understanding of how the Earth's climate system operates. This understanding will lead to improvements in GCM's and in their predictions of future global warming.

Spencer, R.W.; Christy, J.R.; Grody, N.C.: Analysis of "Examination of 'Global Atmospheric Temperature Monitoring with Satellite Microwave Measurements.' " *Climatic Change*, vol. 33, pp. 477–489, 1996.

Spencer, R.W.; Braswell, W.D.: "How Dry is the Tropical Free Troposphere? Implications for Global warming Theory." Bulletin of the American Meteorological Society, submitted, 1996.

Sponsor: Office of Mission to Planet Earth

University/Industry Involvement: The University of Alabama in Huntsville; Nichols Research Corporation

Biographical Sketch: Dr. Roy W. Spencer (AST, Atmospheric Measurements) has been employed by MSFC for 10 years, and leads a passive microwave research group that performs research and provides data sets to the climate research community. He received his Ph.D in atmospheric science from the University of Wisconsin in 1981.

Sensing Sea Surface Winds With Passive Microwave Techniques

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The turbulent interactions of the two fluid bodies representing the Earth's atmosphere and its oceans are key parameters affecting regional weather, ocean circulation, and global climate. One agent of this interplay is the atmospheric wind blowing across an ocean surface which transports energy, moisture, and gases between the two fluids. Thus, a true understanding of the air-sea interface relies upon being able to quantify the strength and direction of sea surface winds blowing over the entire globe. Real-time mapping of near-surface ocean winds also provides crucial information for the commercial and military seafaring vessels navigating the world's open seas.

Historically, ocean buoy and ship measurements have been the primary source of marine wind speed and direction. These discrete point sources, however, do not provide the uniform global coverage required for near-surface ocean wind mapping. In recent years, active and passive microwave radiation detection methods have shown great promise in providing this global coverage from spaceborne platforms. Both techniques rely on detecting wind-generated changes to ocean wave structures. Active microwave sensors called scatterometers are currently flying on satellites which can remotely sense both ocean wind speed and direction while passive microwave instruments called radiometers are measuring only wind speed from present day satellites.

The next evolutionary step to sea surface wind measurement from space is the development of passive microwave radiometers which could retrieve both wind speed and direction. As technology improves, this goal appears to be more attainable than had been previously envisioned. Shrinking governmental budgets have, in turn, made this goal a necessity for future satellite programs because radiometers can be built with significantly less expense than can scatterometers.

To help determine the feasibility of this goal, a prototype satellite instrument is currently being developed by Marshall to passively sense both sea surface wind speed and direction. The instrument is called the conically-scanning two look airborne radiometer (C-STAR). It has been designed to test spaceborne measurement techniques from a NASA high-altitude aircraft flying at a nominal altitude of 20 km. C-STAR will scan beneath the aircraft in a circular pattern subtended by an angle of 53 degrees from the aircraft nadir. Microwave radiation naturally emitted by the Earth and its atmosphere at a 37.1 GHz frequency will be detected by four receivers aligned to intercept energy at four different polarizations (i.e., horizontal, vertical, +45 degrees from vertical, and –45 degrees from vertical). By comparing data imagery collected at different segments of the circular scan as well as at different polarizations, the anisotropic nature of the radiometric signature of the sea surface wind should be revealed.

The first test flights of the C-STAR will take place in early 1997 off the western coast of the United States. The aircraft missions will be flown over ocean buoy sites providing ground truth wind vector (i.e., speed and direction) measurements. These ground truth data will validate and quantify the magnitude of the sea surface wind signals mapped by the C-STAR imagery. This investigation will highlight the capabilities and limitations of near surface ocean wind vector retrievals which could be derived from satellite passive microwave imagery. This type of knowledge is important to the planners and designers of future spaceborne instrumentation who have the dual challenge of seeking to increase our understanding of the Earth's weather and climate while being mindful of cost-efficient measures.

Sponsor: Center Director's Discretionary Fund; Office of Mission to Planet Earth; National Polar-orbiting Operational Environmental Satellite System

Industry Involvement: Hughes STX Corporation; Mevatec Corporation

Biographical Sketch: Robbie Hood is an atmospheric scientist within the Earth System Science Division of the MSFC's Space Sciences Laboratory. She manages high-altitude aircraft field experiments supporting the passive microwave measurement research activities of the Earth System Science Division. Hood earned her B.S. in atmospheric science from the University of Missouri and an M.S. in physical meteorology from the Florida State University. She has been with MSFC for 9 years.

Remote Sensing of Winds Using Airborne Doppler Lidar

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The wind occupies a central role in weather and climate, and its effects can be observed over a wide range of spatial and temporal scales. The wind transports heat, moisture, momentum, radiatively-active trace gases, biogeochemicals, and microscopic particles (aerosols). This redistribution and the interaction with latent heat and radiation produce weather and climate. On a daily basis these interactions can take the form of processes and features that are easily recognizable, such as convection and clouds, precipitation, jet streams, extratropical cyclones, and hurricanes.

For nearly 30 years, coherent Doppler lidar (or laser radar) has been used to remotely sense the atmospheric wind. Lidar is an acronym for light detection and ranging. The term "coherent" refers to the use of the phase information in the outgoing and incoming radiation. During lidar operation a pulse of light is emitted from the laser, scattered backward along the line of sight by clouds, dust, or other aerosols, and a Doppler frequency shift imparted by the relative motion of the scatterers. The lidar receiver converts the signals to line-of-sight (LOS) velocity as a function of range. Doppler lidar measures signals primarily from optically clear air, however velocities can be measured within or through thin clouds. Doppler lidar has a demonstrated capability to measure atmospheric dynamical processes and features over locations and scales of motion that are frequently beyond the measurement capabilities of conventional sensors. When placed on an aircraft, the measurement capability of Doppler lidar is enhanced considerably.

Scientific recognition of the relative contribution of small-scale atmospheric processes, and in particular their interaction with large-scale processes, has grown over the past 10 to 15 years. In parallel, technological advances in high-energy lasers have expanded the potential of Doppler lidar remote wind sensing for atmospheric research. The lidar remote sensing groups of MSFC, NOAA Environmental Technology Laboratory (ETL), and Jet Propulsion Laboratory (JPL) developed an airborne scanning Doppler lidar termed the multi-center airborne coherent atmospheric wind sensor (MACAWS). The centerpiece of MACAWS is a high-energy CO_2 gas laser, making this perhaps the most powerful Doppler lidar developed for airborne atmospheric research. MACAWS has the key capability to measure winds remotely over a three-dimensional volume. During operation, pulses of eye-safe laser radiation (or "beams") are directed into the atmosphere through the left side of the aircraft using a pair of internally mounted, counter-rotating germanium prisms. By refracting the lidar beam forward and aft of the aircraft heading in an alternating manner such that the LOS velocity vectors fall within a common plane, two-dimensional wind velocities may be calculated at points of intersection between the forward and aft-pointing beams (fig.154). The contribution to the Doppler shift along the line of sight due to scan angle and aircraft attitude and speed are removed by using measurements from a dedicated inertial navigation system located near the scanner. The net results are measurements of ground-relative wind velocity. The vertical distribution of wind and aerosols over a three-dimensional volume may be obtained by scanning at multiple levels with arbitrary angular separation (fig. 155).

MACAWS was flown on a short series of science demonstration flights for the first time in September 1995 aboard the NASA DC–8 research aircraft. Missions were conducted over the western United States and eastern Pacific Ocean. Highlights included the first airborne simulation of a satellite Doppler wind lidar, and the first Doppler velocity measurement within a

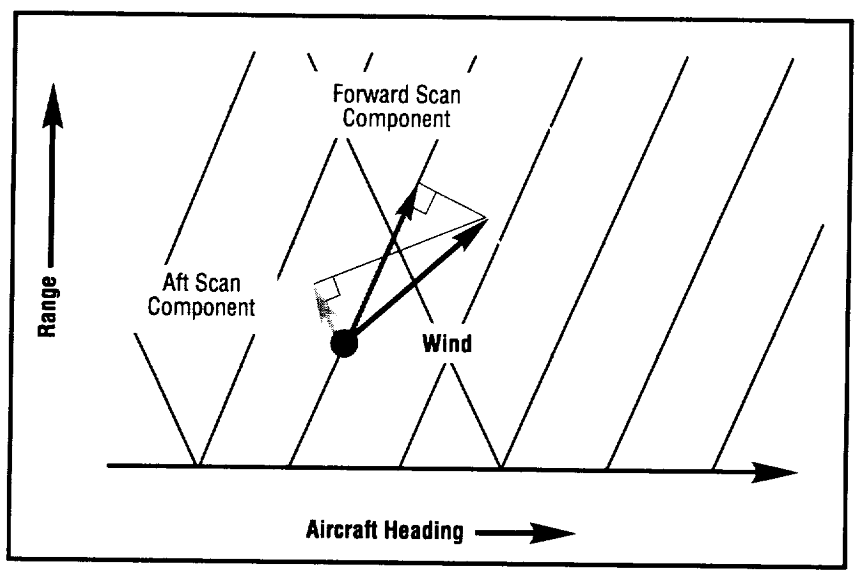

Figure 154.—Co-planar scanning method for obtaining two-dimensional wind field measurements. Scanner alternately directs lidar beam forward and aft of aircraft heading; two-dimensional wind vectors are calculated using trigonometry.

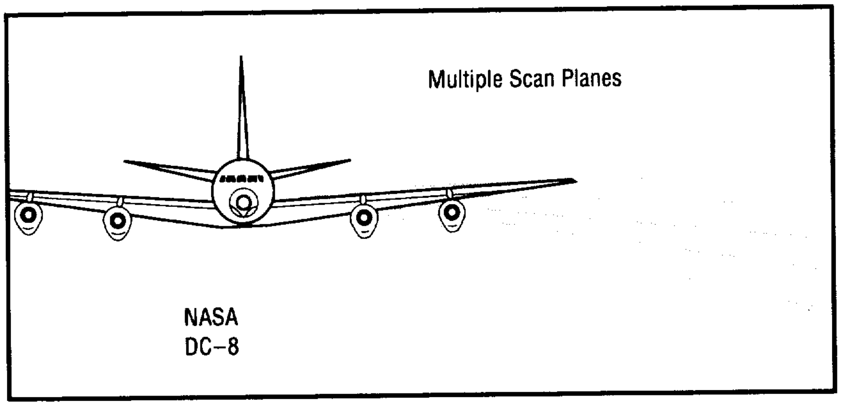

FIGURE 155.—Method for obtaining volumetric coverage of wind measurements by generating multiple two-dimensional scan planes. Depending on slant range, intervening atmosphere, and other factors, scan planes inclined below horizon may terminate with surface returns.

hurricane. An example of multilevel wind measurements in the Pacific marine boundary layer is shown in figure 156. Additional flights were made in June 1996 over the Pacific northwest and central United States. Highlights included the first Doppler lidar intercomparison with near-sea wind surface measurements by a space-borne scatterometer, ERS–2.

Observing system simulation experiments (OSSE's) indicate that global wind measurements from space with Doppler lidar will significantly improve the understanding of the atmosphere while simultaneously improving the capability to make better forecasts. In the absence of a heritage of satellite Doppler lidar wind measurements, performance simulations with measured—rather than simulated—data are highly desirable to reduce modeling uncertainties and to begin to develop the necessary interpretive skills. Ground-based lidar measurements alone do not address all design and performance-related issues. Measured data are invaluable for evaluating and improving OSSE's, which are used to quantify the benefit of lidar compared to existing measurement systems. The results of such simulations critically depend on instrument design, which is currently focused on instruments in the small-satellite class. Constraints on satellite power, mass, volume, and heat rejection must be carefully evaluated against performance. Through appropriate aircraft maneuvers, MACAWS can simulate the Doppler wind lidar perspective from space in order to address a variety of issues, including optimum scanning strategies, verification and improvement of Doppler signal processing algorithms, velocity retrievals at marginal signal levels, impact of spatial wind variability, effect of aerosol vertical gradients, velocity distribution in and around clouds, and Doppler velocity correction using land and ocean surface returns. Clouds will constitute a frequent scattering target for spaceborne lidar; annually over 60 percent of the globe is covered by cloud of some type at some level. MACAWS can be used to assess cloud porosity, cloud-free line-of-sight, cloud dimensions, and optical properties. All of these factors must be taken into account when assessing the representativeness of satellite Doppler lidar wind measurements, and ultimately the impact of these measurements on climate and global change studies and numerical weather prediction.

Long-term applications of MACAWS measurements will address a broad range of issues in atmospheric dynamics, climate,

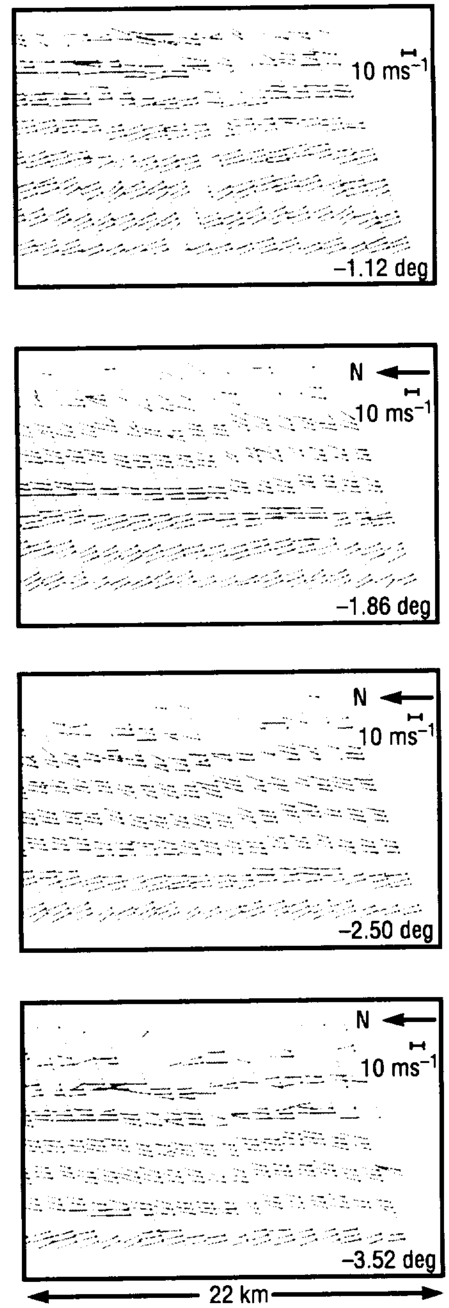

FIGURE 156.—Wind measurements in the marine boundary layer over the Pacific Ocean near the northern coast of Oregon; wind vectors point into the wind. Figure shows vertical distribution of winds measured within four scan planes. Aircraft altitude was ~900 m (3,000 ft) above sea surface, and approximately 100 m (330 ft) above the top of the boundary layer.

and hydrology, including the role of unresolved processes in hydrological and climate numerical models, improvement in mesoscale modeling and predictive capabilities, and more realistic simulations of prospective satellite Doppler wind lidar. MACAWS will be used as part of the validation effort for the NASA scatterometer (NSCAT) which measures global sea surface winds. Moreover, plans include studies of extreme weather phenomena which can affect sustainable growth.

Sponsor: Office of Mission to Planet Earth

University/Industry Involvement:
Dr. Dean R. Cutten, University of Alabama in Huntsville; Dr. R. Michael Hardesty, National Oceanic and Atmospheric Administration; Dr. Robert T. Menzies, Jet Propulsion Laboratory

Biographical Sketch: Dr. Jeffry Rothermel is an atmospheric measurement specialist within the Earth System Science Division of MSFC's Space Sciences Laboratory. He leads an intergovernmental agency team which conducts airborne atmospheric research, and satellite validation and simulation using a jointly developed coherent Doppler laser radar. Rothermel also leads a team within ESSD which conducts observations and modeling of aerosol properties with the goal of better quantifying direct and indirect aerosol effects on climate and global hydrology. Rothermel earned a Ph.D. (atmospheric science) from Purdue University, and has been with MSFC for 7 years.

Remote Sensing of Aerosol Composition From CO_2 Lidar Backscatter

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A high resolution technique for remote sensing atmospheric aerosol composition from aerosol backscatter measurements is being developed using a new infrared, wavelength-tunable, coherent, continuous-wave, focused, CO_2 Doppler lidar to be used as a "spectrometer." Such an instrument, applicable both for airborne as well as ground-based operations, has not been developed before.

The basis of this new instrument rests on the spectral response of backscatter in the middle infrared (9 to 11 μm) regime which is extremely sensitive to aerosol composition. This is due to material resonance anomalies in absorption which causes peaks in backscatter spectrum at specific infrared wavelengths, characteristic of complex refractive indices of aerosol composition. As an example, ammonium sulfate has a peak at the 9.1-μm wavelength but not at the 10.6-μm wavelength which gives rise to a difference in backscatter of a factor of 9 for typical atmospheric particle diameter <0.8 μm found in the middle and upper troposphere. Using this fact, a new method is being developed to infer aerosol composition from the measured wavelength-dependent backscattered signal using a rapid-tunable, multiwavelength continuous wave (CW) CO_2 lidar. This would allow identification of climatically significant atmospheric aerosols such as sulfates, sulfuric acid, dust, sea salt, water, and ice which have a specific signature in the 9 to 11 μm from their absorption spectra and hence backscatter spectra. Multiple wavelength tunability will also enable distinction between hygroscopic and nonhygroscopic aerosols, enabling identification of cloud condensation nuclei (CCN). This characterization is important for understanding and modeling of cloud microphysics, precipitation and hydrological cycle. This new application of a single lidar as a "spectrometer" for remotely inferring aerosol compositions offers many important advantages over existing aerosol chemistry sensors:

- It samples aerosols remotely, thereby, avoiding any physical and chemical contamination that are associated with aspirated samples;
- It provides much larger sample volumes with fewer particle count statistics problems than particle counters; and
- It offers large-scale atmospheric sampling with unprecedented high-spatial/temporal resolution (~5 sec ~1 km) even in quite low-aerosol concentrations, and could give even finer resolution in higher concentrations.

The proof of concept has been recently demonstrated with the comparison of dual-wavelength lidar backscatter data obtained by two NASA/MSFC CO_2 Doppler lidars operating at wavelengths 9.1 and 10.6 μm to identify sulfate aerosols.[1] The validity of inferring aerosol composition from the relative backscatter at several wavelengths is shown in figure 157. Figure 157 shows atmospheric measurements during the global backscatter experiment (GLOBE II) in 1990 taken at an 8-km altitude in transit from Tokyo, Japan to Honoulu, Hawaii. The backscatter ratio β_R is defined as the ratio of backscatter β at the lidar wavelengths 9.1 and 10.6 μm, given by $\beta_R = \beta(9.1)/\beta(10.6)$. For $\beta_R > 2$ indicates presence of sulfate composition. The direct lidar measured β_R is compared with modeled β_R using simultaneously measured aerosol microphysics data by a laser optical particle counter (LOPC). The state-of-the-art LOPC aerosol counter measures real-time aerosol distribution and composition from which β_R can be modeled using Mie theory, the electromagnetic scattering from a dielectric sphere. The modeled LOPC β_R and measured lidar β_R agree very well, showing overall similar trends. In view of the major differences in the lidar versus aerosol counter instrumentation and sampling, this reasonably good agreement indicates that

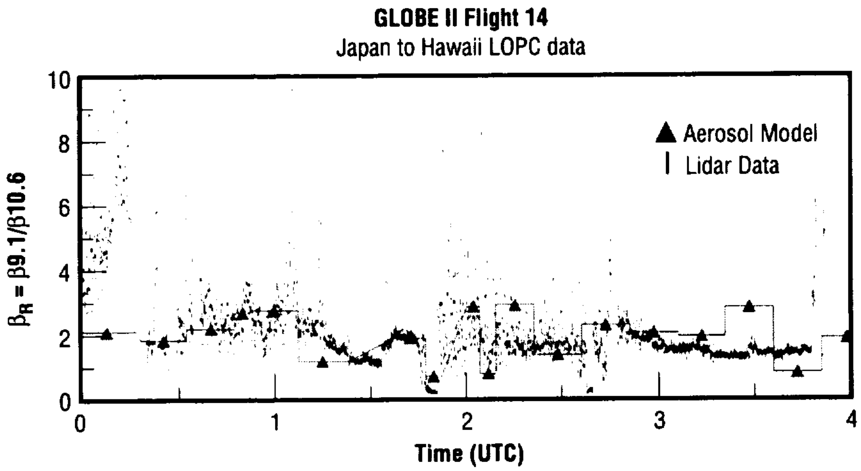

FIGURE 157.—Time series of backscatter ratio $\beta_R = \beta$ (9.1)/β (10.6) from lidar data in comparison with that obtained from the modeled results from the laser optical particle counter (LOPC).

measurements of composition from LOPC can be used to predict β_R; thus inversely measured lidar β_R can lead to good inference of aerosol composition.[1]

There is a critical need to determine aerosol composition variability on a regional as well as global scale as it can have major impact on the Earth's radiative balance, affecting climate. The emphasis within NASA on remote sensing of various atmospheric constituents motivates a deeper understanding of composition of atmospheric aerosols for better inputs to circulation models. This wavelength-tunable lidar provides an innovative technology for application of a lidar in remotely inferring atmospheric aerosol composition on a large scale with very high spatial and temporal resolution. This will thus strengthen NASA's role on characterization of climatically significant aerosols.

[1]Srivastava, V.; Bowdle, D.A.; Jarzembski, M.A.; Rothermel, J.; Chambers, D.M.; and Cutten, D.R.: "High Resolution Remote Sensing of Sulfate Aerosols From CO_2 Lidar Backscatter." Geophysical Research Letter, 22, pp. 2373–2376, 1995.

Sponsor: Center Director's Discretionary Fund

Biographical Sketch: Dr. Maurice Jarzembski earned a Ph.D. in physics from New Mexico State University and has been with MSFC for almost 8 years. He is a physicist within the Earth System Science Division of MSFC Science and Engineering Directorate and is in the field of remote sensing using lidars.

A Convective-Stratiform Rainfall Classifier for Composite Radar Reflectivity Maps

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The objective of this study is to develop an algorithm to characterize rainfall fields from a multiyear data base of high spatial and temporal resolution radar reflectivity measurements. The radar reflectivity data product, referred to as NOWRAD, is composited in real-time from the U.S. National Weather Service network of WSR–57, WSR–74 and WSR88–D radars and provided to us by Weather Services, Inc. The spatial resolution of each pixel is 2 km across the United States with a temporal resolution of 15 min.

The individual images are classified into convective and stratiform rainfall components. The integration of the 96 images received each day yields a daily rainfall estimate. Daily rainfall estimates are next integrated into monthly and seasonal estimates. These data sets are then to be used to examine the natural variability of rainfall in the United States from year to year during the period 1994 through 1996. Convective and stratiform rainfall regions are identified and then partitioned into convective and stratiform rainfall using two Z-R relationships.

A training data set using 10 days in April 1994 was used to develop and test the methodology. Two case studies were then examined from rainfall episodes on April 11, 1994, and April 21 and 22, 1994, within the Arkansas-Red River Basin to assess the algorithm performance. The first objective was to establish a threshold function to select convective centers. Next, the gradient between each pixel and its neighbors was computed to isolate these centers. The neighborhood reflectivity was

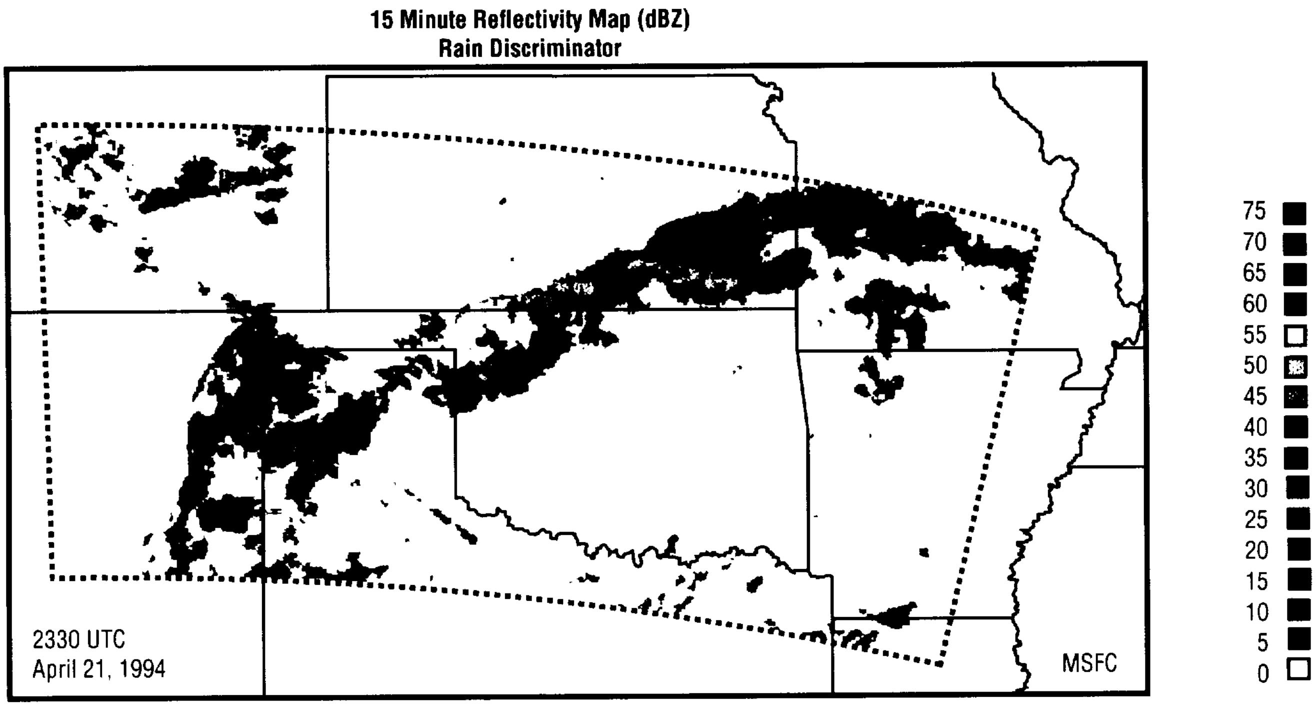

FIGURE 158.—NOWRAD composite reflectivity for the Red River Basin domain at 2,300 UTC on August 21, 1994. The area enclosed by the dotted line represents the basin.

specified to be the linear average of nonzero reflectivities, Z, in a 100 km^2 region centered at any pixel. Finally, the rainrate, R, in convective and stratiform rain areas is performed with $Z=300R^{1.4}$ applied to the convective areas and $Z=200R^{1.6}$ applied to the remaining rain areas.

Figure 158 shows the basin domain and reflectivity observed at 2,330 UTC on April 21, 1994. Figure 159 shows the area-averaged hourly rainfall estimates derived from the NOWRAD (NRD) data for the entire month, and separated into convective (CNV) and stratiform (STR) components. These estimtes are compared with the NWS Stage-III River Forecast Center (RFC) rainfall estimates during the same time period. The hourly RFC estimates are derived from raingage-adjusted WSR88-D reflectivity fields. The trends in both estimates are similar and the differences over the basin are a few millimeters per day (fig. 160).

Our initial attempt at classifying rainfall over one large river basin on a monthly time period is promising. Our 28-day sample data set for April shows low RMSE values of 0.12 mm (or 45 percent of the Stage-III

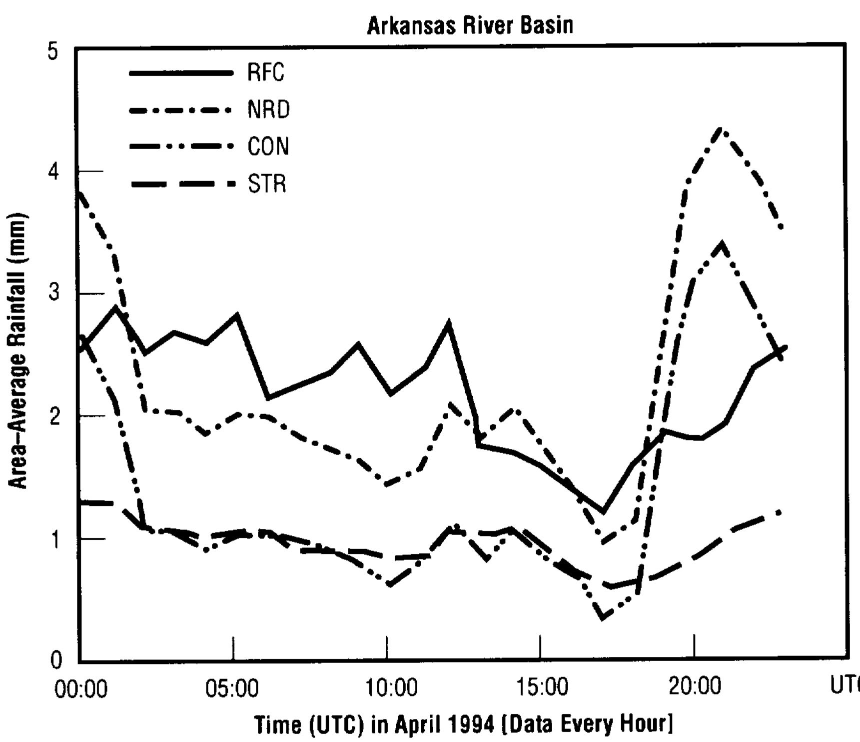

FIGURE 159.—Area-averaged hourly rainfall for April 1994 over the Red River Basin.

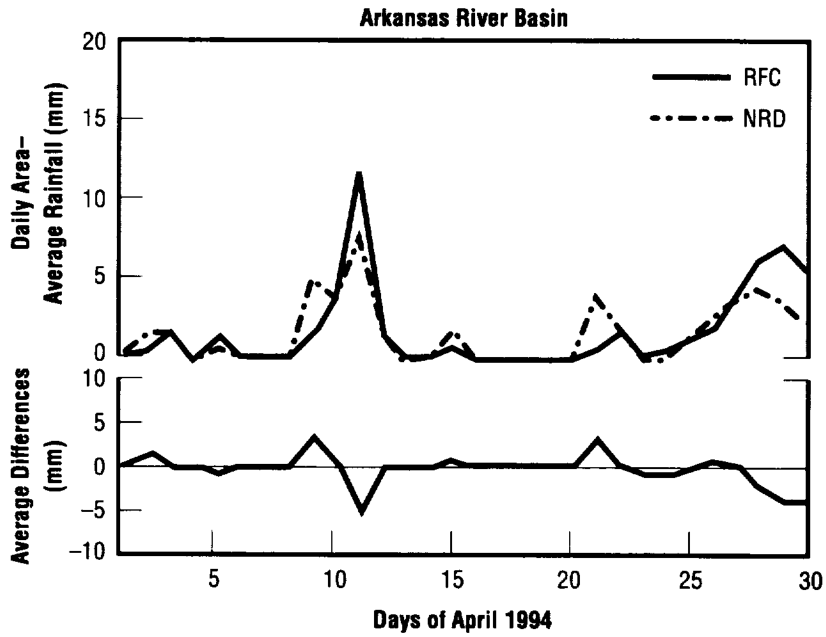

Figure 160.—Daily area-averaged rainfall over the Red River Basin for April 1994. The difference between the Stage-III (RFC) and the NOWRAD (NRD) estimates is also shown.

area-averaged hourly mean rainfall) with a bias of 0.01 mm. It appears that the methodology should produce sufficiently accurate estimates of rainfall over large spatial domains and over multiyear time periods to characterize the year-to-year differences in rainfall. These rainfall distributions and characterizations can be used by MTPE scientists as input or validations to regional modeling experiments to learn more about the seasonal-to-interannual behavior of rainfall and its response to larger scale atmospheric forcing. This data base may also be of use in recomputing extreme rainfall statistics for improved water management models and decision aids.

Crosson, W.L.; Duchon, C.E.; Raghavan, R.; Goodman, S.J.: "Assessment of Rainfall Estimates Using a Standard Z-R Relationship and the Probability Matching Method Applied to Composite Radar Data in Central Florida." *Journal of Applied Meteorology*, 35, pp. 1203–1219, 1996.

Sponsor: Office of Mission to Planet Earth

University/Industry Involvement: Ravi Raghavan, Universities Space Research Association (USRA)

Biographical Sketch: Dr. Steven Goodman is an atmospheric physicist within the Space Sciences Laboratory of the MSFC Science and Engineering Directorate and the Global Hydrology and Climate Center. His research interests are in cloud precipitation and electrification processes and their regional, global, and interannual variability. He serves as a member of the EOS lightning imaging sensor instrument team and as the project scientist for the LIS science computing facility. Dr. Goodman has a B.A. in atmospheric and oceanic science, an M.S. in atmospheric science, and a Ph.D. in systems engineering. He has been with MSFC since 1981.

The Lightning Imaging Sensor on the Tropical Rainfall Measuring Mission

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The lightning imaging sensor (LIS) is a small, calibrated optical instrument designed to investigate the global incidence of lightning, its correlation with ice and precipitation, and the global electric circuit. Conceptually, LIS is a simple device, consisting of a staring imager optimized to detect and locate intracloud and cloud-to-ground lightning with storm scale resolution over a large region of the Earth's surface, to mark the time of occurrence, and to measure the radiant energy. From the tropical rainfall measuring mission (TRMM) orbit, it will monitor individual storms within its field of view (FOV) for over 60 sec, long enough to estimate the lightning flash rate. Location of lightning flashes will be determined to within 5 km over a 600- by 600-km FOV.

The LIS design uses an expanded optics wide-FOV lens, combined with a narrow-band interference filter that focuses the image on a small high-speed, charge-coupled-device focal plane. The signal is read out from the focal plane into a real-time event processor for event detection and data compression. The sensor design results from the requirement to detect weak lightning signals during the day when the background illumination, produced by sunlight reflecting from cloud tops is much brighter than the illumination produced by lightning.

A combination of four methods is used to take advantage of the significant differences in the temporal, spatial, and spectral characteristics between the lightning signal and the background noise. First, spatial filtering is used to match the instantaneous FOV of each detector element in the LIS focal plane to the typical cloud top illuminated area by a lightning event. Second, spectral filtering is applied, using a narrow band interference filter centered about the strong OI (1) emission multiplet in the lightning spectrum at 777.4 nm. Third, temporal filtering is applied. The lightning pulse duration is on the order of 400 μsec, whereas the background illumination tends to be constant on a time scale of seconds. The lightning signal-to-noise ratio improves as the integration time approaches the pulse duration. Accordingly, an integration time of 2 msec is chosen to minimize pulse splitting between successive frames and to maximize lightning delectability. Finally, a modified frame-to-frame background subtraction is used to remove the slowly varying background signal from the raw data coming off the LIS focal plane. If after background removal, the signal for a given pixel exceeds a specified threshold, that pixel is considered to contain a lightning event.

LIS investigations will further our understanding of processes related to, and underlying, lightning phenomena in the Earth/atmosphere system. These processes include the amount, distribution, and structure of deep convection on a global scale, and the coupling between atmospheric dynamics and energetics. Lightning activity is closely coupled to storm convection, dynamics, and microphysics, and can be correlated to the global rates, amounts, and distribution of precipitation, to the release and transport of latent heat, and to the chemical cycles of carbon, sulfur, and nitrogen. Lightning is an unique indicator of deep convection and is the only means presently available to detect deep convection from space without a land-ocean bias. In this way, LIS will strongly support TRMM studies of the hydrologic cycle. It will continue the development of a thunderstorm and lightning climatological data base that has been started by the Optical Transient Detector (OTD).

The OTD, a predecessor of LIS, was launched on April 3, 1995. It has completely validated the LIS design concept, providing unique lightning data to the scientific community. For the first time, global lightning is available with high-detection efficiency and spatial resolution.

Sponsor: Office of Mission to Planet Earth

Biographical Sketch: Dr. Hugh Christian is a senior research scientist with the Earth System Science Division. He obtained his Ph.D. in physics from Rice University in 1977 and began his career with Marshall in 1980.

Solid-State Lightning Field Sensor

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The primary goal of this project is to develop a new, ground-based, solid-state instrument for detecting thunderstorm electrostatic fields. An attempt will be made to extend detection into radio frequencies.

Electric field measurements are fundamental in diagnosing the electrical state of the atmosphere and the potential for lightning. Some adverse effects of lightning include: human fatality, electric power outages, forest fires, and hazards to aircraft and space vehicle operations. The NASA Kennedy Space Center (KSC) and the USAF Eastern Space and Missile Center (ESMC) currently operate and maintain a ground-based electric field mill network as a lightning warning system for space vehicle operations, including launch protection. Field mills and antenna systems that detect electric field changes represent the primary means for detecting lightning and other electrical phenomena in the atmosphere.

Generally speaking, these devices employ a flat plate antenna which, when exposed to the ambient field, becomes polarized. The amount of polarization charge induced on the plate is related to the ambient field strength. The induced charge (or current) can be amplified and recorded.

Anisotropic electro-optic crystals offer a different approach to sensing small electric fields. When a voltage is placed across a crystal (e.g., potassium di-hydrogen phosphate (KH_2PO_4, also known as KDP), barium titanate ($BaTiO_3$)) the refractive indices of the crystal change in a particular way. This change alters the polarization state of a laser light beam propagating down the crystal optic axis. Hence, with suitable application of vertical and horizontal

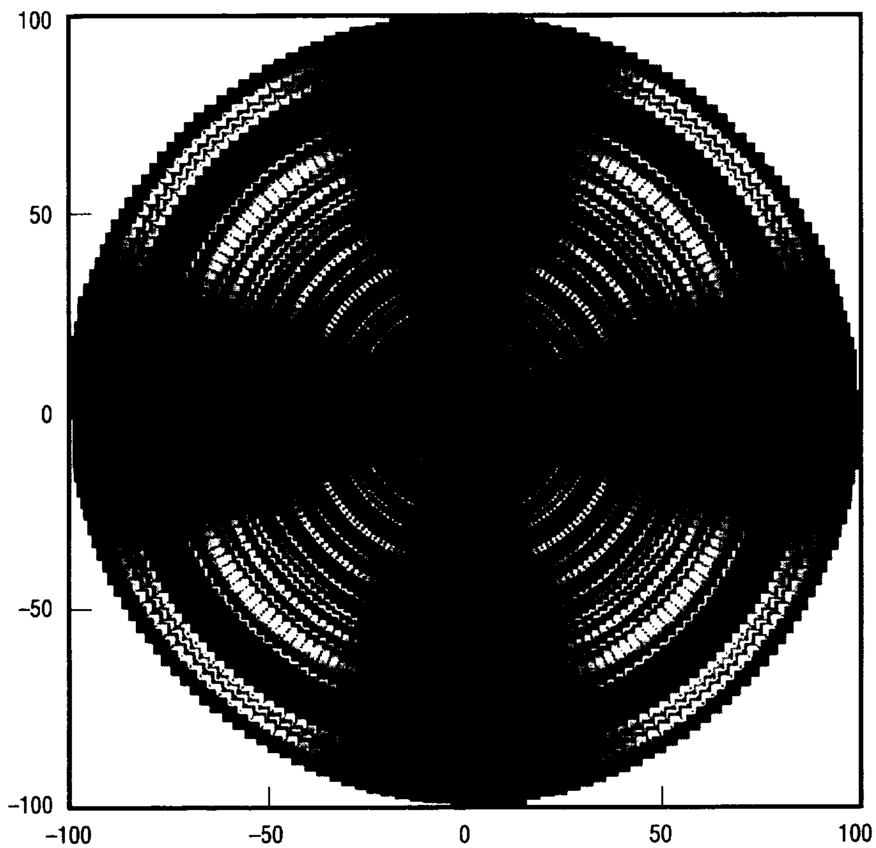

Figure 161.—Diffuse crystal output showing the isogyre pattern for a perfectly aligned optical system.

polarizers, a light transmission measurement can be related to applied crystal voltage (or electric field across the crystal). This is the basis of the solid-state lightning electric field sensor.

During the past year, all critical optics (i.e., KDP, polarizers, retarders, laser, filters, detectors) were procured and assembled, and a data acquisition system was integrated for breadboard testing of the crystal. In addition, fabrication of a three-axis crystal holder was completed for preliminary alignment tests. These tests were conducted by illuminating the crystal with a diffuse beam and inspecting the diffuse crystal output with a screen. The output of an aligned optical system is that of an isogyre pattern. Such a pattern was reproduced in the laboratory and was used to help align the optical system. Based on these tests, recommendations for final crystal holder requirements were completed and procured.

Preliminary sensitivity tests were conducted using the optical breadboard system, a 12-bit DT2833 analog-to-digital board, and Microcal Origin data acquisition software. The investigators completed the first vital step in verifying the presence of the electro-optic effect in the test crystal.

In future months, the investigators plan to continue upgrading the crystal performance. The parameters associated with crystal alignment shall be optimized. A crystal holder with micrometer adjusts and a new vendor-sealed/electrode-installed KDP crystal will be obtained. Sensitivity shall be optimizated by adjusting the orientation of the polarizers and a quarter wave retarder plate. In addition, dc optical offsets will be removed to eliminate overranging when photodetector amplifier gain is increased. An attempt to reduce the dc components by simple electronic means will also be investigated.

Pending further sensitivity improvements, the prototype electro-optic field sensor shall be deployed to collect thunderstorm data at NASA/MSFC. Because solid-state technology is used, future designs of the sensor can be largely scaled down in physical dimension, making them an attractive alternative to standard measurement techniques. In addition, sensor gain can be controlled by adjusting laser power, laser wavelength, or crystal properties and therefore is not limited to purely electronic means of amplification.

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Sponsor: Center Director's Discretionary Fund

University Involvement: Co-investigator Dr. Richard Solakiewicz, Chicago State University

Biographical Sketch: Dr. William Koshak is an atmospheric physicist within the Earth System Science Division of MSFC's Science and Engineering Directorate. He supports lightning research activities as part of the Global Hydrology and Climate Center (GHCC) cooperative agreement. He received a Ph.D. from the University of Arizona, Institute of Atmospheric Physics, in 1990.

Geophysical Fluid Flow Cell Experiment

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The Geophysical Fluid Flow Cell (GFFC) experiment simulates a wide variety of thermal convection phenomena in spherical geometry. By applying an electric field across a spherical capacitor filled with a dielectric liquid, a body force analogous to gravity is generated around the fluid. The force acts as a buoyant force in that its magnitude is proportional to the local temperature of the fluid and in the radial direction perpendicular to the spherical surface. In this manner, cooler fluid sinks toward the surface of the inner sphere while warmer fluid rises toward the outer sphere. The value of this artificial gravity is proportional to the square of the voltage applied across the sphere and can thus be imposed as desired. With practical voltages, its magnitude is only a fraction of Earth's and so requires a microgravity environment to be significant.

The GFFC flew aboard the second United States Microgravity Laboratory (USML–2) October 20 to November 5, 1995 on *Columbia*. The instrument carried out 29 separate 6-hr runs using different parameters (cell rotation rate, heating distributions, etc.). Eighteen of the runs were nominal in terms of instrument performance, except for indications that suggested higher-than-expected temperatures along the outer sphere's equator. Because of this overtemperature problem, science activities were focused on situations with spherically symmetric heating (the so-called "solar model" cases). The last 11 runs were affected by a problem with the 16-mm film transport, leaving the video as the primary data source. This was compensated for by running experiments towards the end of the mission with commanded boundary temperatures similar to those run earlier in the mission on which film data is available.

The following are the preliminary results based on video downlink recorded during the USML–2 mission (analysis of the 16-mm film data has recently commenced at the University of Colorado). The experiments fell into several classes depending on the rotation rate (rapid or slow: e.g., solar-like or mantle-like). In each case new states were observed and are summarized here.

Studies of rotating convection with spherically symmetric heating revealed possible multiple jets in latitude, with prograde (same sense as the basic rotation) motion of thermal waves at low and high latitudes and retrograde pattern rotation at mid-latitude. Such differential pattern propagation has not been previously seen in computational models, and these results may provide an alternative view on the mechanisms for "banded"-looking structures in planetary atmospheres like Jupiter. However, contrary to suggestions from our Taylor-column idealized models, no vacillatory (periodic global pulsation) states were observed.

An extensive study of slowly rotating convection was carried out, and two distinct convection patterns were observed in experiments with the same external parameters but with different initial conditions. This means that the long-time evolution of modestly convecting flows in slowly rotating spherical shells (like Earth's mantle) is not unique, but depends on initial conditions. Equivalently the "climate" can be persistent, or locked, for long times as external conditions change slowly. In addition, information was obtained on how these persistent states evolve as parameters are increased across stability boundaries. Experiments produced an instability of "horseshoe convection," wherein the off-center ring of convection breaks down by north-south oriented stripe formation as the voltage is increased from 1.44 kV to 1.56 kV.

A large data set (several different rotation rates, many different heating rates) was obtained on the transition between anisotropic north-south oriented "banana convection" and more isotropic nonaligned convection. These results, when quantified by digital analysis of the data films and tapes, will permit testing of simple scaling arguments for this transition. Once verified, these scalings can be used to classify the expected global convection regimes of planets and stars.

Experiments with latitudinal heating gradients showed evidence for baroclinic waves. This instability is interesting because it has combined attributes of both ordinary thermal convection and rotating slantwise convection. The latter instability is central to the circulation of the Earth's atmosphere, but its occurrence as a combined instability supports recent computational modeling of such instabilities in rotating spherical shells.

Other experiments with latitudinal heating showed how spiral wave convection breaks down to turbulence by secondary branching.

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Sponsor: Office of Life and Microgravity Sciences and Applications

University/Industry Involvement: University of Colorado, Boulder, CO

Biographical Sketch: Fred Leslie is a scientist in the Microgravity Science and Application Division at MSFC. He served as a payload specialist astronaut aboard the Space Shuttle *Columbia* on the USML–2 (STS–73) mission in October/November 1995. He operated a number of experiments during the 16-day mission including the GFFC investigation.

Astrophysics

The Burst and Transient Source Experiment on the Compton Gamma-Ray Observatory

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Since its launch in April 1991, the Burst And Transient Source Experiment (BATSE) has been returning a continuous stream of data and produced new discoveries in high-energy astrophysics. Not only have new properties of previously known objects been uncovered, but entirely new types of objects have been found. Collapsed objects such as neutron stars and black holes are found in our galaxy that produce gamma rays which vary greatly; some systems vary on a scale of months and others on a scale of milliseconds. These collapsed objects emit gamma rays when they pull matter from a companion star onto themselves, a process called accretion. The neutron stars in binaries also emit x rays when their surfaces burn in thermonuclear explosions. The neutron stars without companions emit gamma rays when their spin induces a current of relativistically moving particles. The latter systems form one of the two types of pulsars. The other type consists of a neutron star binary system undergoing accretion as the neutron star rotates.

The spin of the neutron star in both pulsar systems produces very regular variation in x-ray and gamma-ray emission; this regularity provides a strategy for finding new pulsar systems. Some systems show a rich variety of behavior; a recent example is the bursting pulsar (GRO J1744–28), discovered by BATSE in December 1995, which in flared from being unobservable to being the brightest gamma-ray source in the galaxy within 2 weeks. In addition to pulsed radiation, it also emitted brilliant bursts of gamma rays lasting only several seconds. Several other binary systems are seen in the radio region to produce jets of matter that move at nearly the speed of light.

The bursting pulsar is near the center of our Milky Way Galaxy. More than 2,000 hard x-ray bursts from this object have now been detected, each having remarkably similar properties. Never before had an object been observed that displayed both the bursting behavior combined with the periodic behavior of a pulsar. Both the bursting (flaring) nature of this object along with the pulses (~0.5 sec) are shown in the average profile of many outbursts superimposed as shown in figure 162.

Other highly transient and variable objects have been studied by BATSE as well. Gamma-ray bursts, for example, are nonrepeating blasts of radiation that last typically last a few seconds and come from random directions in the sky. Their origin still remains a mystery. Another example are the soft-gamma repeater objects (SGR's), different from gamma-ray bursts in that they produce lower energy bursts of radiation, are observed to repeatedly blast gamma rays and x rays into space, and are located within the disc of our own galaxy. The BATSE experiment on the Compton Gamma-Ray Observatory (GRO) is expected to operate for at least 5 more years, providing a wealth of new information about high-energy objects and phenomena in the sky.

Sponsor: Office of Space Science

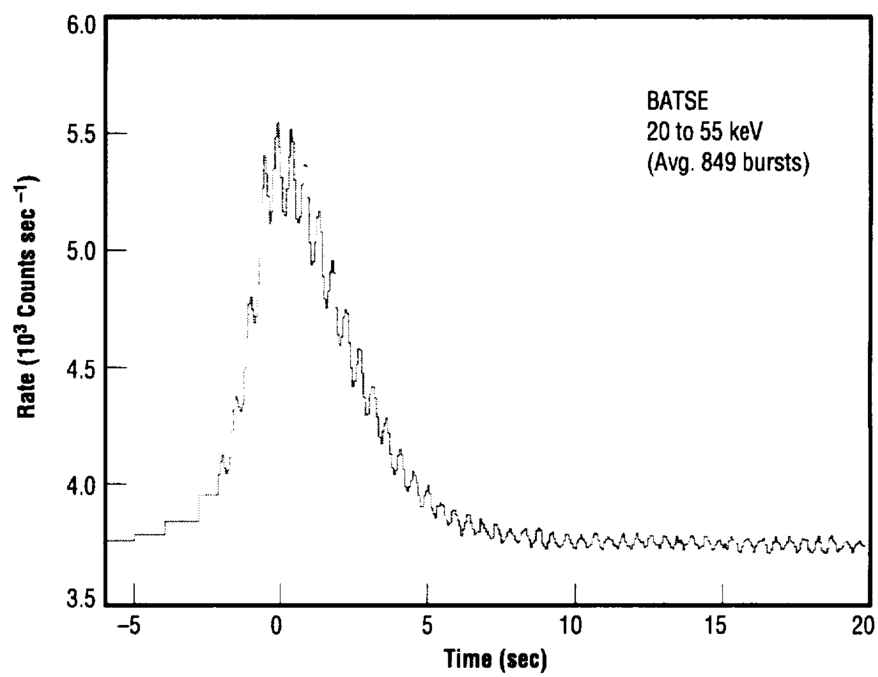

Figure 162.—The time profile of the Bursting Pulsar (GRO J1744-28). This unique Galactic object was discovered by BATSE in December 1995. It is the only known pulsed x-ray source to produce intense outbursts. Shown here is the superposition of a large number of outbursts, clearly showing the average shape of the bursts and the pulsed emission throughout.

University/Industry Involvement: University of Alabama

Biological Sketch: Gerald J. Fishman is an astrophysicist in the Space Sciences Laboratory of MSFC and is head of the gamma-ray astronomy research group. His primary research has been in the fields of gamma-ray astronomy, nuclear astrophysics and background radiation in space. Presently, he is the principal investigator of the BATSE on the Compton GRO. He obtained his Ph.D. in 1969 from Rice University.

Advanced Gamma-Ray Telescope

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This year, MSFC Space Sciences Laboratory scientists have become part of a new effort to establish a future mission for studies in gamma-ray astronomy in the timeframe following the Compton Gamma-Ray Observatory (GRO). The generic term for the new mission is the gamma-ray large area space telescope (GLAST) and the MSFC contribution to the effort is the development of a scintillation fiber telescope for energetic radiation (SIFTER). This research and technology development activity is being conducted in collaboration with investigators at the University of Alabama in Huntsville and Washington University in St. Louis.

In the energy regime above 20 MeV, the most energetic processes and most luminous objects in the universe are studied. The observational difficulties of this region have resulted in a relatively slow start in this new branch of astronomy, but the successes of the Compton GRO have pointed the way to new discoveries and avenues of research for the future. Among the many discoveries and studies made in this high-energy region have been active galactic nuclei (AGN's), a new type of high-energy object called blazars, diffuse gamma radiation from cosmic-ray/molecular cloud interactions, high-energy gamma rays (prompt and delayed) from gamma-ray bursts, several new gamma-ray pulsars and as-yet unidentified sources.

A review panel chartered by NASA Headquarters' Office of Space Science has indicated that a major new thrust in high-energy gamma-ray astronomy (>30 MeV) with at least 10 times the sensitivity of previous missions should be pursued. This new mission would build on the discoveries of the Energetic Gamma-Ray Experiment Telescope (EGRET) on the Compton GRO and extend the field into new domains of temporal variability and spectral measurements. As shown numerous times in modern astronomy, new classes of sources and phenomena may be expected with an order-of-magnitude increase in sensitivity.

The detector system under study uses the same basic principle (tracking of the initial electron-positron pair and its subsequent development, scattering, and absorption) as that used in all detector systems in high-energy gamma-ray astronomy above ~20 MeV. Many variations of the tracking elements have been developed or proposed. These include spark chambers, drift chambers, gas microstrip detectors and solid-state strip detectors. We propose to utilize a different technology: scintillating fiber optics.

For most other proposed detector systems for high-energy gamma-ray astronomy, such as silicon solid-state strip detectors, the major cost of the system is in the active detector elements. Thus, their cost scales directly as the sensitive area. A 1-m^2 system is usually specified in order to stay within a reasonable cost constraint. By contrast, in the scintillating fiber optic system proposed to be developed here, the active detecting elements (plastic scintillating fibers) are a small fraction of the total detector cost. The major cost is the optical read-out system, around the perimeter of the active area. Thus, the cost scales as the square-root of the active area and total active areas of several square meters should be well within the cost constraints of a medium-sized Explorer mission. Furthermore, continuing developments in the high-energy physics community as well as new optical technologies can be utilized for the system proposed here for both increased performance and reduced costs.

Recent advances in optical fibers, image intensifiers and solid-state optical readout systems have now made this technology feasible as the basis of a low-cost, large-area detector system for high-energy gamma-ray astronomy. The scintillating

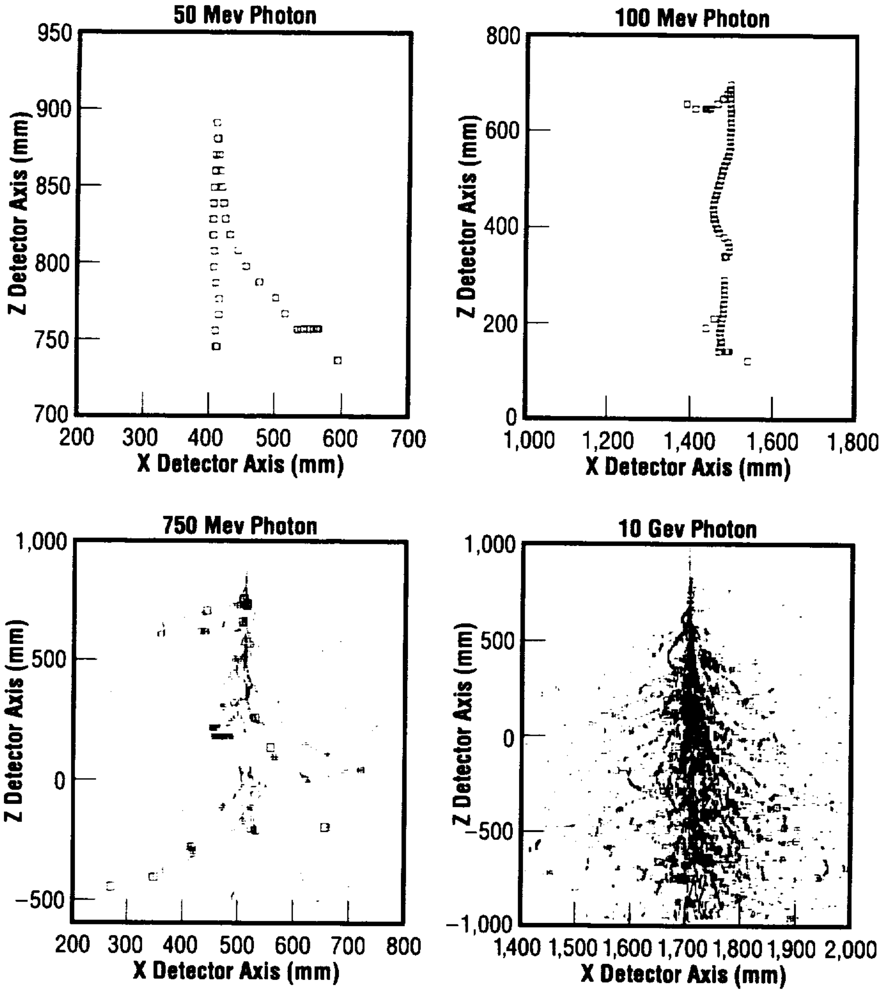

FIGURE 163.—Computer simulations (x-y views) of gamma-ray-produced tracks through an array of plastic scintillator fibers and lead sheet stack at two different energies.

fiber technique is already well-demonstrated and is successfully used in many applications for high-energy physics and cosmic ray research. Calculations and simulations have been performed to indicate reliable and accurate gamma-ray identification and characterization using a multilayered scintillation fiber and lead sheet array. Simulated gamma-ray tracks in a SIFTER are shown in figure 163. From these tracks, both the direction and the energy of the incoming gamma ray can be determined. The first 2 years of this development will be devoted to continuing computer simulations with various array configurations and determining the performance of such arrays directly by gamma-ray beam tests at a particle accelerator.

Sponsor: Office of Space Science

University/Industry Involvement: University of Alabama in Huntsville; Washington University (St. Louis)

Biographical Sketch: Gerald J. Fishman is an astrophysicist in the Space Sciences Laboratory at MSFC and is the head of the gamma-ray astronomy research group there. His primary research has been in the fields of gamma-ray astronomy, nuclear astrophysics and background radiation in space. Presently, he is the principal investigator of the Burst and Transient Source Experiment (BATSE) on the Compton GRO. He obtained his Ph.D. in 1969 from Rice University.

X-Ray Astronomy Research

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The thrust of the group's experimental research focuses on the development of detectors for x-ray astronomy. Two balloon flight instruments are currently being built, each incorporating new techniques developed in-house and each based on gas-filled proportional counters. The first of these, the Marshall Imaging X-Ray Experiment, No. 2, (MIXE2[1]) detector, utilizes special gas mixtures and construction materials and incorporates a novel microstrip electrode array, fabricated using microlithographic processes, which greatly improves the detector performance over conventional (discrete wire) proportional counters. An in-house development program, coupled with facilities provided by outside vendors, has led to the production of very large area devices (30 cm by 30 cm) one of which will be flying in the Spring of 1997 from Fort Sumner, NM, aboard a high-altitude balloon for x-ray astronomy observations.

The second instrument is a hard x-ray imaging polarimeter which utilizes an intensified CCD camera to image the photoelectron tracks produced by x-ray interactions.[2] It makes use of a special kind of gas counter, an optical avalanche chamber, which produces extremely large quantities of light photons (>10^7) under x-ray irradiation. Analysis of the initial ejection direction of the photoelectron permits a measure of the polarization of the incident x-ray photon. After extensive initial tests, a final design of a flight instrument has been completed and many of the components are either on order or in-house. The full-up instrument is scheduled to be completed by mid 1997.

To date, our flight experiments have been flown on a gondola in collaboration with Harvard College Observatory, but work is underway to develop an MSFC gondola. This will incorporate a novel pointing system, the heart of which is an attitude determination technique based on the global positioning system. By determining the relative x, y and z positions of several antennae around the gondola, the true orientation of the gondola can be ascertained and folded into the control loop to give pointing accuracies of a few arc minutes.

Various research projects support or spin off from the balloon flight programs and may lead to flight instruments in their own right. Typical of these is an investigation of the properties of ultra-high-pressure (50 to 100 atm) xenon ionization chambers that can extend the energy range of a conventional low-pressure (1 to 5 atm) gas-filled detector up to much higher energies (MeV region). Several prototype instruments have already been built and tested.[3] Similarly, we are investigating liquid xenon as a detection medium, using microstrip and microgap techniques developed for gaseous detectors. Liquid xenon is potentially very attractive as it is 500 times more dense than gas and hence offers much greater absorption capabilities. This large increase in density also results in the potential for much improved spatial resolution and the possibility of enhanced energy resolution. A small prototype chamber and associated gas liquification/purification system has recently been constructed and tests are underway. Finally, as a potential payload for future mini satellites, we are developing a Thomson scattering polarimeter sensitive over an energy range from 10 keV to 20 keV.[4] Polarization measurements are notoriously difficult to make and demand long observation times which in turn necessitate a dedicated mission. As the scattering polarimeter is simple in concept and combines low weight with low-power consumption, it is ideally suited to future lightweight, low-cost, fast-turnaround missions.

Another major research effort is the development and production of Wolter-1 x-ray optics using electroformed-nickel replication (ENR) off an electroless-nickel-coated aluminum mandrel. Our goals are to develop improved techniques for figuring, polishing, and coating the mandrel, plating and separating the mirror shell, controlling contamination, and testing the optic in x rays. Production of a replicated optic begins by turning a stress-relieved high-purity aluminum cylinder close to the desired optical figure. This mandrel is then plated with a thin (typically 0.16 mm) electroless-nickel/phosphorous layer, and machined to the precise optical figure. The mandrel is then polished (goal: microroughness <5 Å), and a weakly adherent gold coating is applied to the polished surface. The gold layer is later separated from the mandrel and becomes the inner reflecting surface of the x-ray optic.

Advances in Mirror-Shell Replication.

The most serious issue in replication is that standard nickel electroforming intrinsically produces a shell with high internal stress (typically several thousand lb/in^2), causing the shell to deform after separation. In collaboration with researchers at the University of Alabama Center for Applied Optics, we developed a method for stress-free electroformed-nickel plating, using thin-membrane sensors to monitor stress during the nickel plating and to reduce the average internal stress to zero by controlling the plating current density.

End effects encountered during electroforming also presented a problem. The higher electric field at the sharp ends of the mandrel results in nonuniform nickel deposition. In addition, the plating extends over the end of the mandrel, thus preventing separation. For our early replicated optics, we machined the ends of the mandrel/optic combination to remove the offending material. Such an approach was unsatisfactory because it introduced significant contamination between the optic and mandrel during machining, and shortened the mandrel with each subsequent replication. To avoid this, we developed a three-part mandrel, comprising the principal mandrel and two end caps, each cap being ~1-in long. The entire three-part mandrel, rigidly bolted together, undergoes the usual diamond turning, electroless-nickel plating, polishing, and gold coating. Just prior to the final electroforming of the mirror shell, the three-part mandrel is disassembled and thin Teflon spacers are inserted between the end caps and the main mandrel. These thin, dielectric spacers do not alter significantly the electric field; the plating is uniform on either side of the discontinuity. However, the spacers do facilitate removal of the end caps after electroforming, leaving a mandrel/optic combination ready for separation.

The final step in producing a replicated optic is separation of the mirror shell from the mandrel, by cryogenically cooling the mandrel until differential contraction causes complete detachment from the nickel shell. Initially, we found it very difficult to separate the mirror shell without scratching the gold reflecting surface or the highly polished mandrel. Furthermore, the extremely cold optical surfaces condensed atmospheric water vapor, leading to surface contamination. To eliminate these problems, we designed and built a separation fixture which allows precise withdrawal of the shell from the mandrel. During the separation procedure, both the optic and the separation fixture are maintained in a clean, dry-air environment to avoid contamination.

The culmination of these process improvements is that we have successfully produced mirror shells from several mandrels. The best of these mandrels has an excellent surface (6-Å RMS microroughness), measured to be the same before and after replication.

X-Ray Test Results.

In January 1996, we x-ray tested two 1/10-scale AXAF-P6/H6 shells (replicated from the same mandrel), using MSFC's 100-m "stray-light" facility outfitted with commercial electron-impact x-ray sources. The blur introduced by the finite-size source and the finite distance is negligible (≈0.5 arc sec (")). To detect the focused image, we employed an x-ray-sensitive Charge Injection Device, with a 528 by 528 array of 28-mm pixels. Figure 164 shows an image at 8.0 keV. A preliminary analysis of the results of these tests (FWHM ≈8", HPD ≈27" at 8 keV) document a significant improvement over our previous efforts (table 12). Future research will be directed toward creating lighter-weight optics while maintaining or improving the angular resolution demonstrated here.

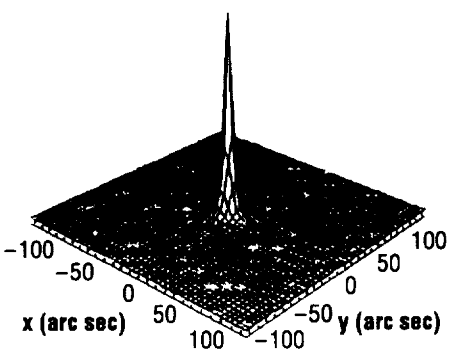

FIGURE 164.—Image at 8 keV of optic No. 1.

TABLE 12.—*X-ray test results.*

	4.5 keV	6.4 keV	8.0 keV
HPD (") Optic 1	15±2	—	27±2
HPD (") Optic 2	23±2	26±2	28±2

Related efforts include the development of extensive software tools to model all aspects of photon (and subsequent charged-particle) interactions within flight instruments. These programs have recently shown the importance of modeling photoelectron tracks in gas detectors if true response matrices are to be developed for instrument calibration.[5] They are also being used to develop software for analysis of data from the forthcoming SXRP[6] experiment, on which the x-ray astronomy group is collaborating.

As a complement to the above experimental program there is an active theoretical effort within the group. This work includes the calculation of high-resolution x-ray spectra from galaxy clusters through models for galaxy-cluster atmospheres. The goal of this research is to identify promising spectral diagnostics for cluster spectroscopy from x-ray observatories such as ASCA, AXAF and ASTRO-E. These diagnostics will help determine the basic properties of the cluster plasma, such as temperature, density and elemental abundances. Another goal of this research is to determine whether effects such as multiphase plasma flows, radiative cooling, or plasma shocks by cluster merging possess unique quantitative spectral signatures.

A large body of software has been developed, in support of the AXAF program, which has widespread application, for example, in the design of x-ray optics or the design and evaluation of imaging systems. One typical current application is the design of novel continuously graded multilayers for broad-band x-ray optics in the hard x-ray region. Such multilayers are currently being developed for MSFC under the Small Business Innovative Research Program and would be of use not only in astronomy, but in medical physics and such areas as x-ray photolithography.

Finally, also in support of the AXAF program, a technique has been developed for in-situ monitoring of surface contamination of x-ray telescopes.[7] This utilizes radioactive source to measure the reflectivity at several wavelengths and offers many benefits over the traditional technique of witness samples that accompany the optic and are examined at appropriate intervals.

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[7]O'Dell, S.L.; Elsner, R.F.; Joy, M.; Ramsey, B.D.; Weisskopf, M.C.: "A New Approach for Contamination Monitoring of X-Ray Telescopes." *SPIE*, vol. 2279, 1994.

Sponsor: Office of Space Science

Biographical Sketch: Brian D. Ramsey received his Ph.D. in astrophysics from The University of Birmingham, England, in 1978. After a 5-year postdoctoral fellowship in Birmingham, he came to MSFC in 1983, and currently works in the x-ray astronomy group of the Physics and Astronomy division. His principal duties include providing support for the AXAF program, and overseeing the MSFC X-Ray Balloon Program and the developments of new instruments for x-ray and gamma-ray astronomy.

Martin C. Weisskopf received his Ph.D. from Brandeis University in 1969. From 1969 until 1977, he was at Columbia University—first as a research associate, and then as assistant professor of physics. In 1977, he came to MSFC to start the x-ray astronomy group and is currently senior scientist for x-ray astronomy at MSFC and project scientist for the AXAF mission.

Interferometric Imaging of the Sunyaev-Zeldovich Effect at 30 GHz

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Observations of the Sunyaev-Zeldovich (S-Z) effect have been attempted since the effect was first predicted 25 years ago. The effect is a spectral distortion of the 3-K cosmic microwave background radiation resulting from inverse-Compton scattering of the microwave photons as they pass through the hot x-ray-emitting gas in the extended atmospheres of clusters of galaxies. The spectral distortion appears as a temperature decrement at frequencies below 218 GHz (>1.4 mm) and an increment at higher frequencies. Although the magnitude of the effect is small (~1 mK at radio wavelengths), its promise of providing an independent estimate of the Hubble constant and of the peculiar motions of distant clusters of galaxies has continued to motivate increasingly sensitive observations. The first observations of the effect were made in the radio regime with single-dish telescopes. The reported results show considerable differences, reflecting the difficulty of the measurement. These observations illustrated the need for telescopes and receiver systems designed explicitly to minimize differential atmospheric emission and ground pickup.

Interferometric observations offer several advantages over those made with single dishes for detecting and imaging weak emission. An interferometer measures only the correlated signal received by separate telescopes. Furthermore, the correlations are performed after compensation for the changing differential delays introduced as the array telescopes track the celestial source. This synchronous detection ensures that a well-designed interferometer will not suffer from the systematic effects associated with atmospheric and ground emission that are so difficult to determine and control in single-dish observations. A further advantage of interferometry, especially for relatively low frequency observations, is the ability to image and then remove emission from point sources that otherwise contaminate the S-Z effect. Last, interferometry provides a two-dimensional image of the emission.

In this paper we present images of the S-Z effect obtained with the millimeter-wave array of the Owens Valley Radio Observatory (OVRO) outfitted with centimeter-wave receivers. Using an array designed for millimeter wavelengths at centimeter wavelengths is ideal for imaging the S-Z effect and alleviates most of the problems discussed above. Additionally, the two-dimensional layout of the array makes it possible to obtain good u, v coverage and high brightness sensitivity, even for equatorial sources.

Low-noise receivers utilizing cooled high electron mobility transistor (HEMT) amplifiers that operate from 26 to 36 GHz were built and mounted at the Cassegrain focus of each of the 10.4 m telescopes of the Owens Valley millimeter array specifically to image the S-Z effect. The telescopes operating at 28.7 GHz provide a 4 arc min (') FWHM primary beam. The resulting 1.0 kλ minimum baseline allows imaging angular scales as large as 1.7', although in practice angular scales only less than about 1.4' are imaged well. At these frequencies the surface accuracy is better than λ/100, and the pointing accuracy is better than λ/50 of the primary beam. The observations were obtained with five elements of the array during the period of June 16 to July 9, 1994.

Three clusters were targeted for observations: CL 0016+16, Abell 773, and Abell 1704. Their selection was based on a combination of strong x-ray emission, small angular size, previously reported S-Z decrements, and position. Abell 773 and Abell 1704 are at similar distances, z=0.197 and 0.220, respectively, while CL 0016+16 is much more distant at z=0.541. The S-Z effect toward CL 0016+16 is believed to be strong. The OVRO array is well suited to observations of CL 0016+16 since it allows reasonable u, v coverage at declination 16 degrees, and the 1' synthesized beam is better matched to more distant clusters. The S-Z effect toward Abell 773 was observed by others with the Ryle telescope with a resulting signal-to-noise ratio (S/N) of ~5. We observed it to test our system and to provide a confirmation of their 15 GHz interferometric result. Unsuccessful searches for the S-Z effect toward Abell 1704 have been made by others; we also obtained a null result.

The full paper presents imaging results for each cluster. A decrement and associated sidelobes were clearly detected. In reference 2 an illustration shows our 56.5 in by 51.2 in resolution S-Z image overlaid on an x-ray image taken with the Roentgen Satellite (ROSAT) PSPC instrument, which has a resolution of ~30 in. The bright x-ray emission to the north of the cluster is from an active galactic nucleus (AGN) at z=0.554. The overall similarity of the two images is striking; the positions agree within the uncertainties, and both images show resolved structure elongated at a position angle of ~50 degrees. While the images give an impression of the data quality, quantitative information is best obtained by directly fitting models to the visibility data.

Using the core radius and ellipticity derived from the x-ray data to constrain the model parameters resulted in a decrement for CL 0016+16 of $\Delta T_0 = -717 \pm 65$ μK. Measurements of the S-Z effect can lead to a determination of the Hubble constant and other cosmological parameters. However, a sensitive, unbiased imaging survey of galaxy clusters at both microwave and x-ray wavelengths will be necessary to achieve a reliable determination of these parameters. The results presented here demonstrate the power of using the OVRO millimeter array equipped with centimeter receivers to obtain high S/N images of the S-Z effect toward distant clusters. With the goal of conducting a survey of clusters, we have made several improvements to increase the sensitivity and imaging speed of the instrument.

[1]Carlstrom, J.; Joy, M.; Grego, L.: Astrophysical Journal Letters, 456, 75.

[2]Carlstrom, J.; Joy, M.; Grego, L.: Astrophysical Journal Letters, 461, 59.

Sponsor: MSFC Center Director's Discretionary Fund

University/Industry Involvement: J. Carlstrom, University of Chicago; L. Grego, California Institute of Technology

Biographical Sketch: Dr. Marshall Joy is an astrophysicist in the Space Sciences Laboratory at Marshall. He earned his Ph.D. in astrophysics at the University of Texas, Austin, in 1986.

The JACEE Measurement of the Cosmic Ray Proton and Helium Spectra

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The Japanese-American cooperative emulsion experiment (JACEE) collaboration has now flown 15 balloon-borne experiments to measure the cosmic ray composition, energy spectra, and nuclear interactions above 10^{12} electron volts (1 TeV). Some of these flight opportunities included long-duration balloon flights from Australia to South America and circumpolar flights in Antarctica. The JACEE collaboration includes MSFC, University of Alabama in Huntsville (UAH), University of Washington (UW), Seattle, Louisiana State University (LSU), Institute for Nuclear Physics, Krakow, Poland, and nine universities located in Japan. The instrument package contains multiple layers of doubled-sided nuclear emulsion plates, CR39 etchable track detectors, x-ray films, and lead plates. The emulsion chamber is typically divided into a charge detector, a target section for interactions, a stack of honeycomb spacers, and an ionization calorimeter section for the determination of the cosmic ray energy. To achieve adequate exposure to the meager flux of high-energy cosmic ray protons and helium nuclei, six emulsion chambers , 1.2-m^2 and 20-cm thick, were flown at an altitude of 120 to 125,000 ft for 9 to 15 days. After repeated long duration balloon flights, a total accumulated exposure of 1,436 m^2 hr was realized. To date, we have analyzed 45 percent of this accumulated data resulting in 656 protons above 6 TeV and 414 helium nuclei above an energy of 2 TeV/nucleon. We present in figure 165 the JACEE differential energy spectra for both hydrogen and helium (filled circles) together with previous measurements for comparison. The kinetic energy scale is expressed in units of GeV/nucleon where GeV = 10^9 electron volts. Both the JACEE

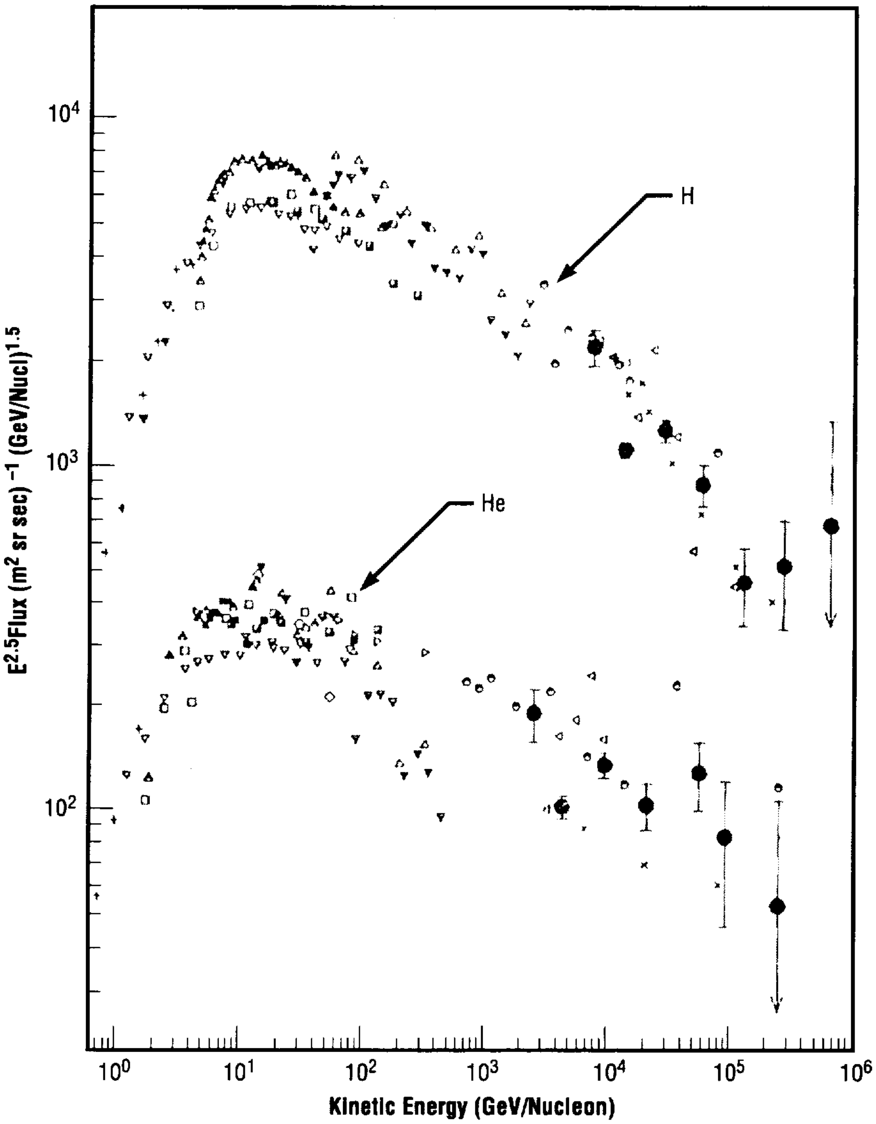

FIGURE 165.—The differential energy spectra of cosmic ray hydrogen (H) and helium (He) showing the latest JACEE results (●) together with earlier results from Frier and Waddington (1968, +), Anand et al. (1968, ■), Ryan et al. (1972, Δ), Verma et al. (1972, ◇), Ramaty et al. (1973, ▼), Smith et al. (1973, □), Badhwar et al. (1977, ▲), Seo et al. (1991, ∇), Dwyer et al. (1993, ▷), Ichimura et al. (1993, ◁), Ivanenko et al. (1993, ●), Zatsepin et al (1993, ×), and Swordy et al. (1995, ◪).

proton and helium data can be fit with an inverse power law in energy with spectral indices $\gamma_H = 2.69 + 0.13/-0.05$ and $\gamma_{He} = 2.54 + 0.13/-0.04$, respectively. We can conclude from this inverse power law fit that the H/He ratio gradually decreases with increasing energy. A helium spectrum slightly flatter than the hydrogen spectrum is consistent with supernova remnant shock wave acceleration into the interstellar medium to explain the hydrogen spectrum and supernova shock wave acceleration into the stellar wind of a Wolf-Rayet star to explain the helium spectrum. The hydrogen and helium data appear to be in good agreement with the predictions of the supernova shock wave acceleration model coupled with the standard "leaky box" model describing the propagation of cosmic rays through the galaxy. The JACEE collaboration has produced the highest energy direct measurement of the cosmic ray hydrogen and helium spectra up to an energy of 800 TeV.

Asakimori, K. et al. To be submitted to the Astrophysical Journal, 1996.

Sponsor: Office of Space Science

University/ Industry Involvement: University of Alabama in Huntsville; University of Washington, Seattle; Louisiana State University; Institute for Nuclear Physics, Krakow, Poland; Kobe Women's Junior College, Kobe, Japan; Kobe University, Kobe, Japan; Kochi University, Kochi, Japan; Waseda University, Tokyo, Japan; Okayama University of Science, Okayama, Japan; KEK, Tsukuba, Japan; Hiroshima University, Hiroshima, Japan; Institute for Cosmic Ray Research, Tokyo, Japan; Tezukayama University, Nara, Japan.

Biographical Sketch: Dr. James Derrickson is a space scientist at the Space Sciences Laboratory located at MSFC. He has experience in the study of the space radiation environment focusing on the field of high energy cosmic ray research. He received his Ph.D. in 1983 from the University of Alabama in Huntsville.

The Utilization of Direct Electron Pairs for the Energy Measurement of Ultrarelativistic Cosmic Rays

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A great deal of progress has been made in our fundamental understanding of the production of direct electron pairs by relativistic heavy ions in matter. The past discrepancies between theory and measurement have been resolved due, in part, to the collaborative work conducted at MSFC, the University of Alabama in Huntsville (UAH), and the University of Tennessee (UT). The accelerator measurements performed by the MSFC/UAH/UT group at the European Center for Nuclear Research (CERN) using relativistic oxygen and sulfur ion beams are summarized in figure 166 along with previous accelerator measurements. Included in this presentation of the direct pair yield is the only other relativistic heavy ion pair measurement at CERN conducted by an Oakridge National Laboratory (ORNL) collaboration using a magnetic field to identify the positron member of the pair and determine its momentum spectrum. The measured direct pair yield from the heavy ion exposures have been corrected for background, pair energy cut-off and bandwidth differences, and normalized as indicated in figure 166 to facilitate comparison with the theory. These recent direct pair yield results based on the heavy ion exposures compare well with a modern calculation performed at MSFC (solid curve).

This gives us confidence in both the measurements and the theory so that it is now possible to consider the application of the direct electron pair process to the measurement of the primary energy of the heavy cosmic rays above 10^{12} electron volts. Unlike other methods dependent on the electromagnetic interaction (e.g., Cerenkov and transition radiation), this energy measurement technique has the advantage of not saturating at ultrarelativistic energies. Through the MSFC/UAH/UT effort, the physical characteristics of the direct electron pairs have been determined. The direct pair energy varies from a few million electron volts (MeV) to several hundred MeV and the emission angle distribution peaks close to the forward direction. This basic information on direct electron pairs will be used in a Monte Carlo simulation of a generic direct electron pair detector to aid in the development of several promising detector designs. If the design effort is successful, a measurement of the ultrarelativistic cosmic ray energy spectra using the direct pair method will provide important clues concerning possible multiple sources of cosmic rays and potential evidence of several acceleration mechanisms.

Derrickson, J.H., et al.: Physical Review A. 51:1253, 1995.

Derrickson, J.H., et al.: 24th International Cosmic Ray Conference, Rome, Italy. Vol. 3, pp. 641, 1995.

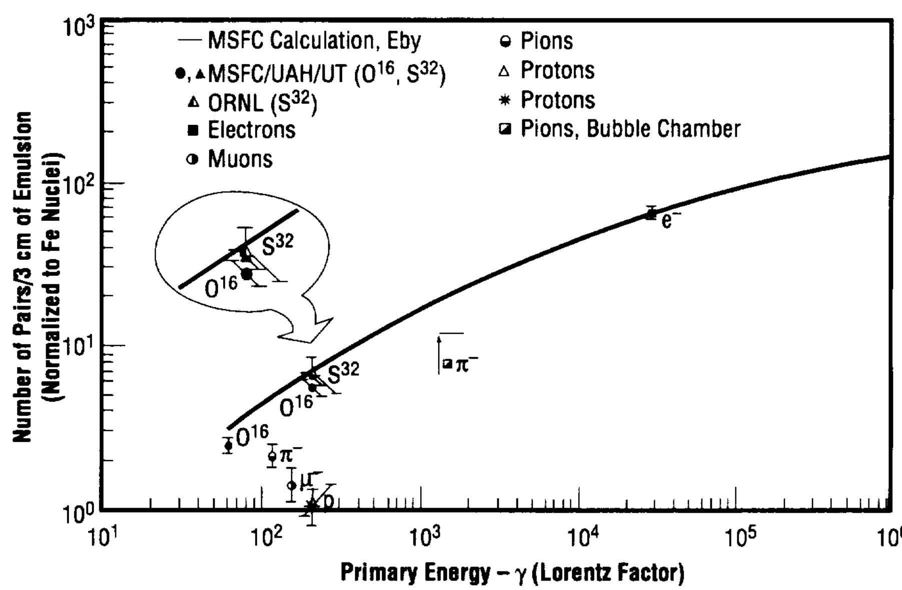

FIGURE 166.—The direct pair production arbitrarily normalized to the equivalent yield of an Fe nucleus in 3 cm of emulsion as a function of the primary energy of the projectile expressed in terms of the Lorentz factor, (γ). This unusual normalization can be tied to the interest the cosmic ray community has in applying the direct pair method to measuring the heavy energetic cosmic rays. The recent MSFC/UAH/UT results (●, ▲) are compared to the measurements from Kinzer et al. (1968, ⊖), Cary et al. (1971, ■), Butt et al. (1973, ✱), Jain et al. (1974, Δ, ◑), Forney et al. (1975, ◪), Vane et al. (1994, Δ). The arrow and bar indicate a correction to the bubble chamber yield to compensate for the high momentum cutoff (10 MeV/c). The solid curve is the calculated total direct pair yield including atomic screening due to Eby (1991). The heavy ion data has been corrected for background and pair momentum detection limits.

Eby, P.B.: Nuclear Instruments and Methods in Physics Research A. 336:189, 1993.

Sponsor: Office of Space Science; Center Director's Discretionary Fund

University/Industry Involvement:
University of Alabama in Huntsville;
University of Tennessee, Knoxville;
Universities Space Research Association (USRA)

Biographical Sketch: Dr. James Derrickson is a space scientist at the Space Sciences Laboratory located at MSFC. He has experience in the study of the space radiation environment focusing on the field of high energy cosmic ray research. He received his Ph.D. in 1983 from the University of Alabama in Huntsville.

Solar Physics

Self-Filtering Solar Telescopes

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Measurements of the Sun's vector magnetic field carried out at MSFC have demonstrated that observations with better spatial, and temporal resolution, and over a wider spectral range, than can be achieved with ground-based telescopes, are required to meet our scientific objectives. Since ground-based telescopes are limited by the variability of the Earth's atmosphere, we are investigating concepts for moderate to large aperture (30- to 60-cm diameter), diffraction limited, spaced-based solar telescopes for operation in the visible and ultraviolet regions of the spectrum. Solar telescopes have unique thermal problems for they act as solar furnaces, focusing large amounts of energy onto the post primary optics. Past and future telescope concepts are usually based on either Cassegrain or Gregorian designs. In the Cassegrain, the secondary mirror is located inside the focal plane of the primary mirror, and the main advantage, for space applications is its compactness. In addition, the secondary mirror provides less central obscuration than the Gregorian design resulting in an improved modulation transfer function (MTF) at angular frequencies just above the diffraction limit. The disadvantage of the standard Cassegrain design is that there is no location for a field stop in the primary optical path. Consequently, the full solar flux, including both the infrared and ultraviolet, is focused onto the smaller secondary mirror. This increased flux creates thermal problems and enhances the potential for the polymerization of hydrocarbons on the mirror surface, which can result in a catastrophic loss of reflectivity. To solve this problem a full aperture prefilter with a bandpass defined by a simple metal[1] dielectric coating can reduce the thermal load on the telescope. This concept has been successfully employed on the MSFC vector magnetograph for the past 25 years. A disadvantage of the approach is that it limits the spectral bands that can be investigated to the visible and in particular excludes the far UV.

In the Gregorian design the secondary mirror is mounted outside the focus of the primary. This allows a field stop to be placed at the primary focus which can be used to limit the total energy striking the secondary mirror. Typically, the stop reduces the field of view to about 2 arc min^2 which results in less than half a percent of the Sun's total flux from reaching the secondary. Because the incident beam is not filtered, the Gregorian design provides access to the full solar spectrum and has applications where the emphasis is on ultra-high spatial resolution over a restricted field of view. The disadvantages of the Gregorian design is that the total length is approximately 30 percent longer than a Cassegrain with the same f-number and it has a larger central obscuration.

The scientific focus of the MSFC group is the study of how the Sun's magnetic field changes with time and how these changes lead to the explosive release of energy in solar flares. To satisfy these objectives the magnetic field observations have to be made over relatively large fields of view. Consequently, a Cassegrain with a full aperture prefilter has been our preferred design. However, as the diameter of the primary aperture increases the fabrication and support of a distortion free, full aperture prefilter becomes increasingly difficult if not impossible.

To overcome this difficulty, we have developed an approach which combines a modification to the design of the primary mirror with advances in thin film, dielectric, multilayer filters to develop a self-filtering Cassegrain telescope which eliminates the requirement for a full aperture prefilter. In this concept the transmission coatings which were previously applied to the prefilter are converted to reflective coatings[2] and applied directly to the front surfaces of the primary and secondary mirrors. The solar radiation incident on the primary is either reflected, if it is within the passband of the filters, or transmitted through the body of the mirror. Our modification is to figure the rear surface of the primary mirror and provide it with an all purpose reflective coating, such as silver, which has high reflectivity in the IR. In the ideal case, the curvature of this rear surface is such that the incident rays, following refraction in the glass, strike the surface normally and are reflected back along their original path and out of the telescope. This condition is met for parabolic surfaces when the radius of curvature of the rear surface is equal to the product of the refractive index and the radius of curvature of the front surface (fig. 167). In practice the refractive index is a function of wavelength and many of the reflected rays will have slight departures from the normal. Therefore, the figure of the back surface is designed to satisfy this condition in the IR so that rays at all shorter wavelengths will exit the primary mirror at angles that are outside the incident ray and consequently will not strike the secondary mirror. Two applications for this technology are under consideration. The first is for a space magnetograph to obtain improved measurements of the vector fields in the photosphere. The magnetically sensitive, spectral lines of interest are in the visible at 525.0 nm and 630.2 nm and the performance of a multiple bandpass filter, which also includes the Hα line at 656.3 nm is shown in figure 168 (b). The design which was prepared for Solar-B, a joint ISAS/NASA mission to measure solar magnetic fields, consists of an f-4 telescope system with a 0.5- to 0.6-m aperture primary mirror. The physical

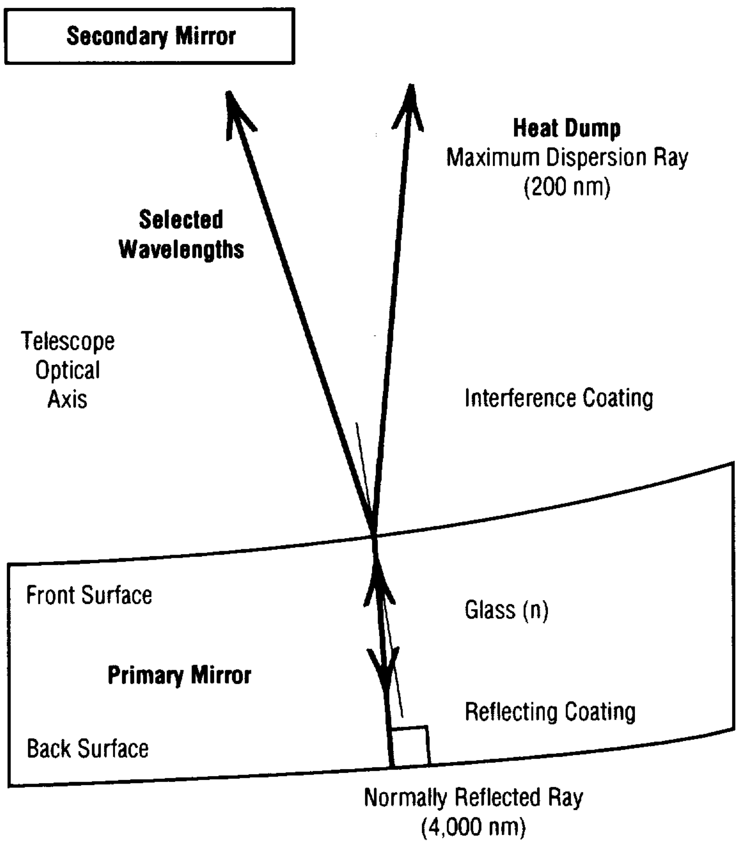

FIGURE 167.—Schematic of the self-filtering mirror concept.

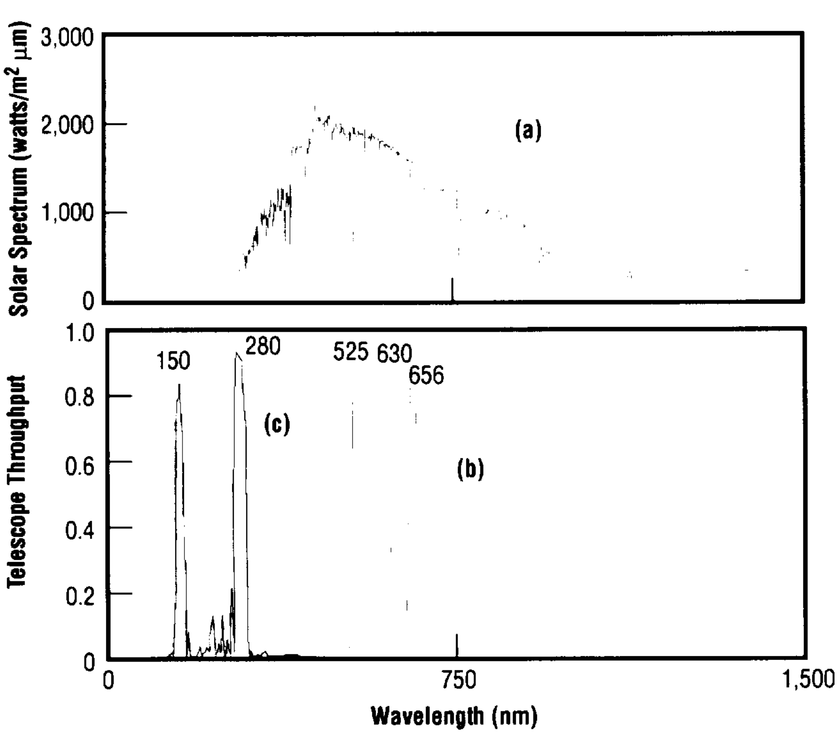

FIGURE 168.—(a) The solar spectrum (b) the passbands of the photospheric vector magnetograph (c) the passbands of the UV magnetograph.

envelope for the telescope provided by the spacecraft is extremely limited and the self-filtering Cassegrain design provides an elegant solution for this case.

The second application is for a vector magnetograph operating in the far-ultraviolet region of the spectrum. Lines in this region of the spectrum are formed at higher temperatures than the photospheric lines, observed in the visible, which in turn corresponds to greater heights in the solar atmosphere. By comparing the UV and visible measurements, an understanding of how the structure of the magnetic field varies with height can be gained. Such information is important because we believe that a significant part of the Sun's dynamic behavior originates in this upper chromosphere-low coronal region. The ultraviolet magnetograph that we are proposing for a suborbital flight opportunity will use the spectral lines of Mg II at 280 nm and CIV at 150 nm. These magnetically sensitive lines are formed in the upper chromosphere and low corona respectively and the measurement of their polarization will provide the first opportunity to observe solar vector magnetic fields in a region where the field lines are unconstrained by the solar atmosphere.

A preliminary design of this telescope has an f-10 system with a 0.3-m diameter primary. To obtain the bandpass performance shown in figure168 (c), a customized dielectric coating consisting of alternating layers of lanthanum fluoride and magnesium fluoride has been designed.

In both these applications practical reasons impose strict limits on the size of the instrument, a condition which is generally true for all space-based solar telescopes. For these situations, where high spatial resolution over wide field of view is also required, the self-filtering Cassegrain concept offers an elegant design solution.

[1]Brueckner, G.E.: "A New Completely Digitized Filter Magnetograph". IAV Symposium no. 43, Reidel: New York, p. 84, 1971.

[2]Zukic, M.; Torr, D.G.; Spann, J.F.; and Torr, M.R.: "Optical Constants of Thin Films". *Applied Optics*, vol. 29, p. 4284, 1990.

Sponsor: Office of Space Science

University Involvement: University of Alabama in Huntsville

Biographical Sketch: John M. Davis received his Ph.D. in physics from the University of Leeds, UK in 1964. He has held positions at the Massachusetts Institute of Technology, and American Science and Engineering, Inc., Cambridge, MA, where the primary emphasis of his work was the design, development and testing of scientific, and especially x-ray imaging, instrumentation for space. He joined the Marshall Center as chief of the Solar Physics Branch whose members are involved in experimental and theoretical studies of solar magnetic fields and their interaction with the solar atmosphere.

G. Allen Gary received his Ph.D. in physics in 1969 from the University of Georgia. He is in the Solar Physics Branch at the Marshall Center, investigating the nature of coronal structures and solar magnetic fields. His research also includes the general study of the magnetic field's configuration, evolution, and morphology together with estimation of the energy content of active regions. His theoretical work involves developing models of linear and nonlinear force-free magnetic fields and electric currents in the solar chromosphere-corona.

Edward West received his B.S. degree in engineering science from Tennessee Technological University in 1973 and his M.S. degree in electrical engineering from the University of Alabama, Huntsville in 1982. He joined the Marshall Center in the fall of 1973 and has been associated with the Space Sciences Laboratory since that time. He has worked with the hardware and software development of both the original vector magnetograph and the breadboard design of a space-based instrument called the EXperimental Vector Magnetograph (EXVM). His main interests are in the development of high resolution, stable polarizing optics that can improve vector magnetic field measurements and in reducing the instrumental errors, both optical and electrical, so that a magnetic resolution of 50 gauss transverse can be achieved. Along with the development of new instrumentation to observe the vector magnetic field on the Sun, he is interested in developing the real-time analysis tools to predict flares, and in studying magnetic evolution and magneto-optic effects of the Sun.

Dr. Alan Shapiro is a coating physicist at the Optics and Radio Frequency Division at MSFC's Astrionics Laboratory. He conducts research on specialized optical coatings, many of which are utilized for astronomical and astrophysics related programs. He also conducts research on the surface morphology of material surfaces. Shapiro earned his Ph.D. in condensed matter physics from the University of Illinois, Urbana-Champaign in 1987, after which he worked at International Business Machine Corporation, East Fishkill, NY. He has worked for NASA at MSFC since May 1989.

Coronal Heating

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The Sun's extended outer atmosphere, the corona, is so hot that it radiates predominantly in soft x rays (1 to 10 nm in wavelength). The upper left panel of figure 169 shows a typical whole-Sun soft x-ray image taken by the Japan/U.S. Soft X-Ray Telescope (SXT) on the Japanese orbiting spacecraft, Yohkoh. This image demonstrates that in soft x rays the corona greatly outshines the underlying photosphere, the Sun's surface seen in ordinary visible sunlight. This requires that the x-ray coronal plasma be maintained at million-degree temperatures, hundreds of times hotter than the photosphere. How the necessary coronal heating is accomplished remains an unsolved puzzle, constituting a long-standing premier problem of solar physics and astrophysics.

Figure 169 illustrates that coronal heating is a magnetic phenomenon: the strongest heating (brightest corona) is seen to be in the strong magnetic field in sunspot regions. (The upper right panel of figure 169 is the same SXT coronal image as in the upper left panel, but with a different scaling of the brightness to show detail within the brightest regions. The lower left panel is a cotemporal photospheric image showing sunspots underlying the most strongly heated parts of the corona. The lower right panel is a conventional magnetogram from Kitt Peak National Solar Observatory showing both the concentrations of strong magnetic field in the bright-corona active regions (in and near sunspots) and scattered weaker fields in dimmer-corona quiet regions (well away from sunspots.) It can be seen from even a cursory comparison of SXT coronal images with conventional magnetograms (maps of the line-of-sight component of the photospheric roots of the magnetic field), such as in figure 169, that the brightest coronal features in an active region occupy only some parts of the

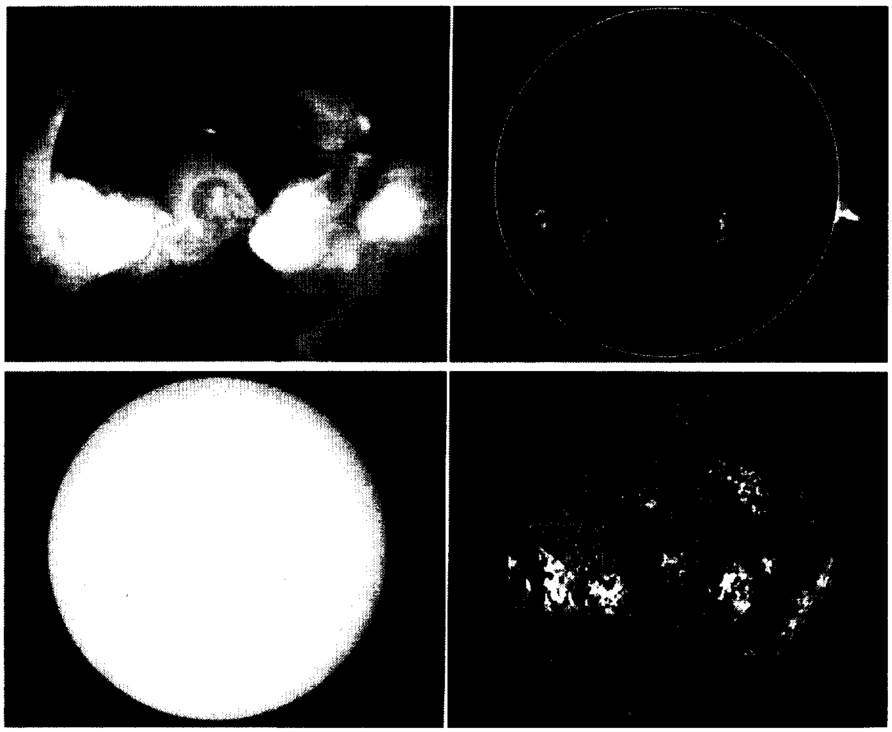

Figure 169.—The x-ray solar corona and its magnetic roots.

strong-field domain of the active region. While it is true that the brightest coronal features are seated in strong fields, there are other places in the active region where the field is as strong or stronger, but the corona is much dimmer, and hence the heating much weaker. Thus, it is clear that the strength of the enhanced coronal heating in active regions depends on more than just the strength of the magnetic field.

During the past year, solar scientists at MSFC, in collaboration with U.S. and Japanese colleagues participating in the Yohkoh Mission, have established some new characteristics of the magnetic origins of the strong coronal heating in active regions. They examined the structure of the magnetic field at the sites of strong coronal heating in five active regions by superposing Yohkoh SXT images on vector magnetograms of these active regions from the MSFC vector magnetograph. (A vector magnetograph maps the transverse component of the photospheric magnetic field in addition to the line-of-sight component mapped by conventional magnetographs.) They found:

- Nearly all of the enhanced (outstandingly bright) coronal features are rooted near polarity neutral lines in the photospheric magnetic flux;
- In most cases the core magnetic field closely straddling the neutral line at the root of the strong heating is strongly sheared;
- The enhanced coronal brightness in the low-lying core fields shows spatial substructure that fluctuates on time scales of minutes, in the manner of microflaring;
- Large parts of extensive enhanced coronal features often last for no more that a few hours; and
- Some strongly sheared core fields and many weakly sheared core fields have no enhanced coronal loops in them or extending from them.

From these results, they conclude that most of the strong heating of coronal loops in active regions is a consequence of some process that:

- Acts only in the presence of a polarity inversion in the magnetic field near at least 1 ft of the loop, and is more effective in the presence of strong magnetic shear, but
- Is not required to act by the presence of a neutral line or strong neutral-line magnetic shear;
- Makes many "substructure microflares" in core fields, and
- Is controlled by some episodic process.

Magnetic flux cancellation driven at the neutral line by episodic convective flows in and beneath the photosphere is a process that plausibly meets all of these requirements.

The MSFC scientists therefore infer from their observations that:

- The strong coronal heating rooted in active regions is done by core-field microflaring paced by magnetic flux cancellation; and
- The microflaring activity directly produces the enhanced coronal heating in the core fields and also generates MHD waves that propagate up into the enhanced extended loops to provide the strong coronal heating in these.

Falconer, D.A.; Moore, R.L.; Porter, J.G.; Gary, G.A.; Shimizu, T.: "Neutral-Line Magnetic Shear and Enhanced Coronal Heating in Solar Active Regions." *Astrophysical Journal*, 1996, in press.

Moore, R.; Porter, J.; Roumeliotis, G.; Tsuneta, S.; Shimizu, T.; Sturrock, P.; Acton, L.: "Observations of Enhanced Coronal Heating in Sheared Magnetic Fields." Proceedings of the Kofu Symposium "New Look at the Sun," ed. S. Enome and T. Hirayama, Nobeyama Radio Observatory Report no. 360, p. 89, 1994.

Porter, J.; Moore, R.; Roumeliotis, G.; Shimizu, T.; Tsuneta, S.; Sturrock, P.; Acton, L.: "Microflaring at the Feet of

Large Active Region Loops." Ibid., p. 65, 1994.

Sponsor: Office of Space Science

University/Industry Involvement: University of Tokyo; Stanford University; Montana State University

Biographical Sketch: Dr. Ronald L. Moore is an internationally recognized solar scientist. He received his Ph.D. from Stanford University in 1972, was a Research Fellow with the Caltech Solar Astronomy group (1972 through 1980), and joined the MSFC Solar Physics branch in 1981. There, he developed and continues to lead a research program on observed solar magnetic fields and their effects in the solar atmosphere. Moore has published over 100 papers on his solar research in refereed journals, conference proceedings, books, and encyclopedias.

Solar Flares

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A solar flare is an explosive event in a magnetic region of the solar atmosphere. Apparently, stored magnetic energy is suddenly released low in the corona, driving bulk mass motion, heating plasma, and accelerating electrons and ions to hard x-ray energies and beyond. In particular, the magnitude and energy spectrum of the resulting burst of hard x rays often indicate that:

- Much of the released energy goes to the energization of electrons to tens of kilovolts;
- The number of these electrons in the burst is comparable to the total number of electrons in the preflare coronal volume of the flaring magnetic field; and
- The total energy channeled into these electrons is a sizeable fraction of the total preflare magnetic energy in the flare volume.

The observed hard x-ray emission from flares thus confronts solar astrophysicists with what is known as the electron bulk energization problem: How does the flare energy-release process manage to be so efficient in energizing electrons to hard x-ray energies? It is this difficulty that makes the plasma energization in solar flares one of the fundamental problems of plasma astrophysics.

An enduring central idea in flare physics is that the conversion of magnetic energy into plasma particle energy is accomplished through reconnection of the magnetic field. Under this precept, the question becomes: How can reconnection provide the required electron bulk energization? A few years ago, MSFC solar astrophysicists pointed out that the main function of the reconnection could be to generate MHD turbulence that, in turn, bulk-energizes the electrons as it cascades to small scales.[1] They reasoned that the MHD turbulence expected in strong flares would be intense enough and voluminous enough to provide the electrons for the hard x-ray emission. The question then became: How is the energy in this MHD turbulence transferred to the electrons? In answer to this question, LaRosa, Moore, and Shore[2] proposed that the electrons are bulk-energized in the turbulence by Fermi acceleration at sufficiently small scales in the cascade. These authors also pointed out that for this to be a viable mechanism for the electron energization, the rate of proton energization by the same turbulence cannot exceed the rate of electron energization. Whether the protons could block the Fermi-acceleration energization of the electrons remained an open question.

During the past year, in a collaboration between solar astrophysicists from Kennesaw State College in Marietta, GA, MSFC, University of Alabama in Huntsville, and Indiana University at South Bend,[3] it has been shown that the protons pose no threat to the electron energization by Fermi acceleration. The energization rate for the electrons was derived from first principles, starting from the elements of the wave-particle interactions that yield the Fermi acceleration in MHD turbulence (fig. 170). The energization rate of the protons was derived in the same way. For typical magnetic field strengths and typical densities and temperatures of the plasma entering the turbulence in flares, the protons have initial thermal speeds much slower than the Alfven speed in the turbulence whereas the electrons have initial thermal speeds much faster than the Alfven speed. This difference between the protons and the electrons results in the proton energization rate being entirely negligible compared to that of the electrons. In this way, electron Fermi-acceleration dissipation of MHD turbulence is now established as a strong candidate mechanism for the electron bulk energization in solar flares, and a new front has been opened for attacking the problem of plasma energization in solar flares.

[1]LaRosa, T.N.; Moore, R.L.: "A Mechanism for Bulk Energization in the Impulsive

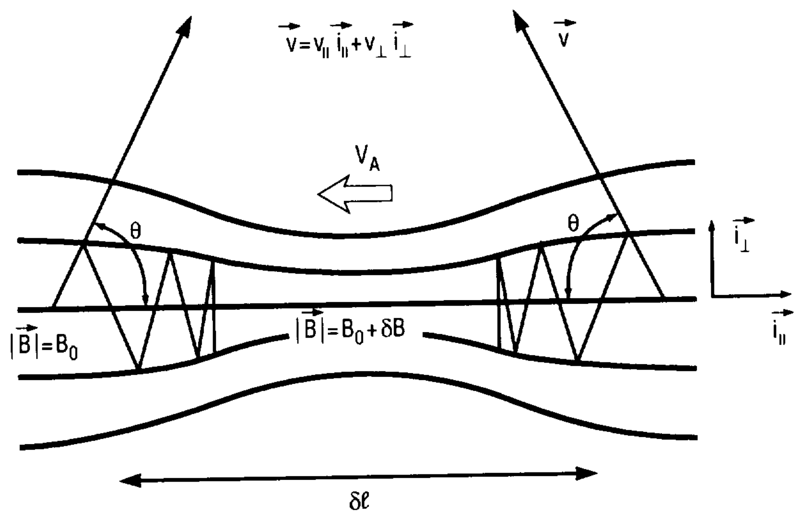

FIGURE 170.—Elements of the wave-particle interactions in the Fermi acceleration of charged particles in MHD turbulence.

Phase of Solar Flares." *Astrophysical Journal*, 418, 912, 1993.

[2]LaRosa, T.N.; Moore, R.L.; Shore, S.N.: "A New Path for the Electron Energization in Solar Flares: Fermi Acceleration by MHD Turbulence in Reconnection Outflows." *Astrophysical Journal*, 425, 856, 1994.

[3]LaRosa, T.N.; Moore, R.L.; Miller, J.A.; Shore, S.N.: "New Promise for Electron Bulk Energization in Solar Flares: Preferential Fermi Acceleration of Electrons Over Protons in Reconnection-Driven MHD Turbulence." *Astrophysical Journal*, 1996, in press.

Sponsor: Office of Space Science

University/Industry Involvement: Kennesaw State College, Marietta, GA; University of Alabama in Huntsville; Indiana University at South Bend

Biographical Sketch: Dr. Ronald L. Moore is an internationally recognized solar scientist. He received his Ph.D. from Stanford University in 1972, was a Research Fellow with the Caltech Solar Astronomy group (1972 through 1980), and joined the MSFC Solar Physics branch in 1981. There, he developed and continues to lead a research program on observed solar magnetic fields and their effects in the solar atmosphere. Moore has published over 100 papers on his solar research in refereed journals, conference proceedings, books, and encyclopedias. ■

Three-Dimensional Rendering and Image Analysis of Coronal Loops

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Since launch in 1991, the Japanese solar satellite Yohkoh has been revealing many new aspects of solar coronal physics: coronal structures and dynamics, gigantic arcades formations, cusp-shaped flares, soft x-ray jets, microflares, single-loop flares, and loop-loop interactions. MSFC was the management center for the Soft X-Ray Telescope (SXT) built by Lockheed for the ISAS (Institute of Space and Aeronautical Sciences) in Japan. MSFC involvement in solar x rays and magnetic fields has been extensive: Apollo Telescope Mount's Solar X-Ray Telescope S–056, MSFC Solar Vector Magnetograph, MSFC and Stanford x-ray telescope rocket programs, High Energy X-Ray Telescope, Soft X-Ray Instrument, and Solar-B. This research is extending this effort.

The objective of this research is to expand MSFC's in-house capabilities by developing innovative three-dimensional dynamic displays, tools, and programs to simulate gaseous configurations, interactions, and dynamics through the rendering of three-dimensional gaseous volumes into two-dimensional images. Having these line-of-sight images allows the backward interpretation of observations to obtain the three-dimensional structure of the solar phenomena. The main intention of the research is to develop pseudo-imaging techniques of soft x-ray emission to compare with observations in order to investigate the structure of the coronal magnetic field by analyzing the field line and emission characteristics. Data analysis techniques will be applied to the MSFC and Themis/France vector magnetograms and the Kitt Peak National Observatory longitudinal magnetograms to characterize the spatial and temporal changes of magnetic and electric current systems within active regions.

In the Solar Physics Branch at Marshall, research is conducted on solar magnetic fields and their physical associations and effects in the photosphere, corona, and interplanetary medium. Extensive efforts have been carried out in relating the MSFC vector magnetograms to flare theories. This research continues this extremely useful research by describing the observed coronal magnetic structures in the solar atmosphere in relation to the observed photospheric magnetic field on the solar surface. The photospheric field is derived from magnetograms. Using this data and observed x-ray images of the Sun, we are developing general data analysis tools to be used to produce the soft x-ray images by reconstruction and using these images to compare with data (fig. 171). The research objective is directed at the overall goal of being able to define the available free-energy via the three-dimensional magnetic and electric current morphology transversing through the solar atmosphere. The research, in part, is the development of software that will display pseudo soft x-ray images given magnetic field lines, density, and temperature. The development process is as independent of specific models as possible to allow for many models in the final version. The crucial development here is to provide an efficient computer algorithm that renders a three-dimensional volume into a two-dimensional image with adequate quality compatible for analysis and comparison with observations (e.g., from soft x-ray telescope (SXT)/Yohkoh). The code will provide a systematic comparison between (1) observed coronal flux tubes and models, and comparison between (2) coronal flux tubes and their photospheric footpoints. Using existing codes and scaling laws to determine the coronal density and temperatures, and an instrument response code, one can determine theoretically the observed emission characteristics for each volume cell (voxel). This analysis package is the major component of the research. With this software, the backward interpretation can begin; that is having a two-dimensional image, the three-dimensional configuration can be inferred and further studies of coronal temperatures, emission characteristics, field modeling, footpoint and photospheric correspondence will proceed.

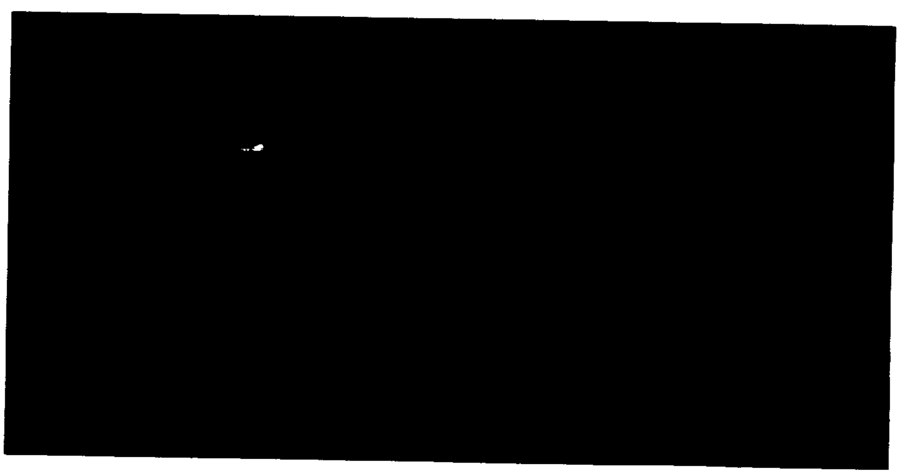

FIGURE 171.—A comparison of a soft x-ray image from the Japanese/American solar instrument SXT/Yohkoh (left) with a set synthesized coronal loops (right) is shown. The synthesized image was produced under the CDDF project. Initial comparison of the results are promising in that the overall morphology of the images are similar. As more detail modelling is included the important physical parameters of the coronal plasma will be established. The views shown here are a low resolution version of the original digital display.

The description of the coronal magnetic field is a key component in understanding solar activity. Hence, this topics is in direct support of flight- and ground-based vector magnetograph programs which are specific NASA programs and a focus of the activities of the MSFC Solar Science Branch. The results are of particular importance to the mechanisms of solar variability (MSV) and space-borne magnetograph programs which are aimed at understanding the physical cause of variations in and from the Sun. The free magnetic energy which drives much of the variation is directly connected to the magnitude of the electric currents and heating in the solar atmosphere. To understand the dynamics of the x-ray imagery (e.g., from Yohkoh) one needs again to understand the electric currents (the source of energy) and the coronal configuration. The general analysis of the magnetic structures and their associate electric current systems will discriminate between contending theoretical models. There is clearly a need for this analysis and relates to observations from the MSFC vector magnetograph and the development of the next generation solar orbiting instruments.

The research program is developing a formal basis for deriving and investigating solar magnetic structures and to obtain a better physical understanding of these results. MSFC magnetograms will be analyzed extensively to characterize the photospheric magnetic fields. The specific strength of this research is that the scientific investigation continues a strong program by the Solar Physics Branch in the area of magnetic field analysis. These studies are of the highest scientific merit to solar physics and are fundamentally important to the NASA Space Physics Program (e.g., Solar-B, Solar Probe, Solar Stereo Missions). The objectives are assured through a thorough technical approach. The relevance of the work to NASA's space physics program lies in the deeper understanding it will provide of the processes underlying the observed structure of solar active regions, which are the main contributors to solar variability in ultraviolet and x rays.

Gary, G.A.: "Rendering Three-Dimensional Solar Coronal Structures." *Solar Physics*, 1996, accepted.

Gary, G.A.: "Potential Field Extrapolation Using Three Components of Solar Vector Magnetogram With a Finite Field of View." *Solar Physics*, 163, 43, 1996.

Falconer, F.A.; Moore, R.L.; Porter, J.G.; Gary, G.A.; Shimizu, T.: "Neutral-Line Magnetic Shear and Enhanced Coronal Heating in Solar Active Regions." *Astrophysics Journal*, 1996, accepted.

Gary, G.A.; Démoulin, P.: "Reduction, Analysis, and Properties of Electric Current Systems in Solar Active Regions." *Astrophysics Journal*, 1995, 445, 982.

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Gary, G.A.; Hagyard, M. J.: "Transformation of Vector Magnetograms and the Problems Associated With the Effects of Perspective and the Azimuthal Ambiguity." *Solar Physics*, 1990, 126, 21.

Gary, G.A.: "Mathematical Basis for the Extrapolation of Solar Nonlinear Force-Free Magnetic Fields." *Memorie della Societa Astronomica Italian*, 1990, 61, 457 .

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Gary, G.A.; Musielak, Z.E.: "A Regularization Method for Extrapolation of Solar Potential Magnetic Fields." *Astrophysics Journal*, 1992, 392, 272.

Sponsor: Center Director's Discretionary Fund (CDDF)

Educational Involvement: The MSFC Student Volunteer Service Program (SVSP) has provided useful research experiments to local high school students.

Biographical Sketch: G. Allen Gary received his Ph.D. in physics in 1969 from the University of Georgia. He is in the Solar Physics Branch at Marshall Center, investigating the nature of coronal structures and solar magnetic fields. His research also includes the general study of the magnetic field's configuration, evolution, and morphology together with estimation of the energy content of active regions. His theoretical work involves developing models of linear and nonlinear force-free magnetic fields and electric currents in the solar chromosphere-corona.

Fractal Analyses of Sunspot Magnetic Fields

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One of the major challenges for solar physics is the understanding of the physical mechanisms which are responsible for the onset of solar flares. Observational data indicate that solar flares and sunspots are strongly linked and that the global structure of the sunspot magnetic field is a factor in the probability for flaring activity; more magnetically complex solar active regions flare more often. Through the use of data obtained with MSFC's vector magnetograph, MSFC and University of Alabama in Huntsville (UAH) solar scientists continue to study sunspot magnetic fields, the presumed source of energy for the solar flares, with fractal techniques of data analysis.

In the late 1970's Benoit Mandelbrot created the term "fractal" to describe objects which are complex on their boundaries and have self-similar subsections. Since that time, fractal-based models have commonly been used to understand natural phenomena that produce irregular structures and to describe complex, rough surfaces. Therefore, it seems reasonable to use the fractal dimension (D_f) to describe the irregularity or complexity of a solar active region and to relate variations in the magnitude of the fractal dimension to flaring activity.

In previous work, MSFC scientists teamed with scientists from UAH to study a fractal technique known as range over standard deviation experimental trend analysis (ROSETA) and identified tantalizing changes in the fractal dimension prior to a solar flare. However, the ROSETA technique is an unfamiliar tool for data analysis and its limitations in this regard have not been studied. Therefore, since ROSETA is based upon a classic fractal algorithm (Hurst's rescaled range analysis), MSFC scientists have, over the last year, conducted studies to determine the efficacy of that and other fractal techniques for sunspot magnetic field research. One study concentrates on Hurst's rescaled range analysis,[1] the other[3] examines a differential box bounting (DBC) method and the Jaenisch technique.

Classical Hurst analysis involves calculating the exponent, H, from well accepted statistical parameters, the standard deviation (S) and the range (R), for various subsets of the data. Hurst exponents are related to the fractal dimension, D_f, by $D_f = 2–H$. A major drawback to the Hurst technique is the transformation of the two dimensional data set to one-dimension, since small scale changes may be masked by the conversion process. The techniques evaluated in the study of Stark et al (1996), differential box counting and Jaenisch, do not require any alteration.

All of the above techniques, Hurst, DBC, and Jaenisch, were applied to three types of data: constructed data, model sunspot data, and MSFC vector magnetograph observations. We find that the Hurst method is sensitive to differences between the constructed data sets illustrated in figures 172 (a) and172 (b). Applying the DBC method to these same data sets shows a systematic increase in the value of the fractal dimension as the complexity of the images increases (i.e., fig. 172 (a) and 172 (c)). The Jaenisch method, on the other hand, is unable to discern the difference between two visually different data sets (fig. 172 (a) and 172 (b)).

Results from fractal analysis of magnetograph data are quite interesting. A series of 10 vector magnetograms obtained throughout the day on June 10, 1991, spanned a large flare which began at 13:45 UT (the start time which is reported in MSFC data records). Hurst analysis was applied to six parameters. Although only the Hurst exponent calculated from the shear parameter[2] shows statistically significant variations over time (fig. 173),

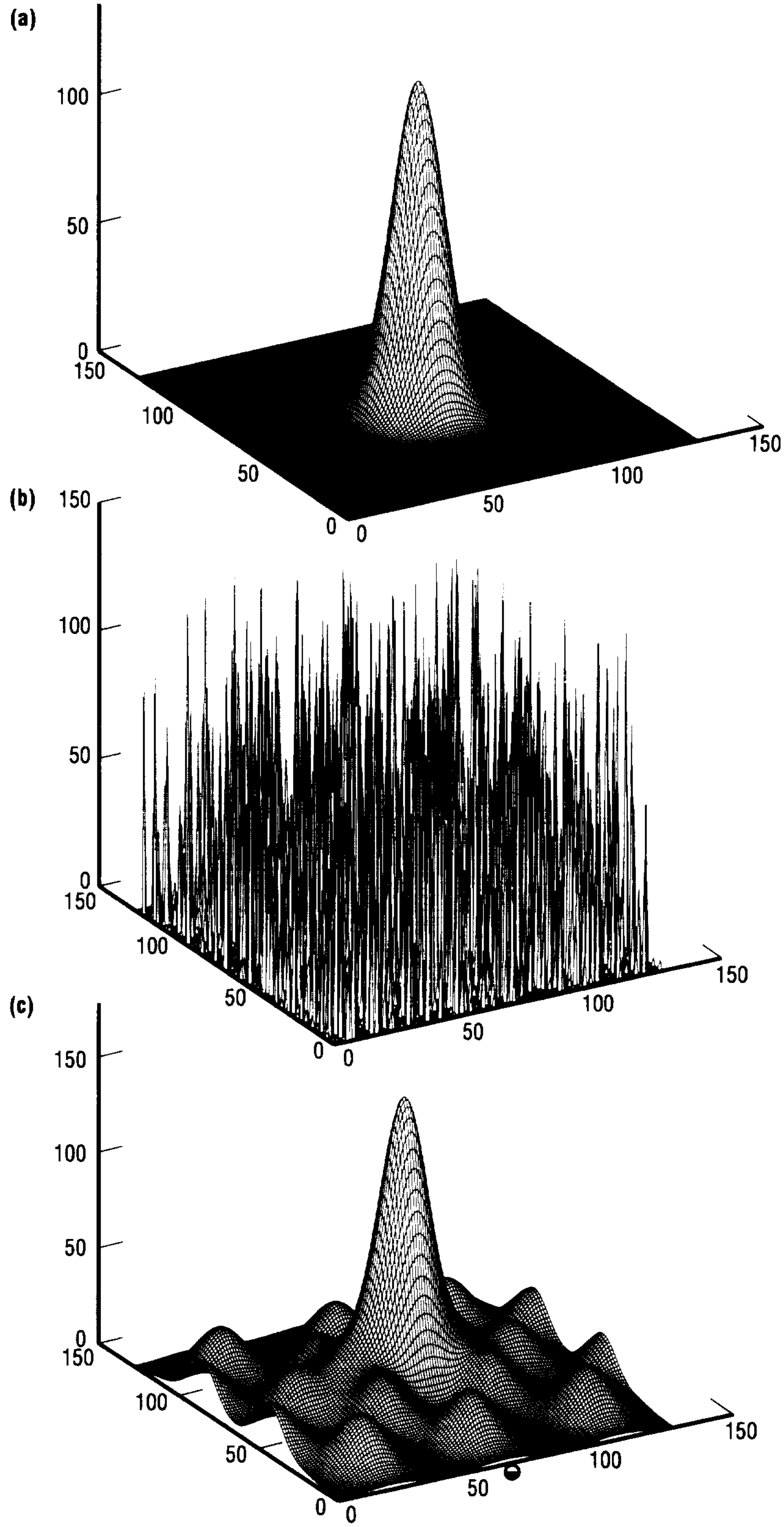

FIGURE 172.—These are examples of the test data: (a) a gaussian surface; (b) has the same array values as (a), but the positions of the data within the array are randomized; (c) a gaussian surface with offset gaussians of 20 percent amplitude of original gaussian (a).

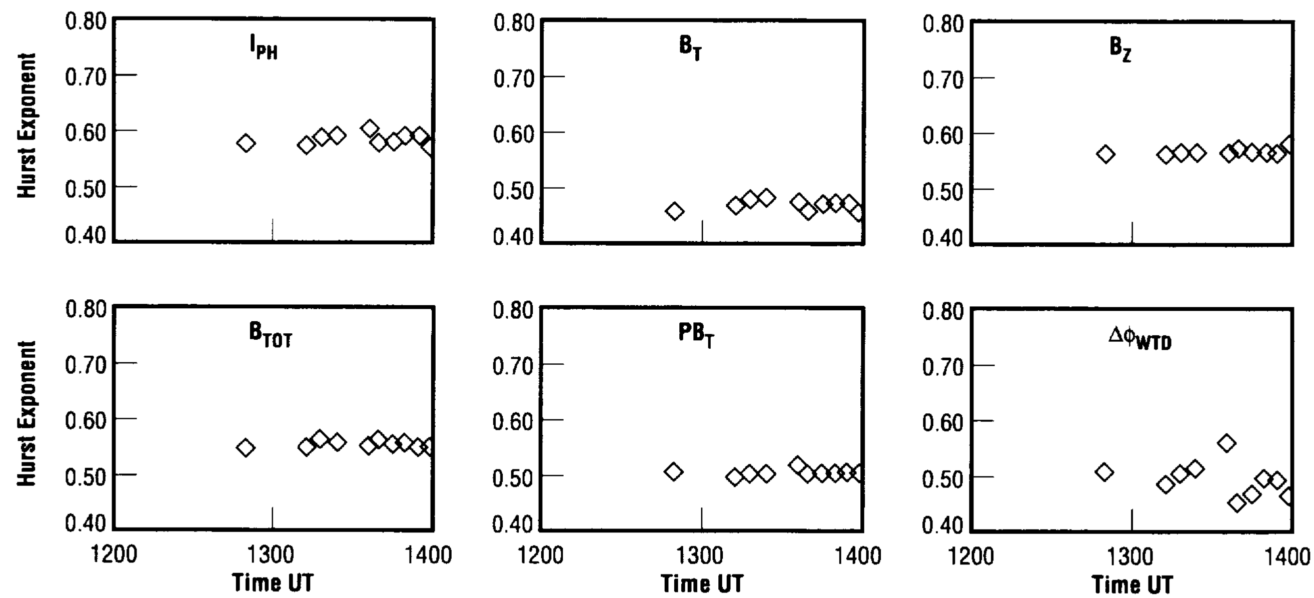

FIGURE 173.—Plots of Hurst exponents as a function of time for various parameters. Reading from left to right and top to bottom, the parameters are: photospheric (white-light) intensity (I_{ph}), the transverse component of the magnetic field (B_T), the line-of-sight component of the field (B_Z), the total field ($B_{TOT} = (B_T^2 + B_Z^2)^{1/2}$), the transverse component of the potential field (PB_T), and weighted shear angle (Df_{WTD}). Only the shear parameter Df_{WTD} shows any significant variation.

this pre- and post-flare behavior suggests that Hurst analysis should be further considered as a possible flare prediction tool.

The DBC method was tested for sensitivity to small scale changes by altering small numbers of pixels within a magnetogram image array. The DBC fractal dimension, as calculated from the unaltered data, differs from the altered data by an amount which is comparable to the effects induced by instrumental noise and is therefore not a useful tool for detecting flare related changes within the sunspot magnetic field.

Our studies indicate that the Hurst method may have some usefulness in detecting global changes over the field of view of a solar vector magnetogram. However, further work should address the most effective method of removing large-scale structures from the data and should investigate the effect of isolating magnetic areas of interest (image masking) to avoid the inclusion of random photospheric measurements in the value of the Hurst exponent. The lack of sensitivity of the DBC method to small scale changes may also benefit from a masking technique to distinguish between the sunspot and the photospheric background These issues will be addressed in the future studies.

The analysis of flare-related changes in sunspot magnetic fields can be quite challenging, since the magnetogram images on which we rely may be contaminated by instrumental effects or atmospheric seeing. Understanding the changes induced by these and other influences and deconvolving them from those caused by solar flares is a necessary step toward solar flare prediction. As we embark upon activities which place us in environments susceptible to the harmful effects of energetic particles and radiation produced by solar flares, the important role of the "solar weather person" is clear.

[1]Adams, M.; Hathaway, D.H.; Stark, B.A.; and Musielak, Z.E.: 1996, *Solar Physics*, accepted.

[2]Hagyard, M.J.; Smith, J.B., Jr.; Teuber, D.; and West, E.A.: 1984, *Solar Physics*, 91, 115.

[3]Stark, B., Adams, M., Hathaway, D.H., Hagyard, M.J.: 1996, *Solar Physics*, in press.

Sponsor: Office of Space Science

University Involvement: University of Alabama in Huntsville

Biographical Sketch: Mitzi Adams is a solar scientist for the Solar Physics Branch of the Space Sciences Laboratory. Her research involves the study of sunspot magnetic fields and the detection of changes in these fields before, during, and after a solar flare. She is currently developing techniques for studying magnetic field data using the concept of fractal dimension. Adams received a bachelor of science degree in physics from Georgia State University in Atlanta, and a master of science in physics from the University of Alabama in Huntsville.

Space Physics

Ultra-Fast Measurements With the Pinhole Ion Velocity Imager

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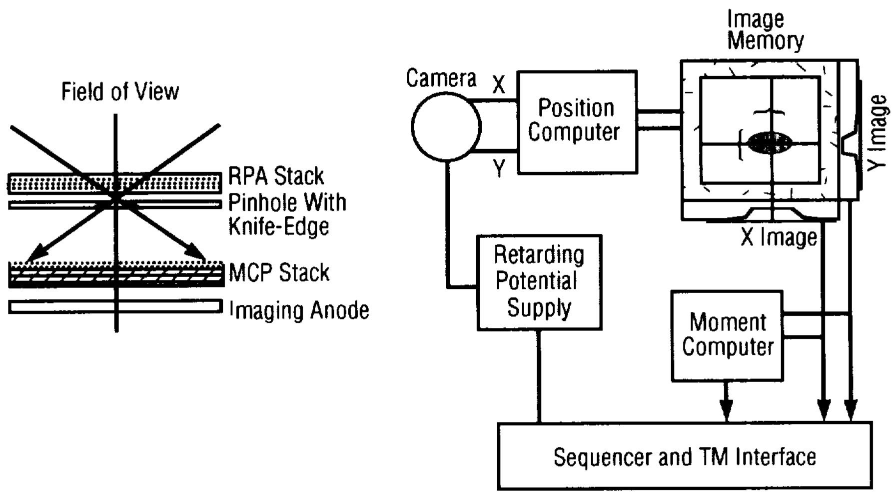

FIGURE 174.—A cross-section drawing of the pinhole camera with its functional schematic. The UV diffraction grating filter is not shown.

Results from recent sounding rocket experiments have led to an increased emphasis on resolving smaller scale ionospheric plasma structures than can be achieved with present methods. For these previous rocket flights, three-diminsional ion velocity distribution measurements were provided by the Scanning Thermal Ion Composition Spectrometer (STICS)[1,2] by varying voltages to measure the particle energy, its incident angle in one direction, and its mass. The spinning of the rocket was used to measure the second angle and therefore obtain the third dimension in velocity. A new charged particle imaging detector called the pinhole ion velocity imager (PIVI) is in development to permit ultra-fast two-dimensional image sampling of the plasma in order to resolve narrow spatial features and fluctuations while traveling at high velocities. The two-dimensional images are reduced on board to parameters used to calculate and describe the macroscopic properties of the plasma given by the density, temperature, and flow velocity components. Faster methods of measuring these characteristics of the plasma at the lowest possible energies are the only way to attain a clearer understanding of the mechanisms involved in particle transport and heating of the ionosphere.

The essential part of the PIVI design is a pinhole aperture used to view the rammed plasma. This pinhole mounts on top of microchannel plates which are thin plates of a million tiny glass channels used to amplify the incident charged particle for detection. Below the MCP stack, an anode with four charge-sensitive outputs resolves the position of the incident particle into two dimensions so that each particle event is separated into X and Y coordinate positions. Other components of the PIVI design are a diffraction grating filter and a retarding

	1	2	3	4	5
Total # of Cnts.	1.23E4	1.0E4	0.98E4	0.94E4	0.90E4
Average X:	68.46	85.66	100.71	121.05	137.47
Average Y:	167.03	175.43	184.86	196.19	208.46
Std. Deviation X:	14.94	19.92	24.90	21.91	17.93
Std. Deviation Y:	20.92	24.90	22.91	18.93	21.91

FIGURE 175.—Five pinhole images from initial testing of PIVI and the computed averages and standard deviations after collapses in both the X and Y dimensions.

potential analyzer (RPA). The filter is on top of the pinhole to suppress unwanted ultraviolet while maintaining sensitivity to the charged particles. Below this diffraction grating is the RPA that selects the incident particle's energy/charge and is managed by a feedback system that varies the energy voltage as it monitors the count rate. Figure 174 shows the cross-section drawing of the pinhole imager and a functional schematic.

During each accumulation, histograms are developed in memory of the number of particle events versus their incident X and the Y position value. In parallel with this time period, the total number of counts, the average, and the standard deviation of the X and Y histograms from the previous accumulation is computed and the memory is reset. Figure 175 shows an example of five pinhole images obtained during initial testing of the PIVI. The pinhole aperture was rotated below the particle source in 5-degree increments and a 60-sec accumulation was taken at each step. A crosshair is placed at the centroid of the image. The table lists the total number of counts, the average and the standard deviation in pixel units for each image dimension. The characteristics of the plasma given by the density, temperature, and flow velocity components are determined with these reduced parameters, the knowledge of the pinhole camera dimensions, the particle energy, and the spacecraft velocity.

PIVI will also provide a significant improvement in our present capability to diagnose the ion source in the low-energy electron and ion facility (LEEIF). This particle source is used for the testing and calibration of instruments before their flight and therefore it is very important to be able to routinely measure the characteristics of the ion source while testing. This pinhole camera design will yield rapid diagnosis of not only the spatial distribution but also the angular distribution of the ion source, which has never been obtained before.

[1]Coffey V.N.; Moore T.E.; Pollock C.J.: The Scanning Thermal Ion Composition Spectrometer. AGU Monograph on Measurement Techniques for Space Plasmas, submitted, 1996.

[2]Moore T.E.; Chandler M.O.; Pollock C.J.; Reasoner D.L.: Plasma Heating and Flow in an Auroral Arc. *Journal of Geophysical Research*, vol. 101, pp. 5279–52971, 1996

Sponsor: Center Director's Discretionary Fund

Other Involvement: Dwight England and Dean Alford, Astrionics Laboratory.

Biographical Sketch: Victoria N. Coffey joined NASA/MSFC in 1984 and supports the flight instrument programs in the Space Physics Branch. She has optimized particle throughput designs, tested and calibrated the instruments before flight, and analyzed flight data to study ionospheric transport processes. She is currently completing her master's degree in physics at UAH.

Plasmaspheric Total Densities

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Because of spacecraft charge, the plasma density measured from spacecraft by particle and wave instruments can be different. The wave measurement derived densities are obtained in such a way that they are not affected by spacecraft charge but they can not always measure composition as can the particle instruments. Each instrument type has its own advantages and limitations. By using both types of instrumentation, more can be learned about the Earth's plasma environment and in some cases, the spacecraft response to the ambient environment. At MSFC, we are taking advantage of the data from the plasma wave instrument (PWI) and the retarding ion mass spectrometer (RIMS) on Dynamics Explorer 1 to explore and expand our understanding of the plasma in the inner magnetosphere. PWI data in the form of total electron densities are being supplied to MSFC by the University of Iowa (the home institution of the PWI principle investigator, Dr. D. Gurnett). Investigators at MSFC and the University of Iowa are cooperating in a study of the plasma-spheric response to geomagnetic and solar input and in an attempt to build a data base on which a global model of the total plasma density can be based. The global model can then be used in space weather applications or in other studies that support future mission such as those that have the purpose of obtaining data on a global scale.

The first step in this study is the examination of the of the plasma density in thew plasmasphere, and that is the purpose of the cooperative effort between MSFC and the University of Iowa. The plasmasphere is a doughnut-shaped area centered on the Earth that contains cold dense plasma. Figure 176 shows a small sampling of the data from PWI in the form of density as a function of

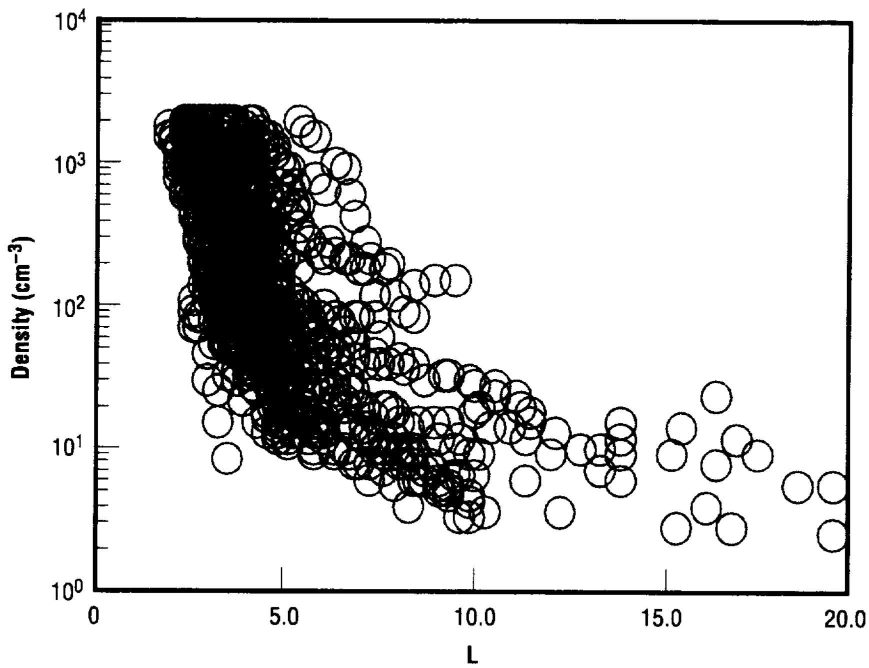

Figure 176.—Density derived from wave measurements as a function of the McIlwain L parameter.

the McIlwain L parameter, a parameter related to the ambient magnetic field. Notice the sharp decrease in the density near L=5. This is the plasmapause and marks the outer edge of the plasmasphere. The position and shape of the plasmapause changes in response to the geophysical environment so that the decrease covers a rather wide range of L values in figure 176. We are presently enlarging the data base of these profiles. When completed, the data base will contain multiple years of data, to which RIMS particle observations can be added to give information on the energy, mass composition, and spatial extent of the plasma.

Sponsor: Office Of Space Science

University Involvement: Dr. Douglas Menietti and Chris Piker at the University of Iowa; Dr. R. H. Comfort at the University of Alabama in Huntsville/Center for Space Plasma and Aeronomy Research.

Biographical Sketch: Dr. Paul Craven has been involved with the analysis of data from the RIMS instrument analysis and is presently working with the thermal ion dynamics experiment instrument on the polar spacecraft. Craven's research interests include the source, transport , and energization of the magnetospheric ions. He received his Ph.D. in physics from the University of Alabama in Huntsville in 1993.

Imager for Magnetopause-to-Aurora Global Exploration

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The Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) mission, led by Dr. James L. Burch of Southwest Research Institute, is the first for all-remote sensing of the Earth's magnetospheric environment. Almost 40 years of point-by-point, in-situ measurement of particles and fields in the terrestrial magnetosphere has led to a detailed understanding of micro- and meso-scale physical processes. The modern challenge in magnetospheric physics is the synthesis of these scattered measurements in space and time into a coherent global picture of energy transport from the solar wind into the ionosphere and particle transport from the ionosphere out into the magnetosphere. The IMAGE mission will provide images of the time-changing ring current, plasmasphere, aurora, and magnetopause. The global morphology of these individual plasma systems and the interrelationships between them will be revealed in a way never before possible.

Along the 45,000-km by 1,000-km altitude polar orbit, six instruments will remotely measure the state of the magnetosphere. Energetic neutral atoms (ENA) emitted by magnetospheric plasmas will be imaged in three energy ranges, low (10 to 300 eV), middle (1 to 30 KeV), and high (10 to 200 KeV). These instruments will measure ENA produced by ions flowing out of the ionosphere at auroral latitudes and produced by energetic ring current ion populations as these populations dynamically respond to magnetospheric storms and substorms. Extreme ultraviolet (EUV) solar light scattered by He^+ ions in the plasmasphere will be imaged by the EUV camera. This cold population of plasma can be used as an indicator of the electric convection forces that dominate storm-time dynamics in the inner magnetosphere. The aurora will be imaged in far ultraviolet light and be used as a familiar guide to the dynamic state of the magnetosphere. The densities and motions of magnetospheric plasmas will be sampled remotedly by the radio plasma imager (RPI). The RPI will broadcast coded pulses of radio waves from 3 kHz to 3 MHz and measure the direction of arrival, time delay, and frequency of returning echos.

Researchers in the MSFC Space Plasma Physics Branch are participating in the university, industry, Government partership that comprise the IMAGE team. Our role involves participation in the development of flight instrumentation, environmental modeling, and the development of data analysis techniques. Led by the Applied Physics Laboratory at Johns Hopkins University, MSFC is participating in the development of the high energetic neutral atom (HENA) camera. This instrument will measure energetic neutral atoms of hydrogen and oxygen. These atoms are produced with high-energy ring current ions that are neutralized through collision with the cold neutral hydrogen gas that extends to high altitudes from our terrestrial atmosphere. The development of auroral cameras is led by the University of California at Berkeley. MSFC is responsible for working with researchers in Canada to provide the wideband imaging camera (WIC) that will measure the far ultraviolet light produced when electrons bombard the upper atmosphere, producing auroral light.

The IMAGE theory and modeling effort is jointly led by MSFC and Rice University. Modeling is required for this mission for the purpose of defining necessary instrument capabilities and for the purpose of preparing the necessary techniques that will be required to interpret the measurements that will be returned. The approach taken by the theory and modeling team has been toward the development of a single, consistent time dependent model for the magnetosphere. The model component for the plasmasphere will be used together with the model for the ring current in order to compute ring current decay due to collisions. Ring current losses into the auroral ionosphere will be used to estimate diffuse auroral photon emissions and to estimate precipitation-driven outflow of plasma from the ionosphere. To these plasma systems, models are being added for polar cusp and magnetosheath plasmas. All models will be "geared" to conditions in the solar wind and all will share use of the Rice magnetospheric specification model (MSM) for the computation of convection electric fields. The Rice Toffeletto-Hill magnetic field model will also be shared by all team members for defining the terrestrial magnetic field near the Earth and at high latitudes.

MSFC and associated researchers are involved in modeling the plasmasphere, the ring current, and auroral ionospheric outfow. This modeling is now being used to support decisions related to the detailed designs of ENA cameras and the EUV camera. An example of that modeling is shown in figure 177. The intensity of scattered solar ultraviolet light at 30.4 nm is shown for a noon-midnight scan across the inner magnetosphere, as would be seen by an observer located about 45,000 km above the north magnetic pole. The scan is centered on the Earth and negative angles are toward the Sun. The reduced intensities at positive angles is because much of this plasma is in the Earth's shadow. The intensity hole at small angles is due to the greatly reduced He^+ densities over the polar region. The density peak at small negative angles is due to the dayside ionospheric density peak in He^+ ions. The plasma-spheric regions of particular interest in the IMAGE mission are those in the outer plasmasphere, where densities and consequently intensities are relatively low. The EUV instrument, therefore, must be designed with sufficient sensitivity to see scattered ultraviolet light with intensities as low as a 0.1 Rayleigh, while avoiding saturation by intensities close to the Earth, that may be more than 150 Rayleighs.

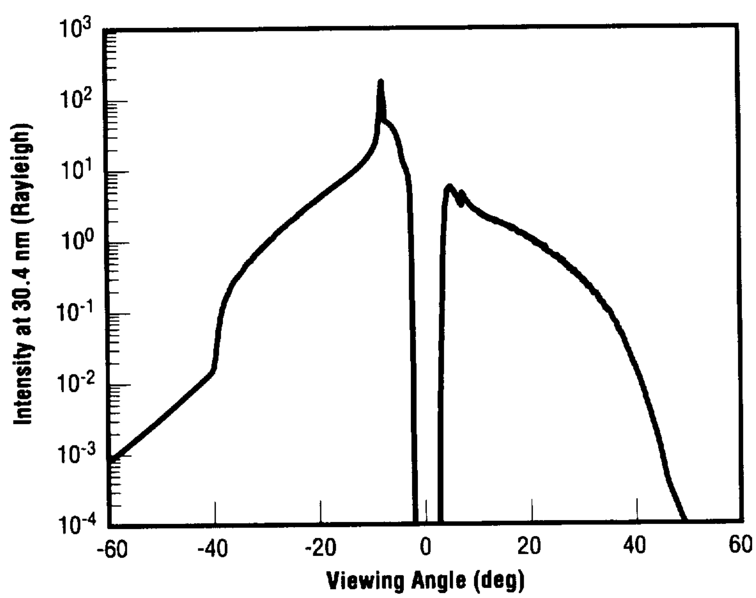

FIGURE 177.—The intensity of 30.4 nm solar radiation scattered by He^+ ions in a model plasmasphere is shown for an observer located at an altitude of about 45,000 km over the North magnetic pole.

Gallagher, D.L.; Craven, P.D.; Comfort, R.H.; and Moore, T.E.: On the Azimuthal Variation of Core Plasma in the Equatorial Magnetosphere. *Journal of Geophysical Research*, vol. 100, pp. 23597–23605, 1995.

Ober, D.; Horwtz, J.L.; and Gallagher, D.L.: Convection Effects on Global Plasmasphere Evolution. 1995 Cambridge Symposium Workshop: Multiscale Phenomena in Space Plasmas, February 20–25, 1995.

Sponsor: Office of Space Science

University Involvement: Mei-Ching Fok, Universities Space Research Associates; Joe Perez, Auburn University/Physics Department; Pat Reiff, Rice University/Department Physics and Astronomy; Gordon Wilson, University of Alabama in Huntsville/Center for Space Plasma and Aeronomy Research

Biographical Sketch: Dr. Dennis L. Gallagher received his Ph.D. in physics at the University of Iowa in 1982. He joined NASA/MSFC in 1984 with responsibilities for conducting magnetospheric plasma physics research and for coordinating the use and development of computer and networking resources for the Space Sciences Laboratory. Today Gallagher is dedicated exclusively to space plasma research and is a co-investigator in the IMAGE mission. His primary focus is on the modeling and simulation of cold plasma ions in the inner magnetosphere.

Imaging the Aurora in the Far Ultraviolet

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The aurorae, seen from Earth as dancing curtains of green and red light concentrated in the polar regions, have captured the fancy of people throughout the ages. Scientists have known for several years that this light is a result of electrons and protons that are energized (accelerated) by the Earth's magnetic field and collide with the Earth's atmospheric constituents, namely atoms and molecules. How much energy is deposited in the auroral zones as a result of this process? How does the energy vary with changes in a solar-terrestrial environment? What was the origin of these energetic electrons and protons, and what was their path ending in collisions in the Earth's atmosphere? What is the source or impetus of the accelerating energy? What triggers a substorm, the sudden intensification of the aurora lasting for hours? These questions are significant to our understanding of the interplay between the Sun and the Earth.

The successful launch and activation of the ultraviolet imager (UVI) in February of 1996 will help scientists find answers to these questions. The UVI is a wide-angle camera that is sensitive in the nonvisible far-ultraviolet wavelength regime (130 to 190 nm). As such it images the light that results from precipitating energetic electrons both on the sunlit and night sides of the Earth. Images of the entire northern aurora, such as figures 178 and 179, are taken enabling the simultaneous correlation of different regions in the aurora with a time resolution of 37 sec. The special state-of-the art filters used in the UVI allow the imaging of different emissions in the far ultraviolet. This results in the ability to quantify the total energy and the characteristic energy of the electrons as a function of time and location on the globe. In concert with data from other instruments on several satellites

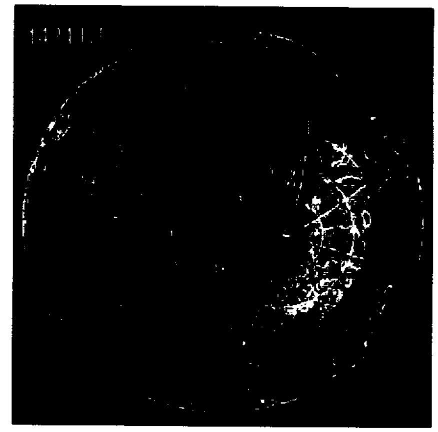

Figure 178.—This image was taken on April 9, 1996, at 14:34 UT. The sunlit portion of the Earth is on the right, over Greenland. In this image the night side aurora is calm as denoted by the thin blue feature.

Figure 179.—This image was taken on April 9, 1996, at 14:44 UT, only 10 min after figure 178. In this image, the onset of a substorm can be seen on the night side over the coastline of Siberia.

and ground-based observatories, scientists around the world participating in the International Solar Terrestrial Physics Program (ISTP) will make use of the UVI images to study the source of the energetic electrons and phenomena that cause their energization.

Torr, M.R.; Torr, D.G.; Zukic, M.; Johnson, R.B.; Ajello, J.; Banks, P.; Clark, K.; Cole, K.; Keffer, C.; Parks, G.; Tsurutani, B.; and Spann, J.:"A Far Ultraviolet Imager for the International Solar Terrestrial Physics Mission." *Space Science Review*, vol. 71, pp. 329–383, 1995.

Sponsor: Office of Space Science

University Involvement: George Parks and Mitch Brittnacher at the University of Washington, Geophysics Program, Glynn Germany at the University of Alabama in Huntsville/Center for Space Plasma and Aeronomy Research.

Biographical Sketch: In 1984, Dr. James F. Spann Jr., received his Ph.D. in physics from the University of Arkansas. In 1986, he joined NASA/MSFC. During his career at NASA, Spann has been involved with the ultraviolet imager and is a co-investigator. Spann's research interests and experience include design and fabrication of space flight instruments, the interaction of single particles with light and plasmas, and the equilibrium phases atmospheric aerosols.

Tethered Satellite System Reflight Electrodynamic Characteristics

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The Tethered Satellite System Reflight (TSS–1R) mission was launched February 22, 1996, on STS–75. The satellite deployment (flyaway) occurred at 2:45 P.M. Central time (MET 3/00:27). All mechanisms functioned as planned and a unique data set was obtained as the tether was deployed to a length of 19,695 m. At MET 3/05:11 (about 7:30 P.M. Central time) during a day pass, the tether broke, without warning, near the top of the deployer boom.

Operations had begun at satellite flyaway so that significant science activities had already been accomplished and 5 hr of science data gathered prior to the time the tether broke (fig. 180). The data obtained are high quality and contain several unexpected and unexplained results that will be of general scientific interest and are important to future technological applications of tethered systems in space.

The system current that was collected by the satellite, as it was biased to various voltages during deployment, was significantly greater than theoretical predictions, as shown in figure 181. Moreover, the potentials required to attract the observed currents to the satellite were far less than predicted. For example, in figure 181, the Parker-Murphy model[1] predicts that +1000 V are required to collect a current of 140 mA, whereas the TSS–1R data show that this current was collected with only +130 V on the satellite. The values of the satellite potential above 500 V have, at this point, an uncertainty of about 15 percent and the theoretical curve may shift slightly when the ionospheric characteristics are better determined. However, the disagreement between the measurements and the

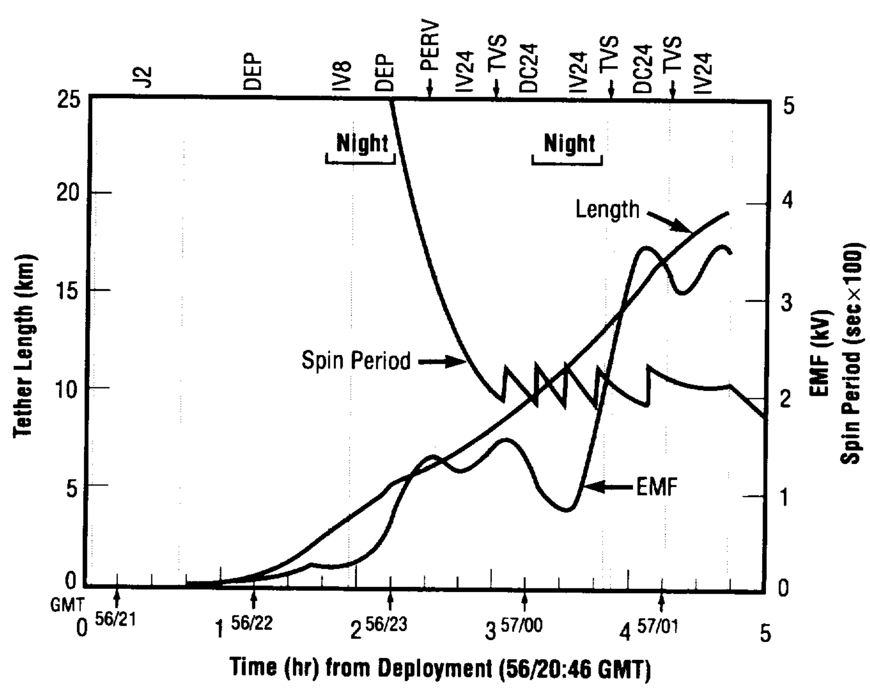


FIGURE 180.—The TSS–1R data set and conditions under which it was obtained.

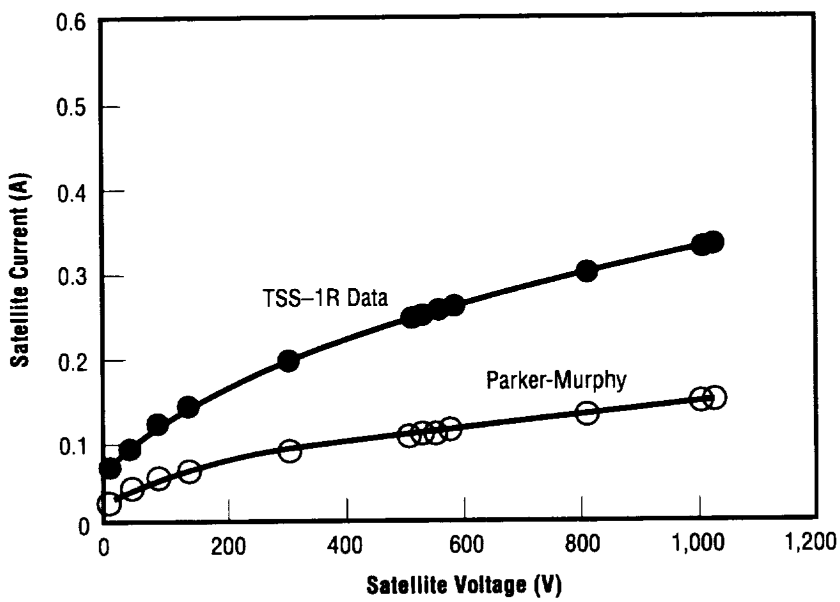


FIGURE 181.—Measured TSS–1R and theoretically predicted current-voltage relationships.

theoretical potential requirements is a factor of ten—far greater than the existing uncertainties.[2] This disagreement may result from orbital motion, which appears to introduce additional physical processes into the tether systems' interaction with the ionosphere. These processes would not be expected to occur in the static case treated by the theoretical models.

The highest current observed during the mission was produced by the tether break event; i.e., approximately 1 A with the tether deployed 19.7 km and developing an emf of 3.5 kV (table 13). By contrast, the Parker-Murphy model predicts a tether current of only 540 mA for these conditions—even with the unrealistic assumption that, except for the IR drop in the tether, all of the tether emf was available to collect electrons at the satellite (i. e., no voltage required for charge collection at the orbiter). In fact, a 600 V potential drop was observed between the orbiter and the ionospheric plasma. Even more surprising, the tether current did not change appreciably as the tether broke and separated from the Orbiter. The orbiter potential and tether current, measured at the orbiter, both vanish—indicating no contact with the tether—while the satellite potential and tether current measured, at the satellite, remain approximately unchanged across the break event (table 13). The validity of the satellite current measurement was shown by simultaneous measurements of an elevated satellite potential and a 40-nT magnetic field enhancement at the satellite—both of which were consistent with a tether current of 1 A.

The current collected by the satellite during the break event disagrees with the theory by approximately the same factor as in nominal operations with the tether in tact. Collection of 1 A by the orbiter—even at –600 V—is not fully understood. However, the fact that current closure was unaffected by the tether break was apparently due to the tether construction, which resulted in air being trapped inside the Teflon™ insulation. When ruptured, the escaping gas could easily ignite into an electrical discharge at the high voltages available. This process is under investigation.

The MSFC research on orbital plasma-electrodynamics investigation[3] consistently observed suprathermal (or energetic) electrons, coincident with current flow in the tether, that peaked in flux intensity at an energy of approximately 200 eV. (This is high compared to the ambient ionospheric thermal electrons, which typically have energies in the range of 0.1 eV.) The source of the energy transferred to the suprathermal electrons may come from the

TABLE 13.—*Anthology of the Tether Break Event.*

Observation	3/05:11:00	3/05:11:18	3/05:12:15
Tether Current–Measure at Satellite (mA)	0	960 to 1,100	1,100
Tether Current–Measure at Orbiter (mA)	0	0	0
emf-Measure at Orbiter (V)	3,500	~100	0
Satellite Potential (V)	0	~1,000	>1,000
Orbiter Potential (V)	0	–600	0
Satellite Acceleration (mg)	–8.4	–8.4	0
Conclusion	Tether Intact	Discharge to Orbiter Ground	Tether Open Circuit

reflection of streaming ionospheric ions by the positive space potential in the frontal region of the satellite. The ionospheric ions have 5-eV ram energy (resulting from the orbital motion of the tether system) and, therefore, will be reflected by a 5-V potential. In agreement with this, an outflow of ions from the satellites' plasma sheath was observed, and the potential within the sheath became noisy, whenever the satellite became biased above approximately 5 V.

The Italian satellite was deployed 19.7 km above the orbiter during the TSS–1R mission—making TSS–1R, electro-dynamically, the largest manmade structure ever placed in orbit. The demonstrated capability to extract sizable currents from the ionosphere will have a direct impact on the application of electrodynamic tethers for the production of electrical power or electrodynamic thrust. Scientific investigations can also benefit from space plasma processes that are produced and uniquely controlled by an electrodynamic tether system (e.g., neutral gas-magnetoplasma interactions, generation of various plasma instabilities, generation and propagation of plasma waves, and the transport of energy through electrical currents in plasmas). Such investigations may elucidate the physics of processes that are common to the Earth's environment but much more difficult to study when produced naturally. Clearly, the TSS has opened the door to a new technology that provides exciting new research opportunities, and can contribute significantly to future scientific and technological missions.

Results from the TSS-1R mission are the product of more than a decade of work by the TSS science investigator team; i.e., Carlo Bonifazi, Agenzia Spaziale Italiana (ASI); Brian Gilchrist, University of Michigan; Dave Hardy, USAF/Philips Lab; Stephen Mende, Lockheed; Marino Dobrowolny, ASI; Franco Mariani, 2nd University of Rome; Nobie Stone, NASA/MSFC; Silvio Bergamaschi, Inst. of Appl. Mech.; Adam Drobot, Science Applications International Corp.; Bob Estes, Smithsonian Astrophysical Observatory (SAO); Gordon Gullahorn, SAO; and Georgio Tacconi, University of Genoa. The TSS-1R mission was supported by NASA Headquarters and the data analysis effort.

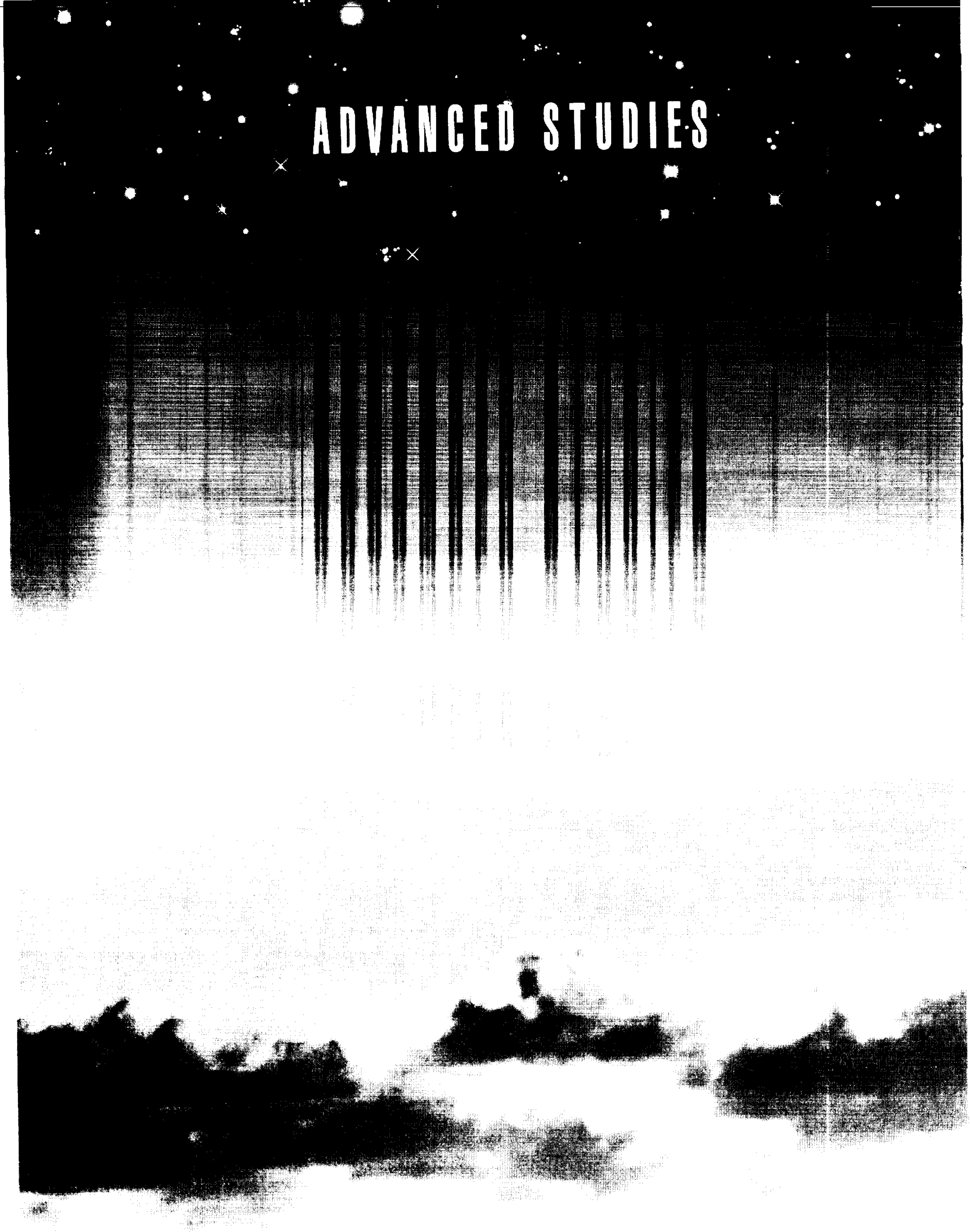
[1]Singh, N.; Wright, K.H., Jr.; Stone, N.H.: "Current Collection From Space Plasmas." NASA Conference Publication, p. 3089, 1990.

[2]Stone, N.H.: "Electrodynamic Characteristics of the Tethered Satellite System During the TSS–1R Mission." AIAA Paper no. 96–4472, 1996.

[3] Stone, N.H.; Wright, K.H. Jr.; Winningham, J.D.; Biard, J.; Gurgiolo, C.: "A Technical Description of the TSS–1 ROPE Investigation." *Il Nuovo Cimento 17C*, 85, 1994.

Sponsor: Office of Space Science

Biographical Sketch: Nobie Stone is an astrophysicist in the Space Sciences Laboratory at MSFC. He received his B.S. and M.S. degrees from Florida State University in 1966 and 1968, respectively, and his Ph.D. degree from the University of Alabama in 1979. He served as project scientist for the TSS program, was mission scientist for the TSS–1 and TSS–1R missions, and is the principal investigator for the TSS–1 and TSS–1R research on orbital plasma electrodynamics investigations.


ADVANCED STUDIES

"Beyond Our Boundaries," the title of this year's Research and Technology Report, is a fitting reminder of what advanced studies are all about: Peering into new areas of scientific and technical interest that may lead to solutions for problems uniquely encountered beyond our boundaries. Consider the difficulty of reboosting an orbiting space station, removing debris from the path of an orbiting spacecraft, developing transportation elements for a return to the lunar surface, or routinely returning payloads from the *International Space Station.* These problems and others are being addressed through the advanced studies now underway within the Program Development Directorate.

Read on to discover more about our work. And we invite you to share your thoughts with us regarding these efforts.

Axel Roth
Director
Program Development

Space Systems

Space Station Reboost Via Orbiter Towing

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The *International Space Station (ISS)* must be periodically reboosted in altitude to counter the effects of atmospheric drag. The primary means of achieving this reboost is via thruster firings of an attached Russian vehicle. Multiple Progress missions are required annually to accomplish this task.

The orbiter (Space Shuttle) could provide the same service, but due to *ISS* design, only early in the assembly sequence. Transfer of propellant from the orbiter to the *ISS* requires complex and expensive system modifications to maintain Station altitude. In contrast, towed reboost of the *ISS* by the orbiter requires minimal new hardware, little changes to existing hardware, and minimal, if any, changes to Station design. Towing would occur late in a mission, and any orbital maneuvering system (OMS) propellant reserved but not used for phasing and docking could be used for towing. Additional OMS "top-off" propellant could be flown on missions having launch performance margins that permit it, providing more propellant for towing. This Station reboost concept makes use of a derivative of the Small Expendable Deployer System (SEDS) and a noncon-ducting, expendable tow line. Orbiter towing appears feasible and attractive for *ISS* reboost during both assembly and operational phases with a nearly one-to-one savings in ISS reboost propellant for each kilogram of OMS propellant expended. Using the orbiter as a supplementary method to reboost *ISS*, particularly in its assembly phase, reduces the risk of sole dependence on Russian vehicles and provides a U.S. contingency reboost capability for relatively low cost. A precursor mission, shown in figure 182, is being studied in which the orbiter tows a significant mass such as a Progress vehicle. Validation of the towing process by such a demonstration enhances capability to perform towing of *ISS* during the assembly and operational stages.

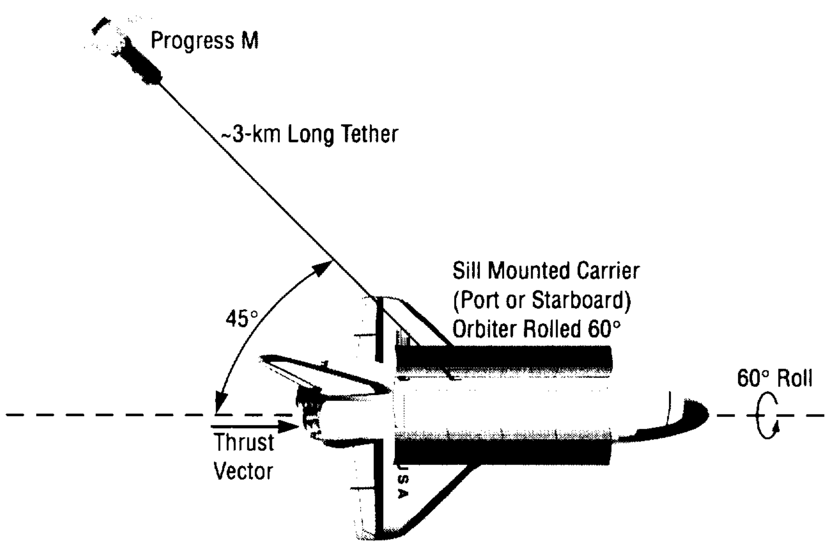

Figure 182.—Orbiter towing-thrust vector along local horizontal.

MSFC, Boeing Defense and Space Group, and Tether Applications: "Downmass Deployment/Disposal From *International Space Station* Using Tethered Systems." Contract NAS8–50000, Schedule F, TOF–007, Final Report, January 1996.

Keller, V., et. al.: "Space Station Reboost Via Orbiter Towing." Paper No. 4252, AIAA Space Programs and Technologies Conference, September 24–26, 1996, Huntsville, AL.

Sponsor: Office of Advanced Concepts and Technology

Industry Involvement: The Boeing Company, Tether Applications Company; Spar

Biographical Sketch: Vernon Keller is the study manager for Space Station reboost via orbiter towing as well as for additional studies of tether applications for the *ISS*. He works in the Advanced Systems and Technology Office, within the Program Development Directorate. He has a B.S. in physics, an M.S. in physics and a Ph.D. in physics with specialty in atmospheric physics. He holds two U.S. patents. He has been employed at MSFC since 1978.

Connie Carrington is the lead systems engineer for *ISS* towing and other tether activities in Program Development. She holds a Ph.D. in spacecraft dynamics and controls, and has 23 years of engineering experience in industry, government, and academics.

Station Tethered Express Payload System

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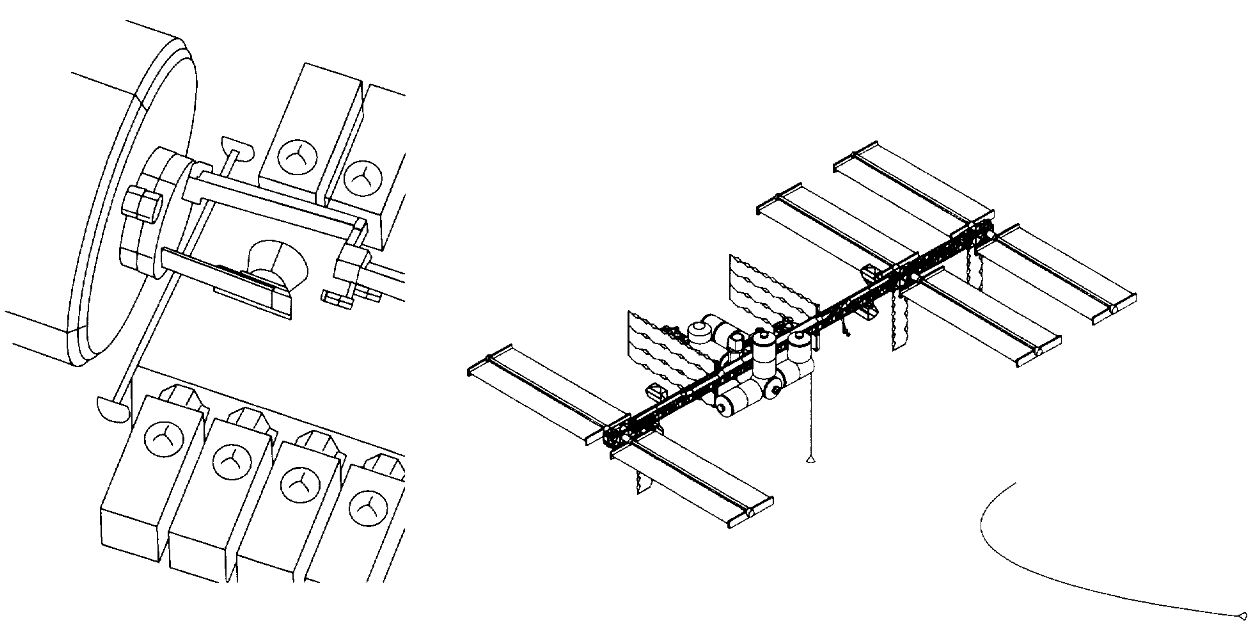
Payload return opportunities from the *International Space Station* to Earth are now limited to the Shuttle, Soyuz, and Raduga. This traffic is being clustered to lengthen microgravity periods on the station, so payload return opportunities are often 2 to 3 months apart. This can be a severe constraint, especially on inherently iterative research and development projects. A NASA SBIR Phase II project is addressing this need for more frequent payload return with Station tethered express payload system(STEPS). STEPS uses Apollo-shaped capsules 78 cm in diameter with a payload capacity of 100 L (3.5 ft^3). STEPS is small enough to fit through the Japanese experiment module airlock allowing deployment without extravehicular activity. STEPS is both deorbited and oriented for reentry by a 2.5 kg expendable tether, so no rocket motor is needed. The tethered deorbit and "kite tail" orienting effect before reentry were both demonstrated on the first flight of the Small Expendable Deployer System (SEDS). The STEPS deployer is a small easily reloadable version of the SEDS deployer. It is part of a reusable ejector/deployer assembly that remains on the Station. The empty capsule plus its tether weigh 10 kg and take only 30 L of storage space. The ejector/deployer stow in a 20×40×100-cm volume. A STEPS precursor flight is planned as a Delta secondary payload. It will test the heat shield, modified SEDS deployer, tether control law, and a soft mid-air recovery technique.

Sponsor: NASA Headquarters, Small Business Innovation Research Program

Biographical Sketch: Charles Rupp is a senior engineer in the Advanced Systems and Technology Office of Program Development and has been working on space tethers since 1975. He helped develop the tethered satellite system and the small expendable deployer system. He also helped provide hardware and software for the plasma motor/generator tether mission flown by the Johnson Space Center and the tether physics experiment flown by the Naval Research Center. Rupp received his BSEE and MSEE degrees from Auburn University in 1961 and 1964 and has been employed by the Marshall Center since 1964.



Capsule and Deployer Mounted on JEM Airlock Arm

Initial Deployment from Station

Beginning of Capsule Reentry

FIGURE 183.—STEPS deployment from *International Space Station.*

Electrodynamic Tethers for Transportation and Power Generation

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Electrodynamic tethers can provide propellantless thrust for free-flying spacecraft or the *International Space Station (ISS)*. As was demonstrated on the Tethered Satellite System Reflight (TSS–1R) mission, they can also generate electrical power. Studies are underway at MSFC to examine the utility of electrodynamic tethers for power generation and reboost of the *ISS* and for propulsion of free-flying spacecraft and upper stages.

TSS–1R drew currents on the order of 1 A, which corresponded to a magnetic force on the Shuttle-tether system of around 0.4 N (though as a drag rather than a thrust due to the direction of current flow in the tether).

An electrodynamic tether can work as a thruster because a magnetic field exerts a force on a current-carrying wire. This force is perpendicular to the wire and to the field vector. If the current flows downward through a tether connected to a spacecraft in Earth orbit, the force exerted by the geomagnetic field on the system has a component that accelerates the spacecraft along the direction in which it is already moving (fig. 184).

An orbiting system, by virtue of its motion through the Earth's magnetic field, experiences an electric field (**VxB**) perpendicular to its direction of motion and to the geomagnetic field vector. For an eastward-moving system, such as the *ISS*, the field is such that the electrical potential decreases with increasing altitude (at a rate of around 100 V/km for the *ISS* orbit). In order to drive a current down the tether, it is necessary to overcome this induced voltage. Thus, such a system requires a power supply and may be considered a type of electrical thruster. Preliminary calculations indicate an average thrust of 0.5 N from 5 kW and 0.8 N from 10 kW. In each case, the tether is 10-km long with a mass less than 200 kg.

Outfitting *ISS* with an electrodynamic reboost tether severs the most critical and constraining dependency on Earth—propellant resupply. The Station can currently supply its own power but not its own propellant. Add a tether to the *ISS* and it is theoretically possible to eliminate the need for propellant resupply!

In addition to *ISS* application, an electrodynamic tether can be used on a free-flying spacecraft or upper stage to raise orbit or change inclination without the use of propellant. MSFC is defining an electrodynamic tether upper stage flight demonstration that will, for the first time, show a measurable boost and inclination change from such a system. The demonstrator would be launched into a 220-km orbit, boost to 500 km, change inclination by 5 degrees, and then deboost back to reentry.

As was demonstrated on TSS–1R and Plasma Motor Generator (PMG) missions, tethers can be used to generate electrical power. For *ISS* the tether would tap electrical energy from the Station's great reservoir of orbital energy to support either a supplementary system for temporary high-demand periods or emergency power applications. A flexible system could deliver a continual power of 6 kW (leveling batteries required to make up an average of 670 W), day and night, or variable output with orbital average power of 9 kW or more depending on requirements and drag

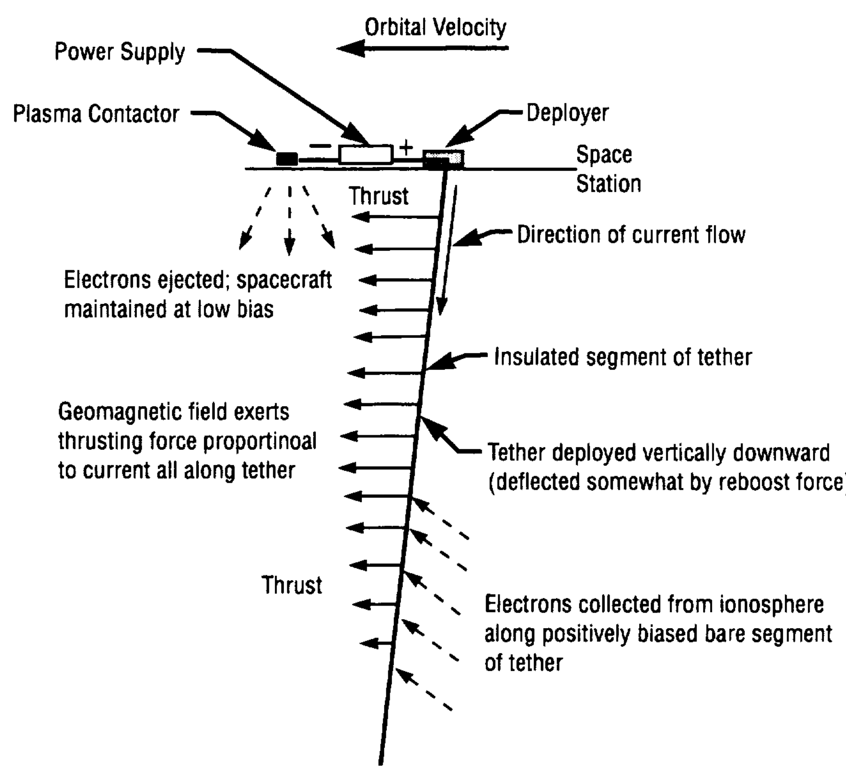

FIGURE 184.—An electrodynamic tether reboost system for the *International Space Station*.

tolerance. A relatively short and light tether (less than 20 km, 300 kg) is required, thus minimizing the impact on the *ISS*.

Tether power is not a "free lunch," however. The Earth's magnetic field exerts a drag force on the current-carrying tether (1 to 2 N for the 6- to 9-kW systems discussed above), thus increasing the reboost requirements of the ISS.

Sanmartin, et al.: *Journal of Propulsion and Power*, vol. 9, 1993.

Sponsors: Office of Advanced Concepts and Technology; Advanced Space Transportation Program

Industry Involvement: The Boeing Company; Tether Applications Company; Tethers Unlimited

Biographical Sketch: C. Les Johnson has a B.A. in chemistry and physics from Transylvania University, Lexington, KY, 1984, and an M.S. in physics from Vanderbilt University, Nashville, TN, 1986. From 1986 through 1990, Johnson worked at General Research Corporation, Huntsville, AL, as task manager for development of neutron sensors for neutral particle beam systems. He began working at Marshall in 1990. He is manager for future tether mission studies and managed the concept definition of the flight-approved Magnetosphere Imager mission.

Atmospheric Tether Mission

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Understanding the plasma and atmosphere around the Earth in the lower altitude regions of the mesosphere and lower thermosphere/ionosphere is important in research of the global electric system. An upper atmosphere tether mission is being considered to collect much needed data and further our knowledge of these regions. The Atmospheric Tether Mission (ATM) would use a set of instruments housed in an endmass that is deployed downward from the Shuttle by a 90-km long tether. The instrument package would cut through the atmosphere collecting data at three different altitudes over a 6-day mission.

A science definition team (SDT) was formed by NASA Headquarters to define the scientific objectives of the ATM. The SDT defined a set of science measurements that together would meet all ATM mission objectives. A summary of these measurement requirements is shown in table 14.

For the ATM mission, the orbiter will enter a 220-km circular orbit at 57 degrees inclination. On the first day, the tethered endmass will be deployed downward 50-km to 170-km altitude and remain there for

TABLE 14.—*ATM scientific measurement requirements.*

Parameter	Dynamic Range	Accuracy	Resolution
Neutral Atmosphere Composition	$10^5 - 10^{11}$ cm^{-3}	<±10% smaller for major species	$\frac{\Delta M}{M}$ = 1 at M=30 5%
Neutral Wind Vector	–500 to 500 m–s^{-1}	±10%	1 m–s^{-1}
Ion Composition	1 to 10^5 cm^{-3}	±10%	$\frac{\Delta M}{M}$ = 1 at M = 16 1%
Ion Drift Velocity Vector	–2 to +2 km–s^{-1}	±10%	1 m–s^{-1}
Ion/Electron/ Neutral Temperature	300 to 3,000 K	±10%	50 K
Electric Field Vector d.c.	–200 to +200 mV–m^{-1}	±10%	0.05 mV–m^{-1}
Current Density/ Magnetic Field	–65 to +65 K–nT	±0.1%	0.01%
FUV Imaging	10 R – 50 KR	0.5%	N/A
Energetic Particles	10 eV to 30 KeV >10^7 to 10^{10} cm^{-2} /s/st/eV	±5%	N/A

2 days. On day 3, an additional 20 km will be deployed, lowering the endmass to an altitude of 150 km for 2 days. On day 5, the final 20 km of tether will be deployed, lowering the endmass to its final 130-km altitude where it will remain for 2 days. The orbiter altitude is maintained by use of the orbiter thruster system. On day 7, the tether is cut and the endmass begins a reentry course.

The preliminary concept of the ATM endmass is seen in figure 185.

Sponsors: Office of Space Flight; Office of Space Science

Industry Involvement: Lockheed Martin, Tethers Unlimited

Biographical Sketch: C. Les Johnson has a B.A. in chemistry and physics from Transylvania University, Lexington, KY, 1984, and an M.S. in physics from Vanderbilt University, Nashville, TN, 1986. From 1986 to 1990, Johnson worked at General Research Corporation, Huntsville, AL, as task manager for development of neutron sensors for neutral particle beam systems. He began working at Marshall in 1990. He is manager for future tether mission studies and managed the concept definition of the flight-approved Magnetosphere Imager mission.

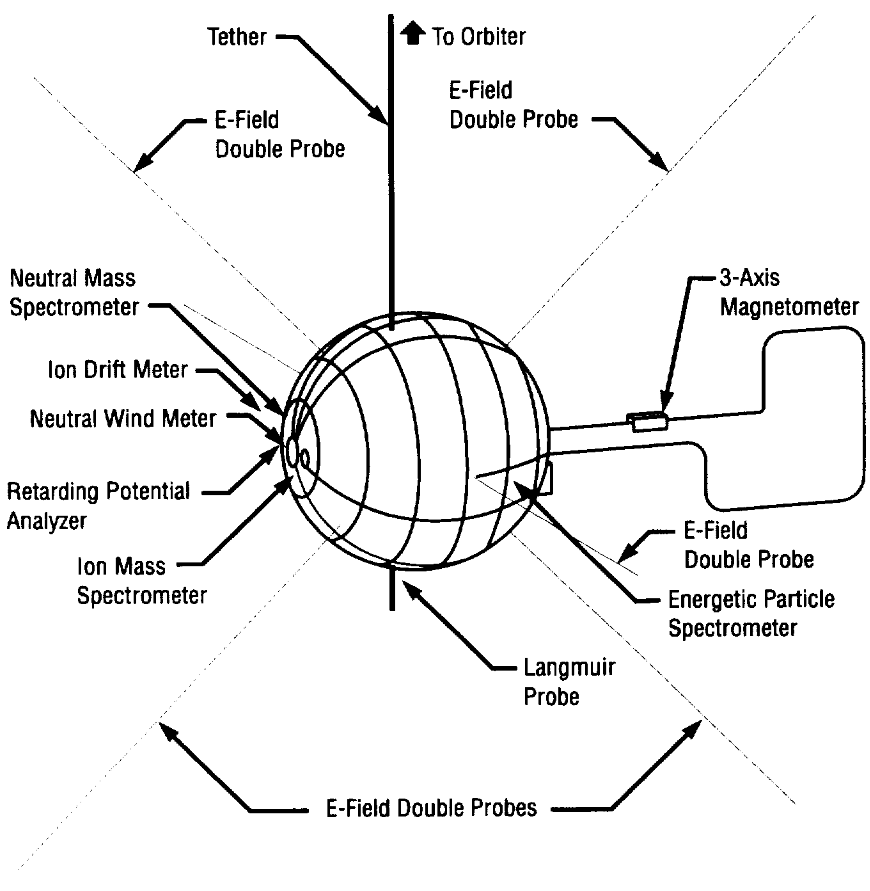

Figure 185.—ATM tethered endmass preliminary configuration.

Project ORION: Orbital Debris Removal Using Ground-Based Laser and Sensor Systems

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Presently, it is estimated there are 150,000 orbital debris particles ranging in size from 1 to 10 cm. This size range is too small to be reliably tracked, too numerous to easily allow avoidance mitigation, and too large to easily allow shielding mitigation. This debris at altitudes above 200 km pose a significant threat to many low-Earth-orbit space-based platforms such as Space Station. A study was conducted to determine the feasibility of using ground-based laser and sensor (e.g., radar) systems to remove this debris.

This study was initiated by Ivan Bekey at NASA Headquarters, co-sponsored by the USAF Space Command, and included a team of laser experts managed by Dr. Jonathan W. Campbell at MSFC. The study team included the USAF Phillips Laboratory, MIT Lincoln Laboratories, MSFC, Northeast Science and Technology, Photonic Associates, and the Sirius Group.

The objective of this work was to determine the feasibility of using ground-based lasers and sensors to accomplish orbital debris removal.

All aspects of the problem were considered including the nature and characteristics of the orbital debris population, the interaction of a number of different lasers and radars with the spectrum of debris categories, laser atmospheric transmission effects, available laser and sensor technology, and associated costs. Current and near-future laser technology are not sufficient to vaporize a debris particle in low-Earth orbit; however, a thin layer of the debris surface can be ablated. This ablation then provides a small change in the orbital velocity of the particle. If the point of interaction is chosen carefully by the laser operator, this velocity will lower perigee. A pulsed laser produces a large number of these interactions over a short period of time ultimately bringing perigee below the critical altitude of 200 km. Below these altitudes, atmospheric drag will dictate particle reentry in a few hours to a few days at most.

The study was completed successfully showing that it was feasible with substantive margin to remove orbital debris by using ground-based systems.

The launch costs associated with shielding just one critical asset, the space station, against 1- to 2-cm debris is estimated to be on the order of $100 million. For a similar cost, all debris could be removed below 800 km and all space-based assets at and below these altitudes could be protected.

A demonstration experiment could be accomplished for about $20 million using existing off-the-shelf laser and sensor hardware. This experiment would demonstrate the feasibility of detecting, tracking, pointing, and changing the orbit of selected debris targets using a ground-based laser/sensor system.

Also, the study revealed that for $60 million using near-term technologies all orbital debris below 800 km could be removed, thus protecting Space Station and all other assets at these altitudes. This operational system would consist of a Nd:glass laser operating at 1.06 μm with a pulse width of 5 ns operating at a rate of 1 to 5 Hz. It would have 3.5 m diameter optics, operate with a single sodium guide star, and produce 5 kJ pulses.

For an additional $80 million, more exotic technologies might be employed to remove all orbital debris below 1,500 km.

NASA TM Project Orion: Orbital Debris Removal Using Ground-Based Sensors And Lasers.

Sponsor: NASA Headquarters; Office of Aeronautics; USAF Space Command

University/Industry Involvement: USAF Phillips Laboratory; MIT Lincoln Laboratories; Northeast Science and Technology; Photonic Associates; and the Sirius Group.

Biographical Sketch: Dr. Jonathan W. Campbell is an astrophysicist/space scientist working in the advanced concepts area of Marshall Space Flight Center's Program Development Directorate. Dr. Campbell holds five degrees, including a Ph.D in both engineering and science from both the University of Alabama and Auburn University. He is a colonel in the U.S. Air Force Reserve and a certified instrument flight instructor.

Transportation Elements for the Human Lunar Return Study

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Within the Agency's Strategic Plan, Johnson Space Center (JSC) is the lead for implementing the Human Exploration and Development of Space (HEDS) Enterprise. Because of this assigned responsibility, Mr. Daniel Golden, the Agency Administrator, challenged JSC in the fall of 1995 to develop an innovative strategy for returning man to the Moon and beyond at mimimum cost. One response to this request was to immediately open an in-house project at JSC to investigate the issues and opportunities for a manned return mission to the Moon targeted at the year 2002. The project was formally titled the Human Lunar Return (HLR) study and was managed by Elric McHenry of the Technology and Project Implementation Office. The entire project was sponsored by the Advanced Development Office at JSC. Following two prelminary JSC assessments, engineers from MSFC, Lewis Research Center and Langley Research Center were asked to join the team in April 1996. A 4-month study ensued. MSFC was charged with development of selected transportation elements for this more extensive assessment. A baseline lunar reference mission, which utilized the *International Space Station (ISS)* and is believed to be representative of a "minimum" cost return mission, was developed.

In early May 1996, a team was formed within the Program Development Office at MSFC to develop a pre-phase A-level technical design and cost for selected HLR transportation elements. This 4-month task was in response to a request from JSC to

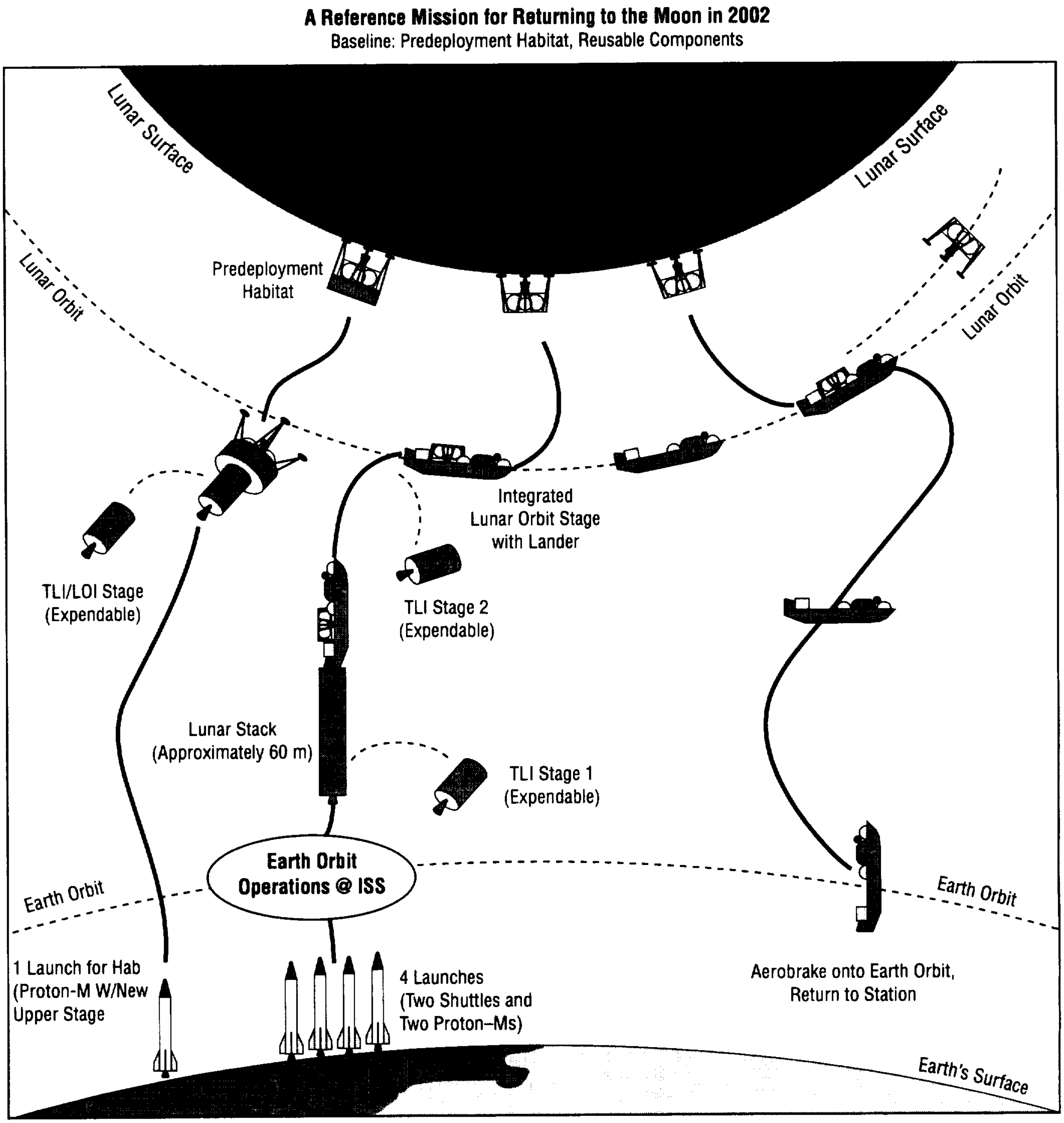

Figure 186.—Design Reference Mission (2002). Baseline: predeployed habitat, reusable components.

support specific aspects of an investigation into a manned return to the Moon. All solutions complied with HLR baseline mission manifest objectives and assumptions developed by the JSC HLR project team. Transportation elements developed included:

- All propulsive elements and associated propellant carrier/transfer kit for the lunar orbit insertion/trans-Earth injection (LOI/TEI) stage which serves as the primary propulsion system for the lunar orbit stage;
- A tandem configured trans-lunar injection (TLI) stage for delivery of the fully integrated lunar orbit stage; and
- A trans-lunar injection/lunar orbit insertion (TLI/LOI) stage for delivery of the lander/habitation module.

Design of the fully reusable propulsive elements of the LOI/TEI stage was completed within 2 months. The design scope included engine selection, propellant requirements, propellant tank sizes, mass breakdown of component parts, materials selected, power requirements, dimensions, schematics, inert stage mass, integration support to JSC, and costs. It is delivered dry to the *ISS* with other mission hardware aboard the Shuttle.

The LOI/TEI stage propellant delivery and transfer system design was completed in less than 1 month from the mid-July 1996 initiation. The design scope included concept selection, operations, configuration, subsystems, mass summary and costs. The LOI/TEI stage propellant carrier/transfer kit is fully reusable and transported to and from the *ISS* via the Shuttle.

The design for the TLI stage was completed in about 2-1/2 months from initiation in early May 1996. The design scope for the TLI stage included an assessment of configuration and deployment options, trades, concept selection, a systems analysis defining the various subsystems required, performance analyses, timelines, configurations, mass statements, schedules and costs. The TLI stage is required to provide the transportation for placing the

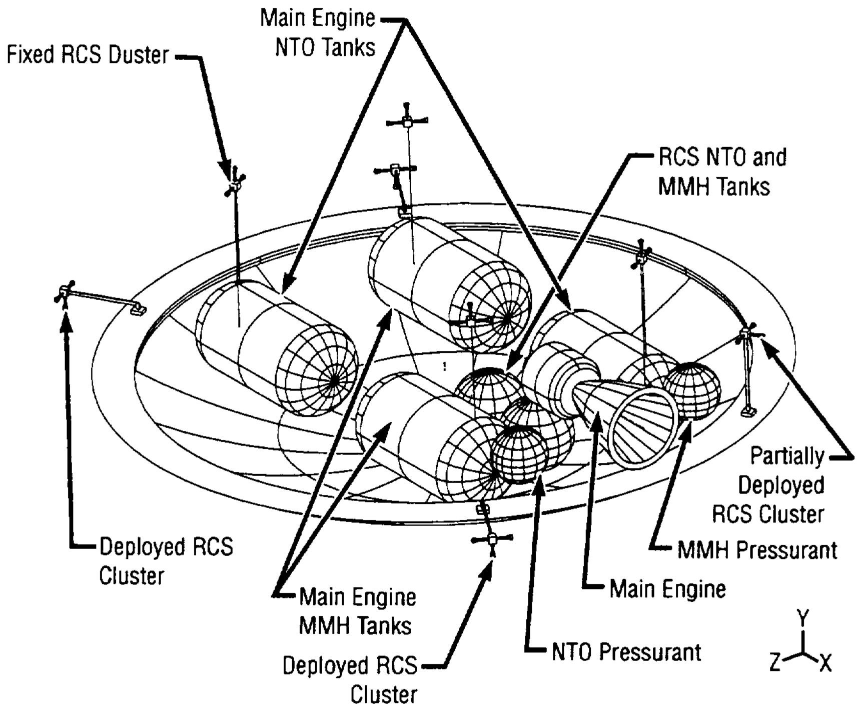

Figure 187.—LOI/TEI propulsive elements.

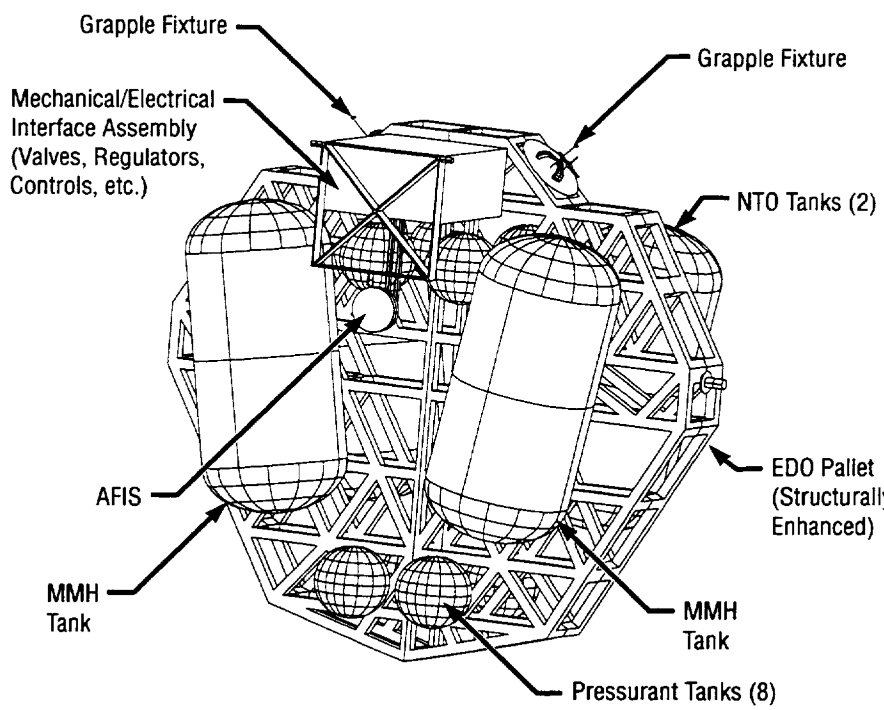

Figure 188.—LOI/TEI propellant carrier/transfer kit.

lunar orbit stage assembly consisting of the crew module, lander, aerobrake and LOI and TEI stage on a lunar trajectory which allows insertion into lunar orbit by the LOI/TEI stage. It is configured as tandem, pump-fed (main engine) expendable cryogenic stages. Once mated to the lunar orbit stage, the subsequent assembly becomes the lunar stack. Stage delivery is accomplished via two Proton-M launches.

The TLI/LOI stage for the lunar lander/habitat module was completed in less than 1 month following a mid-July 1996 start. The scope of the design included mission profile, performance analyses, configurations, timelines, subsystems, mass and costs. The TLI/LOI stage is expendable, and was derived from the TLI stage 2 design. It performs the TLI burn, midcourse corrections, coasts to the Moon and then brakes the lander/habitat module into low-lunar orbit with a single burn of the main engine.

This internal Agency study dealing with human lunar return concluded in August 1996. Included in the results were: a description of the top level vehicle elements; what we want to do at the Moon; and the kinds of lunar resource development and science that could be performed.

All assigned transportation elements were delivered on schedule with a high level of detail. Center to center coordination was excellent. The baseline HLR mission cost was estimated at between $3 to 5 billion or equivalent to about 2 to 5 percent of the Apollo missions and could be implemented within a 3- to 5-year time frame. The baseline implementation plan made maximum use of existing launchers, commonality of hardware design, inclusion of new or emerging technologies, and sought to maximize reusability where beneficial. A cursory investigation was given to a possible alternate mission scenario which departed from the *ISS* but returned directly to Earth. This appears to offer somewhat lower mission costs and the easiest access to all possible lunar surface landing sites. The area of greatest scientific

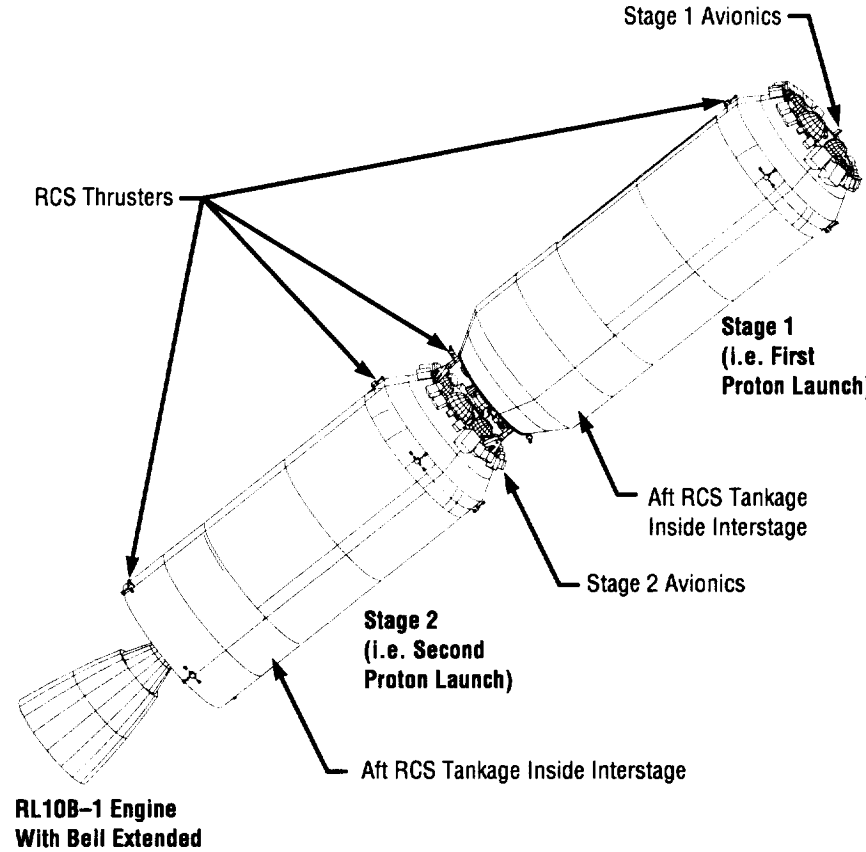

FIGURE 189.—Tandem translunar injection (TLI) stages.

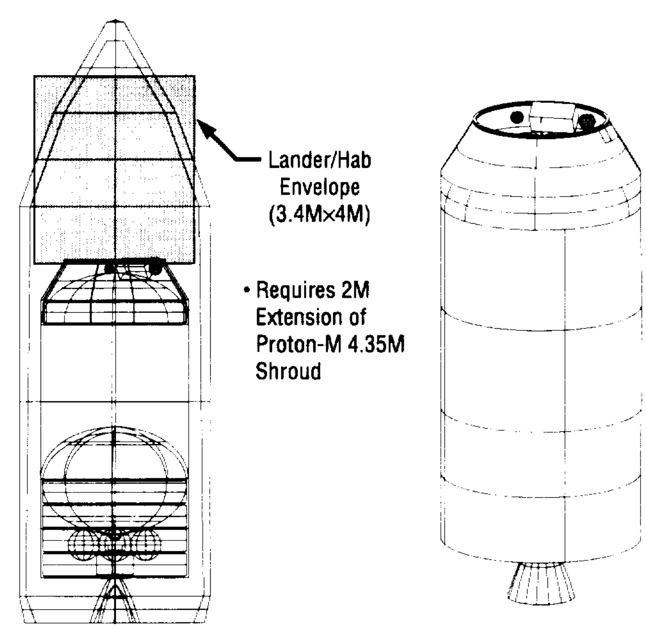

FIGURE 190.—TLI/LOI stage configuration for lander/habitat.

value appears to be the polar ice region. Landing here would drive any developed transportation architecture. It would therefore be best if the final transportation architecture for any manned missions be made following analysis of data obtained by robotic rovers sent to the polar region.

Sponsor: Johnson Space Center—Advanced Development Office

Biographical Sketches: Mark L. Stucker is a project engineer in the Advanced Systems and Technology Office at Marshall. Since joining NASA in the summer of 1987, he has actively applied technical management skills to propulsion technology projects dealing with solid, liquid, and hybrid rocket motors. He has served in numerous positions within the Joint Army-Navy-NASA-Air Force (JANNAF) Interagency Propulsion Committee and was cited in 1993 for outstanding contributions to chemical propulsion technology and service to JANNAF. Stucker received his BSIE and MSIE from the University of Tennessee in Knoxville in 1974 and 1975.

Thomas D. Dickerson is the Mission Analysis team leader in the Preliminary Design Office of the Program Development Directorate at the Marshall Space Flight Center. He served as the lead engineer for the Human Lunar Return study. Dickerson is a 1962 graduate of Middle Tennessee State University and has 34 years experience with NASA. His technical background is in launch vehicle trajectory and performance analysis and orbital mechanics. During his career with NASA, he has served as the lead engineer for other projects including the Aeroassist Flight Experiment, Earth Science Geosynchronous Platform, Aerobrake Design for Lunar Return Vehicles, High Temperature Materials Processing Furnaces for the Space Station Furnace Facility and others.

Research

NASA Air Force Cost Model: A Potent Parametric Cost Estimating Tool

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The Engineering Cost Office of the Program Development Directorate at MSFC provides comprehensive cost estimates for new projects as well as those projects under consideration for development. The following paragraphs provide an overview of the NASA Air Force cost model (NAFCOM). This automated model, currently in its fifth version, makes use of regression analysis methodology and is one of the primary cost estimating tools within the office. It was developed under contract for MSFC by the Science Applications International Corporation (SAIC).

At the core of NAFCOM is its data base. This data base contains elements of cost (including first pound cost), weight, and other data for 9 manned spacecraft, 75 unmanned spacecraft, 10 launch vehicle stages, 4 liquid rocket engines, and approximately 350 space-based scientific instruments. Technical and programmatic data are provided for each program or data point to enhance the understanding needed for the analyst to select analogous data in the development of a weight-driven cost estimate. The first breakout or subdivision of the data base is into one of four major categories:

- Manned spacecraft;
- Unmanned spacecraft;
- Launch vehicle stage and engine; and
- Scientific instruments.

Each project is then further categorized into its system and subsystems/component costs. For each of these further divisions, costs are divided once again into flight unit costs and development costs. A separate cost estimating relationship (CER) is developed for each of these elements. Total project costs are determined as costs for all of these components are summed in the final stages of cost estimating. NAFCOM CER's are subsystem unique and were derived from averages taken from some 100 historical space missions making up over 1,000 subsystem data points.

A comprehensive listing of data points is provided for each project subsystem/component within the NAFCOM data base. The NAFCOM user, in developing a cost estimate, may use overall average CER's, or may generate unique CER's by combining CER's from one or more projects that most closely parallel the new project whose cost he is estimating.

Integration costs are generated for each estimate at the total project level. Integration costs are defined as the costs for integration of components/subsystems and associated system level functions. The following are included elements of integration costs:

- Integration, assembly, and check-out;
- System test and operations;
- Ground support equipment;
- Systems engineering and integration;
- Management; and
- Launch operations orbital support.

Integration cost CER's are also developed by using overall average CER's or generating unique CER's by selecting projects that are similar in system integration activities. Once the hardware and integration costs have been determined, these costs are adjusted for inflation to any desired year by the model.

The search and filter routines in the model allow users to select projects that used low-cost, new ways of doing business approaches. If the project to be estimated plans to use the same low-cost approaches, then the resulting estimate will include similar cost reductions.

Consequently, by means of a user-friendly data base and program, the NAFCOM user can bring together the procedures described above to arrive at legitimate and defensible cost estimate. NAFCOM has proven itself to be a valuable cost-estimating tool at MSFC and is being accepted at other NASA centers and by the U.S. Air Force. Until recently this model was limited to only government distribution because of proprietary cost data included in the data base. However, a nonproprietary version of NAFCOM has been developed and is available upon request to any commercial company willing to provide data to be used within the model. This tool can be of great value to space hardware developers in preparing cost proposals for contracts as well as for evaluation of subcontractor proposals.

"Executive Summary." NASA Cost Model, vol. 1, 1993.

Sponsor: Marshall Space Flight Center Engineering Cost Office

Biographical Sketch: Carey Thompson works in Aerospace Technical Management in MSFC's Engineering Cost Office, where he provides cost estimates for potential new NASA space projects. Thompson earned a B.S. degree at the U.S. Military Academy, and an MBA at the Florida Institute of Technology.

The Virtual Research Center: An Experimental Intranet

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In any typical project, decisions made during the conceptual design stage constitute 75 percent of a product's cost.[1] Many of these decisions are made by teams spread over disparate locations. An Intranet facilitates communication among team members by applying Internet technologies to the management of project information.

MSFC is integrating an experimental Intranet known as the Virtual Research Center (VRC) for geographically distributed concept development teams. The VRC provides an integrated set of tools for collecting, archiving, disseminating, and discussing project-related information. Users gain access to the VRC through a World Wide Web (WWW) browser.

Using the motif of a lunar colony, the VRC Graphical User Interface (GUI) displays a lobby with entrances to a central complex and several project wings. The central complex comprises a museum, library, and auditorium. Each project wing includes a conference room, library, mail station, and laboratory. Rooms within the VRC contain information in a format consistent with that room. For example, the library contains documentation, the laboratory contains analytical files such as spreadsheets, and the auditorium contains multimedia files.

The Advanced Concepts Office at NASA Headquarters established an agencywide team in February of 1995 with members at Johnson Space Center (JSC), Ames Research Center (ARC), Jet Propulsion Laboratory (JPL) and MSFC. The initial prototype integrated public domain software and served as a model for developing requirements. International Space Systems Incorporated (ISSI) supported the integration of the first prototype.

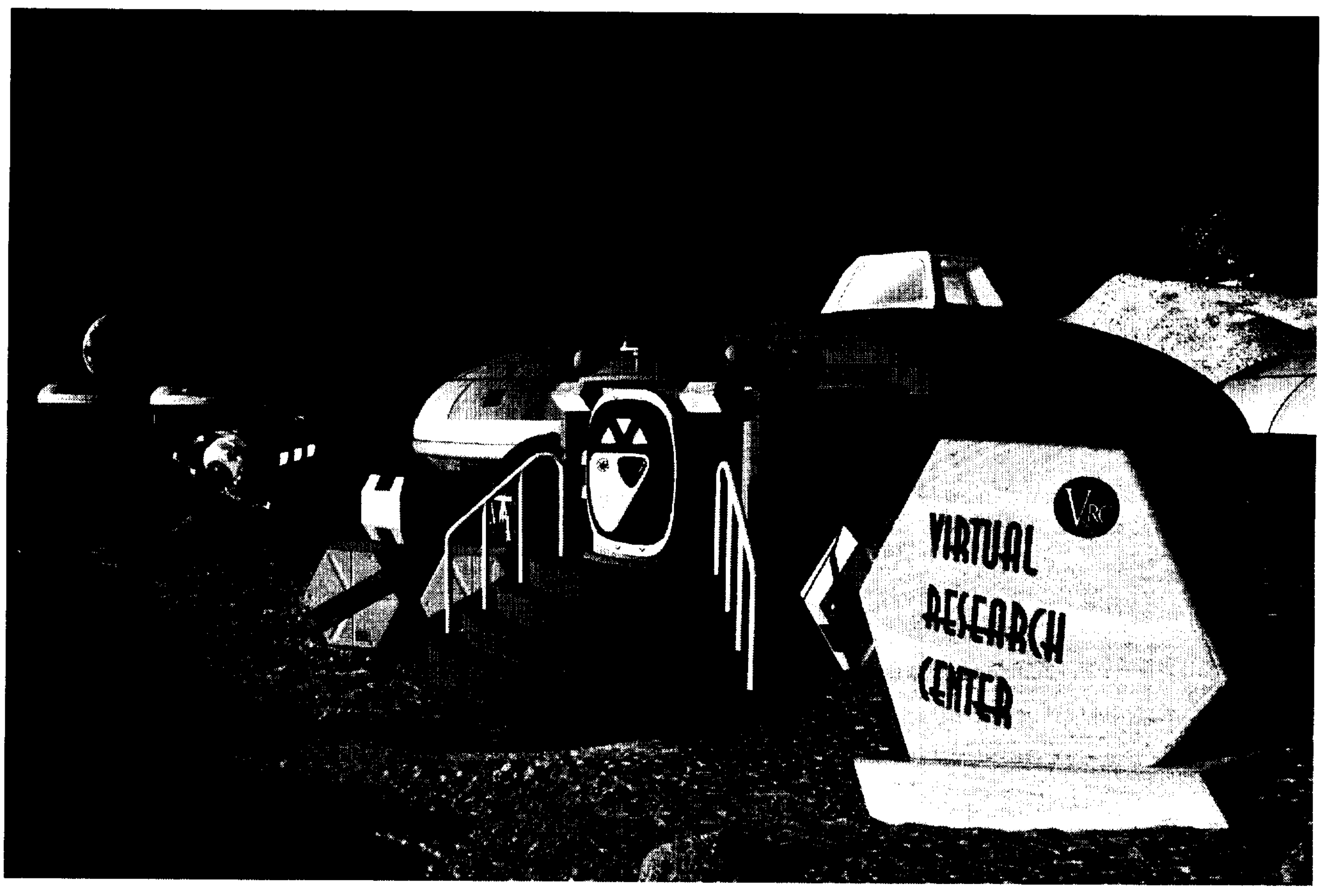


Figure 191.—The VRC home page.

In 1996, products appeared on the market that incorporated many of the functions and features embodied in the public domain Internet programs. The VRC team integrated these new products with support from Auburn University and the University of Alabama in Huntsville. Deployment of the demonstration system began in August of 1996 with the implementation of project wings for the Advanced Concepts Office and the Highly Reusable Space Transportation (HRST) programs.

The VRC organizes information through a spatial reference system. Information of different formats are stored in a room that is appropriate for that format. Each room contains tools for storing, retrieving, or exchanging files. The following paragraphs identify the rooms and the associated tools.

The library provides tools for online publishing, searching, and collecting project-related data.

- Online Publishing—The library provides utilities for converting Postscript files into the Portable Data Format (PDF). Users can view the documents with the free Acrobat reader software from Adobe.

- Document Archiving—Users may read brief descriptions and select a document for viewing from a list of available PDF files.

- Search Engine—A search engine from Verity, Inc., enables users to search through online documents and data bases for key words.

- Project Data Base—An Oracle 7 data base provides a means of collecting project-related data and creating reports.

- Mail Station—Functions in the Mail Station include a file server, e-mail list manager, and a bulletin board.

- File Exchange—Through the mail station, team members may exchange files. An embedded File Transfer Protocol (FTP) program provides a consistent look and feel across heterogeneous platforms.

- Discussion Forum—The mail station also provides a discussion forum or bulletin board. Users can create topics for discussion and other people can write comments about that topic.

Conference Room

Tools within the conference room augment team telecons. Functions include action tracking, scheduling, and desktop video conferencing.

- Action Tracking System—As teams conduct meetings, they can assign action items and record them in the action item tracking system.

- Scheduler—This tool includes a calendar of events. Within the calendar, events appear as a hypertext link that users can select to obtain more information about that event. In addition, the scheduler contains a fill-in form for the NASA Teleconference Center (NTC). The system will generate the form and automatically fax it to NTC.

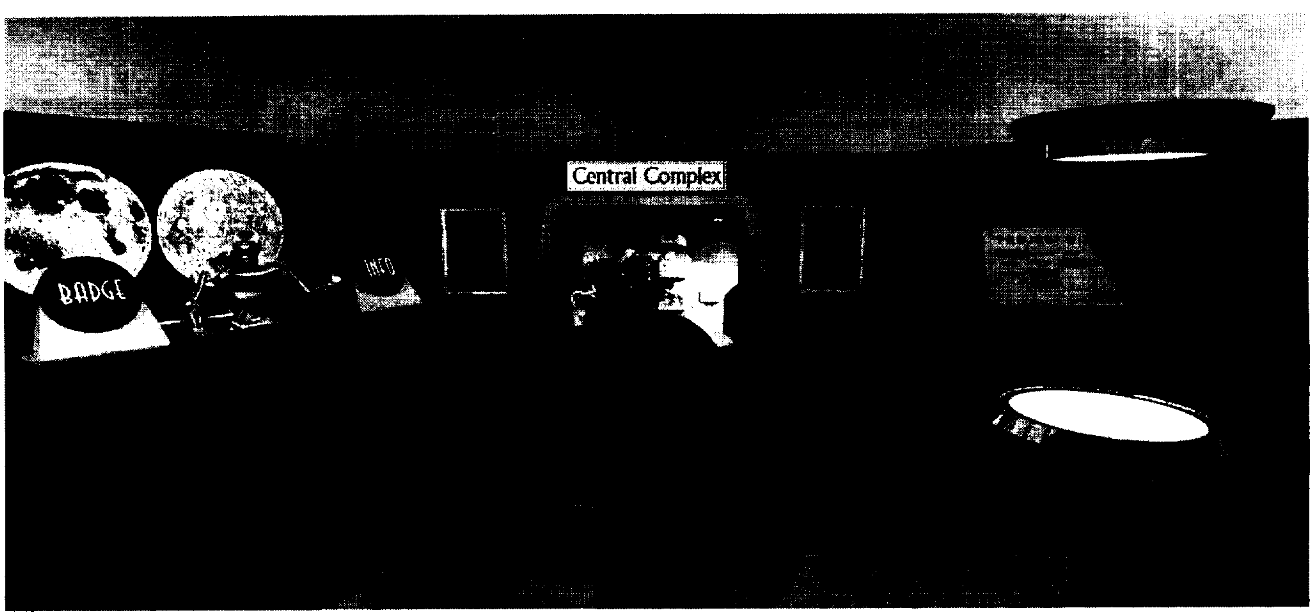


FIGURE 192.—A view of the VRC lobby.

- Meeting Minutes—Teams can capture the important points of a meeting with both text and graphics for later review by the individuals.

- Desktop Video Conferencing—The VRC server includes a CUSeeMe reflector for desktop conferencing. Team members can view one another during telecons.

- White Board—CUSeeMe also provides a white board capability. Users can display images on the white board and all participants can see and mark up the image.

Laboratory

Teams often develop analytical programs, simulations, and spreadsheets to support concept development. The laboratory provides a file management system so people can archive analytical files.

Auditorium

Multimedia presentations on project or organization subject matter will be available in the auditorium of the central complex.

System Administration

Behind the scenes, the VRC provides tools for system administration and multiple levels of security.

- Wing Construction Kit—Creating project wings requires considerable work if done manually. The VRC includes Unix shell scripts that automate the process. A system administrator can simply type in the name of the new project wing, and the script performs the following actions:
  - Creates directories;
  - Copies HyperText Markup Language (HTML) pages into those directories;
  - Changes pathnames embedded in the HTML pages;
  - Creates project data base; and
  - Copies "glueware" that integrates the HTML pages and databases.

- Multiple Security Levels—To ensure a safe environment for information exchange, the VRC offers a multilayer security system. This security system includes password protection, access rights at the operating system level, access rights for the project data base, and data encryption.

Future Plans

To deploy a VRC server for the Space Transportation Research Center (STRC) to support the Advanced Space Transportation Program (ASTP) at MSFC.

Additional Information

All commercial products mentioned in this report are trademarked and copyrighted by their respective companies.

[1]Machlis, S.: "Management Changes Key to Concurrent Engineering." *Design News*, September 17, 1990, pp.36–37.

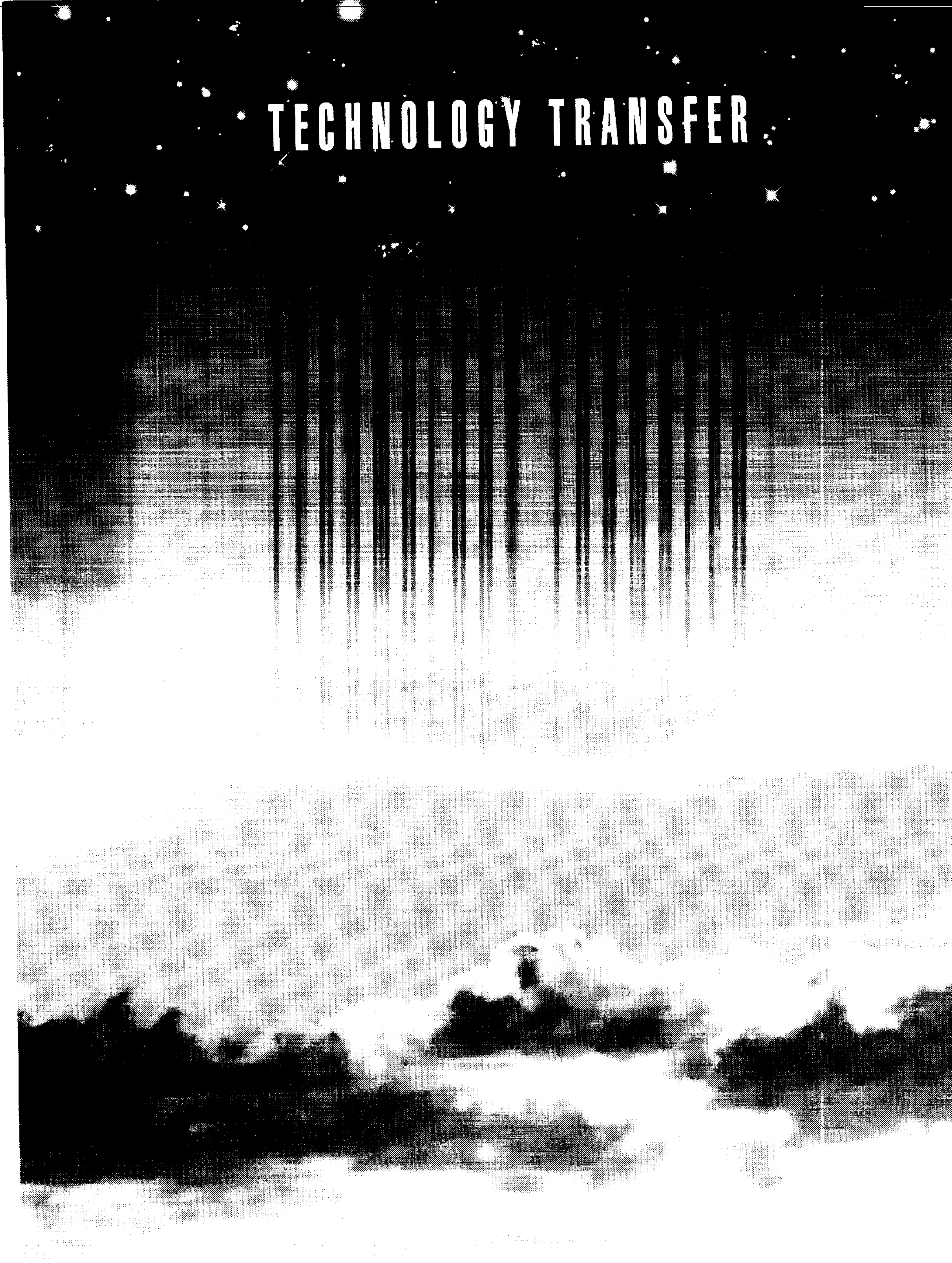
Sponsor: Office of Space Access and Technology

University/Industry Involvement: Auburn University, University of Alabama in Huntsville; International Space Systems Incorporated, Bay Area Multimedia Technology Alliance, 4th Planet

Other Involvement: NASA Headquarters, Ames Research Center; Johnson Space Center; Jet Propulsion Laboratory

Biographical Sketch: Daniel O'Neil has a B.S. degree in electrical and computer engineering from the University of Alabama in Huntsville. He works in Program Development's Advanced Concepts office where he manages the VRC project and other activities related to information systems technologies.

TECHNOLOGY TRANSFER



When it was created in 1958, NASA was charged with facilitating the transfer of technologies derived from the U.S. space program to American businesses, academic institutions, and individual entrepreneurs.

Historically, this was accomplished through technology transfer offices at each NASA Field Center, with each office working independently and pursuing its own agenda, all under the guidance of an associate administrator at NASA Headquarters in Washington, DC.

Recently, however, NASA formed a team to restructure the program, thereby maximizing efficiency, eliminating redundancy, and capitalizing on each Center's strengths. The Nation was divided into six regions, all previously defined during the establishment of the Federal Laboratory Consortium. Each region contains one or more NASA Field Center(s) and a regional technology transfer center (RTTC). The southeastern region, in which the Marshall Space Flight Center is located, includes the states of Alabama, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, and Tennessee. In this region, Marshall works with the Stennis Space Center in Mississippi, the Kennedy Space Center in Florida, and the region's RTTC, the Southern Technology Applications Center at Alachua, FL. Together, these organizations comprise the Southeast Technology Transfer Alliance. While comprised of NASA facilities in the southeastern United States, its scope of operation is nationwide.

The focus of the technology transfer effort is on businesses, schools, and entrepreneurs. It receives policy guidance from NASA Headquarters. Marshall's technology transfer activities are coordinated with the other NASA Centers, particularly when specific technologies held by one Center are needed by industries outside of its region. A wide range of talents are thus available to U.S. businesses, talents available nowhere else. Through the alliance, the American private sector also may access the resources and expertise of the entire 750-member Federal Laboratory Consortium.

Through these governmental facilities, businesses can access unique Government resources, utilize the unique properties of the space environment, participate in regional workshops, collaborate on technical problem solving, jointly advance technology development, attend Government-industry consortia, and arrange for visits by technology transfer outreach teams.

NASA's technology transfer effort is working for America—and many in America are working because of NASA technology transfer.

Sally Little
Deputy Manager
Technology Transfer Office

Technologies Pour Into American Industries, Spurring Growth in Employment and New Products

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"America's space program is paying off for American business and industry. Technologies, developed for the nation's space program by NASA and its contractors, are now at work in thousands of American firms," according to Harry G. Craft Jr., manager of the Technology Transfer Office at MSFC.

"The latest survey of industrial assistance activities conducted by NASA's Southeast Technology Transfer Alliance, of which the Marshall Center is a member, proves that American businesses consistently benefit from NASA's research and development expertise," Craft said.

As a result of NASA's technology transfer and industrial assistance activities, more than 18,500 jobs have been added to the nation's job bank or saved from elimination since January 1993, Craft reported.

Figure 193.—J. Wayne Littles, Marshall Center Director, seated left, joins with William Dunavant, Tennessee State Commissioner of Economic and Community Development, seated right, in signing a memorandum of understanding which renews a cooperative agreement between NASA and Tennessee. This arrangement enables businesses, schools and entrepreneurs to benefit from the wealth of technology being developed by NASA's talented team of engineers and scientists. Looking on from left are: Jeneene Sams of the Marshall Technology Integration Team; Jerry Seemann, Process Management Office Manager; Harry G. Craft, Jr., MSFC Technology Transfer Office (TTO) Manager; William Eads, Tennessee Advisor on Science and Technology; Dr. Kenneth Fernandez, Technology Utilization Office Manager; and Fred Schramm, Marshall TTO liaison to Tennessee. In addition to Tennessee, Marshall has similar agreements with Louisiana, Mississippi, Alabama, Georgia, North Carolina, South Carolina, Florida, Kentucky, and Arkansas.

Assistance from the space program, he said, has enabled American industry to introduce more than 1,212 new or improved products for sale at home and abroad, an increase of more than 150 from just 6 months ago.

Craft said the survey estimates the value of this assistance to American business and industry at $1.8 billion.

One of the most recent beneficiaries NASA's engineering expertise is Systech in Demopolis, AL. The company burns a slurry of waste material as fuel to heat cement kilns. The waste must be ground up before it can be burned, but iron and steel in the waste material was damaging the plant's grinder.

Engineers at the Marshall Center, familiar with similar metal waste extraction problems, were able to link Systech with a private firm that solved the problem. One aspect of NASA's technology transfer program involves linking companies requesting assistance with other firms which offer suitable, off-the-shelf, commercially available products and solutions.

Closer to home, Marshall engineers tackled a problem at Plasma Processes, Inc., (PPI) in Huntsville, AL. The company asked for help in developing a way to make low-cost tooling and metal liners for pressure vessels made from composite materials. The firm applies metal, ceramic and polymer coatings onto substrates for wear, thermal and corrosion protection. The Marshall Center has one of the world's leading productivity enhancement centers which is developing innovative methods of using composite materials industrially. As a result of Marshall's help, the company has increased employment and expanded its product line, thereby increasing sales.

The United Service Equipment Co. (USECO), a food service equipment manufacturer in Murfreesboro, TN, asked Marshall for assistance in evaluating a foam insulation material it had selected for use on food carts of the type used in hospitals to transport meal trays from the kitchen to patients. Lockheed-Martin Co., the NASA contractor that makes the insulation for the space shuttle's external fuel tank, tested the durability of USECO's insulating material and provided the information to the firm's engineering staff.

NASA's Southeast Alliance pools the scientific and engineering research and development resources of the MSFC with those at the Stennis Space Center in Mississippi, the Kennedy Space Center in Florida, and the Southern Technology Applications Center in Alachua, FL.

Despite its name, the alliance's technology transfer efforts do not target the southeastern United States exclusively. American businesses and industries in nearly every state have received technical assistance. The alliance does, however, have formal technology transfer agreements with most southeastern states' economic development agencies. These include Georgia, Alabama, Tennessee, North Carolina, South Carolina, Kentucky, Arkansas, Florida, Mississippi and Louisiana.

Pooling the resources of the alliance's members allows the resources of all four to be brought to bear on technological problems in the private sector. This permits a complementary approach to finding a solution. When appropriate, the resources of the entire 752-member Federal Laboratory Consortium can be accessed through alliance members.

"The alliance expedites American businesses', academic institutions' and entrepreneurs' acquisition, adaptation and application of a broad spectrum of state-of-the-art technologies and techniques which have been proven in the nation's space program to work most effectively and efficiently," Craft said.

As a member of the alliance, the Marshall Center actively solicits requests for assistance from private industry through the use of mobile technology utilization assistance teams. These teams work with state and local governments and economic development agencies to identify candidate industries for receipt of aerospace technological assistance.

"To date, more than 5,000 requests have been received from U.S. firms and processed by the Southeast Alliance's technology assessment board," Craft said. "Nearly 90 percent of these have been resolved successfully. Of the firms which have contacted the alliance for assistance, nearly all have indicated they would again seek NASA expertise if problems arise in the future."

Businesses wishing to discuss ways in which NASA technical assistance programs might benefit them are encouraged to call 1-800-USA-NASA.

Sponsor: Office of Commercial Development and Technology Transfer

Biographical Sketch: Bob Lessels is the technical writer/editor (physical sciences) for the Technology Transfer Office at MSFC. A graduate of the University of Nebraska, he has been a professional journalist for the past 30 years. He joined NASA in 1986.

MSFC Small Business Innovation Research and Small Business Technology Transfer Programs

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The Small Business Innovation Research (SBIR) program was established by Congress in 1982 to provide increased opportunities for small businesses to participate in Federal research and development (R&D) to increase employment and improve our country's competitiveness. The program objectives established by law include stimulating technological innovation in the private sector, strengthening the role of small business concerns in meeting Federal research and development needs, increasing the commercial application of federally supported research results, and fostering and encouraging participation by socially and economically disadvantaged persons and women-owned businesses in technological innovation. The 11 Federal agencies with R&D budgets exceeding $100 million have implemented SBIR programs. Funding is provided by allocating a percentage of each agency's extramural R&D budget for SBIR. Each Agency administers its own individual program within guidelines established by the Small Business Administration (SBA).

Phase I is the opportunity to establish the feasibility and technical merit of a proposed innovation. Phase I contracts last for 6 months and up to $70,000. Phase II is to continue development of selected innovations shown feasible in Phase I that have the highest potential value to NASA and to the U.S. economy. Phase II contracts are for a period of 2 years and up to $600,000. Phase III involves non-SBIR capital to pursue commercial applications of their project results in the private sector and in the Federal Government.

The Small Business Technology Transfer (STTR) pilot program awards contracts to small business concerns for cooperative R&D with a research institution through a uniform, three-phase process. The program was authorized for 3 years beginning in 1994. Program goals are to transfer technology developed by universities and Federal laboratories into private marketplace through the entrepreneurship of a small business. The small business and its partnering institution are required to sign an agreement on how intellectual property will be shared between them. Phase I STTR projects receive up to $100,000 in funds for 1 year; Phase II is limited to $500,000 for 2 years.

The NASA SBIR program is an Agency-wide effort that contributes to NASA's mission in planning, directing, and conducting R&D for civilian uses of space and aeronautics. All 10 NASA field installations and Headquarters program offices participate in the program. MSFC managed nineteen 1995 SBIR Phase I contracts valued at $1.3 million; forty-seven 1993 and 1994 SBIR Phase II contracts valued at $27.6 million; ten SBIR Phase III contracts valued at $2 million, eight 1995 STTR Phase I contracts and ten 1996 STTR Phase II contracts during the past year.

Sponsor: Office of Aeronautics; SBIR/STTR

Biographical Sketch: Helen Stinson manages the MSFC SBIR/STTR program. She graduated with a degree in materials engineering from the University of Alabama in Birmingham and has previously worked in the Structural Analysis division of the Structures and Dynamics Laboratory.

Ceramics for Turbomachinery Systems

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Marshall and a team of industry experts, under a NASA Aerospace Industry Technology Program cooperative agreement, are developing a manufacturing process for silicon nitride ceramic components. Under this agreement, a team of engineers from AlliedSignal Aerospace Equipment Systems, AlliedSignal Ceramic Components, AlliedSignal Technology Team, Allison Engine Company, MSFC, and Lewis Research Center are working to develop and demonstrate ceramic turbine-wheel technology suitable for air turbine starters, with potential applications for other turbomachinery such as turbopumps, turbochargers, and turbogenerators.

Ultimately, the efforts of this team should lead to the commercialization of ceramic turbine-wheel technology. To accomplish this, the team will develop and demonstrate low-cost, high-yield ceramic manufacturing processes. In order to provide the turbomachinery technology outlined in this agreement, the team must develop gelcasting as a low-cost , high-yield ceramic-forming process, develop brazing as a high-load capacity, low-cost ceramic-to-metal attachment, and demonstrate ceramic turbine wheels in an air turbine starter.

The development of this manufacturing process for turbine wheels will build on newly developing uses for gelcasting, while the new ceramic-to-metal attachment will employ current brazing techniques. Once the manufacturing process has been defined, the turbine wheels will be produced and tested in an Aerospace Equipment Systems production air turbine starter. These tests will focus on the entire spectrum of operating conditions, as well as duration testing. Next, Allison Engine Company will provide field service tests of the air turbine starter with the ceramic wheels. Tinker Air Force Base has also expressed intent to test starters with ceramic wheels on service aircraft.

In order to design the turbine wheels and components necessary to adapt the turbine wheels to the existing air turbine starter, the team will take advantage of the developments from a previous ceramic turbine research program. Although the turbines for this project are axial in design, the resulting technology will also benefit ceramic forming processes for radial turbines.

In addition to developing the gelcasting technique, Ceramic Components will conduct material characterization tests and produce the turbine wheels. The ceramic-to-turbine brazing technique, being developed by the AlliedSignal Technology Team, will be transferred to Ceramic Components and Aerospace Equipment Systems.

Since the 1980's, AlliedSignal Aerospace Equipment Systems and Ceramic Components have worked together, designing, developing, fabricating, and testing ceramic turbines for air turbine starters. Their efforts have provided a rich pool of resources and insight into the primary factors necessary to successfully design air turbine starters.

A working model of the turbine wheel has already been released to Ceramic Components to fabricate the tooling that will be used for process development, and Ceramics Components has already begun to optimize the process. Development to date has focused on the slip development, binder burnout and densification phases of the gelcasting process. Ceramic Components is also reviewing past research programs of mold designs under the Aerospace Industry Technology Program. In a concurrent effort, the design and procurement of development molds is underway. The company has planned a program to cast existing turbine-wheel designs to evaluate their dimensional control and repeatability.

The AlliedSignal Technology Team has tested brazed shaft attachments using a variety of sizes, materials, and geometric configurations. Using a simple geometry consisting of a silicon nitride stub shaft brazed onto a steel-stub shaft, full torque strength has been achieved. This team has also improved process repeatability by refining brazed materials and techniques. Short-range plans for the AlliedSignal Technology Team include brazing to achieve final metal properties using a butt-joint configuration with long-term plans to control the integrity of the interlayer materials in the braze joint. These interlayer materials must be maintained to accommodate the differential thermal expansion between the ceramic wheel and the metallic shaft.

As with any new technology development, testing is an important step in the validation process. In this case, the air turbine starter will be tested for mechanical integrity, with in-service conditions applied in the test cell. The air turbine starter will be subjected to both a full range of normal operating conditions and emergency operation situations. Additional testing will evaluate the integrity of the system during prolonged periods of operation. Tests conducted at the Marshall Center and Lewis Research Center will investigate the nature of the cyclic fatigue with ceramic material and the ceramic-to-metal joints.

Sponsor: NASA Aerospace Industry Technology Program (AITP)

Biographical Sketch: Chris Bramon is a project manager in the Technology Investment Office at NASA-MSFC. He works with industry, academia and other Government agencies to develop dual-use technologies that benefit both the public and private sectors. Bramon has an industrial engineering degree from Iowa State University. He has worked for NASA for 12 years.

Mike Effinger is a materials engineer in the Nonmetallic Materials Division at NASA-MSFC. He conducts mechanical property testing on ceramic and ceramic matrix composites. Data generated is used for the design of rocket engine components. Effinger has worked for NASA for 5 years.

Innovative Development of Joining/Fitting Technology for Advanced Composite Piping Systems

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Marshall and the Department of Mechanical Engineering at Louisiana State University (LSU) have teamed up in support of Specialty Plastics, Inc., of Baton Rouge, LA., to develop innovative joining and fitting technologies for advanced composite piping systems. This cutting-edge technology will improve piping systems for the U.S. oil and gas industry.

This new team of industry and university experts and NASA engineers is working to develop high-performance composite materials to dramatically enhance the physical properties—such as strength and durability—of hardware used in the offshore oil and gas industry. One example of the type of composites being used is a combination of polymers with glass or carbon fibers. To date, material costs, along with design and manufacturing complexity, have restricted these types of materials to the manufacture of products for national defense or high-performance sporting goods. However, the cooperative efforts of this team should place high-performance composites into mainstream manufacturing. Specialty Plastics, MSFC, and LSU experts are working to develop joining pipe segments and low-cost, high-strength pipe fittings.

Specialty Plastics has been awarded a $1.8 million Advanced Technology Program grant to help finance research in this high-risk area of technology by the Department of Commerce's National Institute of Standards and Technology (NIST). The company is the first in Louisiana to receive a NIST research and development grant. NIST's Advanced Technology Program provides cost-sharing funding to industries willing to undertake high-risk research and development projects that could spark important, broad-based economic benefits for the United States.

The cost of manufacturing and erecting offshore production platforms can be significantly reduced if even a portion of the heavy metal pipelines could be replaced with lighter weight pipeline systems made of composite materials. Composite pipes could reduce the topside weight of deep-water offshore rigs, known in the industry as tension leg platforms (TLP's). These TLP's are necessary to access deep water petroleum reserves. The replacement composite piping must be developed in such a way that meets the very stringent mechanical requirements and safety concerns for oil operators of sea water piping systems. A large percent of "dead weight" on the deck of an offshore oil platform is the piping system. NIST estimates that the use of composites to access oil from deep water reserves could decrease the cost of deep-water platforms by $250,000/m of water depth, or $150 million per platform by reducing structural weight.

The United States now spends more than $1 billion a week to import oil from other countries. This accounts for half the national trade deficit. A promising source for new oil and gas is from deep-water locations in the Gulf of Mexico. While most offshore production platforms are "fixed" structures based on steel technology, the most economical deep-water platform design includes TLP's. Today, the cost of a TLP is nearly $1.2 billion. For every ton of dead weight saved topside, two tons can be saved below the water line. The weight of steel piping is an important factor in the high costs associated with construction of deep-water platforms. It is essential for Government agencies to be involved in developing the technologies necessary to reduce the capital required for these state-of-the-art TLP's because the costs of developing these deep-water reserves have kept the U.S. oil industry from earning its cost of capital in the past 6 to 7 years. Due to our dependence on hydrocarbons as a primary fuel source for industry and defense, the domestic oil industry is vital to America's economic well-being.

Producing affordable piping made from advanced composite materials will also benefit other U.S. industries. For example, advanced composite piping could have applications for fire water piping, sea water cooling, drainage systems, and sewerage systems without the negative effects of corrosion. Each year, the petrochemical, pulp, paper, and marine industries spend approximately $20 billion to combat corrosion damage to piping made with present-day materials.

Although the benefits of composites—lightweight, corrosion resistant, handling ease, etc.—have long been appreciated, there are technical challenges and barriers to overcome. Some of these challenges and barriers include the lack of confidence in existing joint technology, high costs and intensive labor processes associated with the manufacture of composite pipe fittings, and unreliable composite-to-composite and composite-to-alloy joining methods. The efforts of Specialty Plastics, MSFC, and LSU to develop innovative joining methods will allow advanced composite pipe systems to be considered in essential services, such as fire water systems where copper-nickel pipes are now used. A composite piping system consists of pipe, fittings, joints, and flanges. The limitations of composite piping system applications are due to the joining method and fitting manufacturing process. The current cost of a composite pipe fitting is approximately six times the cost of an alloy fitting.

In order to accomplish their task, this new development team has two distinct tasks—joint technology and fitting manufacturing technology. Where joint technology is concerned, the development of the "integral flange" filament wound directly onto the pipe or fittings eliminates the joint between the pipe and flange and improves the mechanical properties. Another solution involves a heat-activated coupling system which allows the joining of composite pipe to composite and alloy pipes. Improved adhesive bonding must also be a part of this task to ensure a proper bond between adhesives and composites. Fitting manufacturing technology will include processes to improve the overall performance of the piping system. New pipe fitting manufacturing processes will be developed to provide a higher production rate and enhanced properties at a lower unit cost. This task can be accomplished by intelligent filament winding and resin transfer molding of pipe fittings. This is done using two-dimensional woven fabric and three-dimensional shape performs.

New technologies are necessary to improve the reliability of composite components and reduce the cost of manufacturing components such as pipe fittings. These new technologies will ultimately lead to improved joining methods and lower-cost composite pipe fittings, allowing companies to develop suitable alternative products for carbon steel pipes. One of the greatest advantages of composite materials is the flexibility of design. Potential applications for composite pipe on deep-water platforms include process water, cooling water, potable water, nonhazardous waste water, nonhazardous drains and vents, chemical lines, fire water ring main, fire water wet deluge, fire water dry deluge, and ballast water. It has been estimated that composite pipe could be installed for one-fourth the cost of copper-nickel pipe in fire water systems. With lower cost fittings and reliable joining methods, a composite pipe system specifically designed for nonessential services could be installed for approximately the same cost as carbon steel pipe. However, the composite pipe would have an improved life cycle cost and one-fifth the weight of carbon steel pipe. To gain accelerated code acceptance and designer confidence, representatives from Shell Offshore, ARCO, Amoco, American Bureau of Shipping, and the U.S. Coast Guard are serving as collaborators on this project.

Sponsor: MSFC Technology Transfer Office; National Institute of Science and Technology (NIST); Advanced Technology Program (ATP)

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Tom Delay is working as a materials/ manufacturing engineer in the nonmetallic engineering division of MSFC's Materials and Processes Laboratory. His work is primarily in the development of launch vehicle hardware and components out of advanced composites. This hardware includes composite tanks for cryogenic applications, composite pipe and duct systems, and composite molds and tooling. He has a degree in physics from Southwestern Oklahoma State University and an M.B.A. from Oklahoma State University. He has worked at NASA for 8 years.

Maytag and NASA Team Up to Do the Dishes

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Maytag's famous lonely repairman is likely to stay that way, at least if NASA has anything to say about it.

Representatives of Maytag Corporation's Jackson, TN dishwasher manufacturing plant have teamed up with engineers at MSFC to help wash the dishes. Maytag sought to incorporate state-of-the-art aerospace technologies from NASA and its contractors into future dishwasher designs.

Maytag came to Marshall for help in evaluating the changes and finding areas where further refinements and improvements were possible. After an initial assessment and evaluation of the request by the Marshall Technology Transfer Office's (TTO) Technology Applications Board, Maytag's request was given to the TTO's industrial outreach team for Tennessee: NASA engineer Fred Schramm and Jeff Cornelius, an engineer with Lockheed Martin Corp. who serves as that firm's industrial outreach liaison.

Help for Maytag was found at another NASA contractor, Teledyne Brown Engineering (TBE) of Huntsville. TBE's Chester Simmons led an effort that provided Maytag's designers with insights into factors that influence dishwasher performance.

TBE found that Maytag's dishwasher design was very close to its maximum thermal efficiency, but recommended some "fine tuning" to improve performance by 10 to 20 percent. TBE's engineers studied where heat energy is absorbed in a dishwasher as it washes and dries. They found that the thermoplastic polymer tub retained less heat than did the porcelain models. This would affect performance.

Maytag has benefited from the NASA/TBE effort. These insights and various recommendations resulting from TBE's effort have guided design changes for Maytag.

The assistance provided to the Jackson, TN, plant is part of a national industrial outreach program operated by NASA's Southeast Regional Technology Transfer Alliance. The alliance pools the engineering resources of both NASA and its contractors at the space agency's Marshall Center, Stennis Space Center in Mississippi, Kennedy Space Center in Florida and the Southern Technology Applications Center in Florida. Alliance members conduct technology transfer programs of various kinds in nearly every state in the nation.

Up to 40 hours of technical assistance can be provided to U.S. firms, free of charge. "America's space program is paying off for American business and industry. Technologies, developed for the Nation's space program by NASA and its contractors, are now at work in thousands of American firms," Harry G. Craft Jr., Marshall's TTO manager said. "Now Maytag is among them."

"The latest survey of industrial assistance activities conducted by the alliance proves that American businesses consistently benefit from NASA's research and development expertise," Craft said.

"The alliance expedites American businesses', academic institutions' and entrepreneurs' acquisition, adaptation and application of a broad range of state-of-the-art technologies and techniques that have been proven in the Nation's space program to work effectively and efficiently," he added.

As a member of the alliance, the Marshall Center actively solicits requests for assistance from private industries such as Maytag. This is done through the use of mobile technology utilization assistance teams such as the one that helped Maytag refine its designs. These teams work with state and local governments and economic development agencies to identify candidate industries for receipt of aerospace technological assistance.

"To date, more than 5,000 requests have been received from U.S. firms," Craft observed. "Nearly 90 percent of these have been resolved successfully. Of the firms that have contacted the alliance for assistance, nearly all have indicated they would again seek NASA expertise if problems arise in the future." Businesses wishing to discuss ways in which NASA technologies or technical assistance programs might benefit them are encouraged to call 1-800-USA-NASA.

Sponsor: Office of Commerical Development and Technology Transfer

Biographical Sketch: Bob Lessels is the technical writer/editor (physical sciences) for the Technology Transfer Office at the Marshall Center. A graduate of the University of Nebraska, he has been a professional journalist for the past 30 years. He joined NASA in 1986.

NASA Technology Helps American Horses Get a Jump on Their Competition

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While still ensuring America's Space Shuttles lift off and land safely, NASA technology also will be at work helping premiere jumping horses do the same.

Horses are to be fitted with newly developed magnetic hoof protector pads and will wear them while competing.

According to their designer, Linda Hamilton Greenlaw, the pads are now being marketed worldwide under the name "Power Pads." Greenlaw says Power Pads support and cushion the impact of walking, running and jumping on the horse's hooves and legs, serving as an injury prevention product, similar to sneakers for human beings. Magnets implanted in the pads increase blood circulation in the horse's hooves, reducing the chance for injury, yet do not overheat the area. If any injury does occur to the hoof, the magnetic pad enhances blood flow to the area, speeding the healing process and helping to prevent permanent damage, Greenlaw says.

The magnetic material in the pads also works with the naturally occurring electrical impulses of the horse's nerves to reduce or eliminate pain from injuries to the hooves. According to an article, "Magnetic Fields in Animal Health," by Dr. Roger L. DeHaan, D.V.M., published in the February–April 1992 issue of the Journal of the American Holistic Veterinary Medical Association: "Magnets have been used successfully in medical therapy for humans and animals for hundreds of years, particularly for the treatment of osteoarthritus."

FIGURE 194.—A REALLY BIG SHOE. NASA materials engineer Deborah Dianne Schmidt and materials technician Anthony Schaffer show the prototypes for "Power Pads." These are hoof cushioning devices with magnet implanted in them for use on horses. Invented by New Englander Linda Hamilton Greenlaw, the pads' material was tested for fatigue and durability at MSFC.

According to Dr. DeHann's article, experiments at Loma Linda University in California, the Massachusetts Institute of Technology, and several universities in Europe have shown that magnetic devices improve blood flow to damaged tissues, speeding the healing process. Magnetism, the doctor writes, helps to order and align tissue salts in damaged cells. Electromagnetic stimulation gets the damaged tissues' fluids flowing again, helping to speed the elimination of waste products, reduce swelling, and restore normal function.

Magnetic material cannot be inserted directly into the hoof wall, as this can be toxic; thus the pads are the best way of providing the benefits of magnets without the hazards. The pads "fill the need to use magnets in the hoof area without heat buildup or toxicity," Greenlaw said. "Through field testing, we've discovered that the magnetic pads will cause the horse's foot to grow faster and become more resinous, thus correcting the medical problem of 'brittle hooves,' caused by riding a horse on hard ground."

The cushioning material and the magnetic material in the prototype pads were fabricated and stress analyzed at MSFC, by materials engineer Deborah Dianne Schmidt and materials technician Anthony J. Schaffer.

According to Greenlaw, "I became aware of the technology development assistance available to U.S. firms via the Marshall Center through an article which appeared in the Kiplinger Washington Letter. Calling the 1–800–USA–NASA telephone number listed in the news article, I reached the Marshall Center's Technology Transfer Office. Staff there helped me submit a simple, one-page request for assistance in developing and marketing my idea."

The request was forwarded by the Technology Transfer Office staff to Schmidt at the center's Materials and Processes Laboratory for study and evaluation. The lab has an expertise in material stress analysis resulting from decades of such work related to the nation's space program.

"I conducted a fatigue stress analysis of the pads' magnetic inserts and sought to determine the best configuration for them," Schmidt said. "The analysis led to the optimal configuration for durability of the entire pad design. Also, I was able to recommend a simple method to place the magnetic inserts in the hoof pads so as to prevent material failures caused by stress. The hoof pad material is subjected to a good deal of stress as the horse walks, runs and jumps," she said. "The basic design uses a piece of magnetic material held in a cutout area inside each pad." Schaffer cut the pads and magnetic inserts with "surgical precision," Schmidt added.

The magnetic pads are placed on the horse's hooves, then the animal's metal horseshoes are fitted onto the pads. Conventional horseshoe nails hold the pads and horseshoes onto the hoof. They also may be attached with "Easy Glu" for horseshoes. The pads are durable enough to be used for more than one shoeing and should last 6 months to a year.

"The pads—for a horse—are the equivalent of a human being taking off leather street shoes and putting on the proper track shoes for an athletic event. By cushioning the horse's feet from injury, the pads are preventative as well as therapeutic," Greenlaw said. "The pads can be used by horses in any type of situation that puts stress on the animal's hooves and legs, including racing, rodeos, walking, show jumping, mounted police and military operations, and polo, in addition to simple recreational riding. Persons interested in more information about Power Pads should contact: Equine Enhancement Products, Inc., 37A Everett St., Woburn, MA 01801

Greenlaw, a former champion equestrian in the New England area, was left partially disabled following an automobile accident in 1991. Her love of horses led her to develop this product for the animals.

"Since my injury, I've prayed God would let me return to working with horses. I think this is that way," she said.

Sponsor: Office of Commercial Development and Technology Transfer

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NASA Technology Helps Inventor Clean Up

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Technological assistance from MSFC is helping an inventor clean up—literally.

Cecil Thornburg of Millerville, AL, operated the Mr. Clean Janitorial Service in nearby Sylacauga. One of his customers was a Winn-Dixie supermarket with a large parking lot. The lot needed to be swept and have trash picked up. Thornburg felt there should be a way to sweep the lot and collect the trash at the same time.

Working to develop this idea, Thornburg devised a vacuum-sweeper combination that worked, but needed improvement. The amateur inventor got the professional assistance he needed free of charge through the Marshall Center's Technology Transfer Office (TTO).

Working from a technology assistance request submitted by Thornburg, the TTO's representative for Alabama, Benita Hayes, enlisted the help of three of the Marshall Center's mechanical engineers: Matt Marsh, Neill Myers and John R. "Rusty" Cowan. All work in the Propulsion Laboratory's Component Development Division.

After a visit to Thornburg's business to see and discuss the inventor's idea and design, the engineers used their expertise to suggest improvements. These included changing the shape of the vacuum unit's fan blades, introducing weight-saving and weight-redistribution refinements, and devising a way of guiding heavier trash, such as cans and bottles, to a point under the vacuum where suction was the greatest, thereby ensuring its collection.

"We're picking up nearly 100 percent of the litter we roll over," Thornburg said recently.

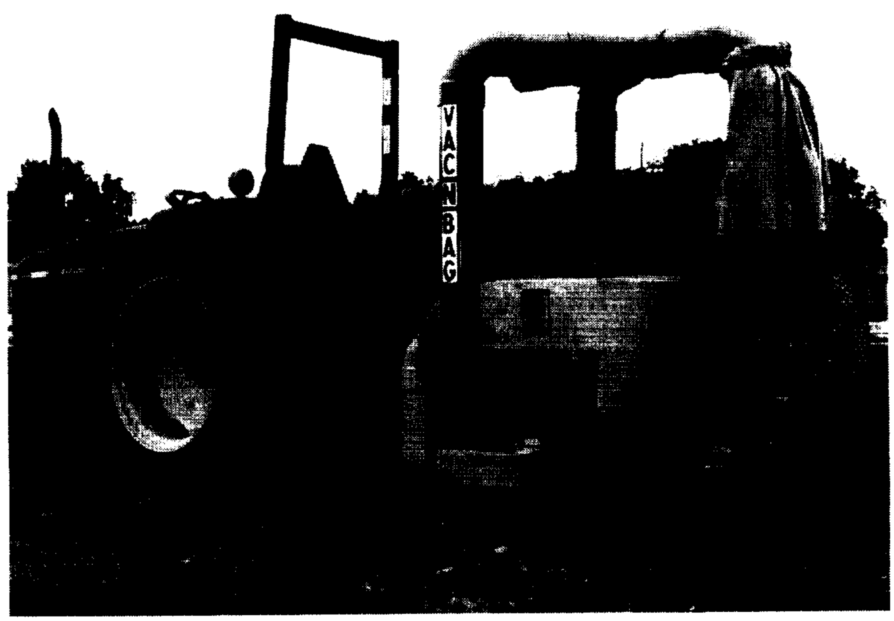

Figure 195.—The "Vac-n-Bag" unit is designed to be towed by a small tractor or truck, such as the one shown here.

FIGURE 196.—The "Vac-n-Bag" is demonstrated for officials of the State of Alabama Department of Transportation in Birmingham.

The new "Vac-n-Bag" design is pulled by a tractor and operates off of the tractor's engine. It has proven itself to be an efficient, cost-effective way of cleaning athletic fields, golf courses, parks and other grassy areas in addition to parking lots. The vacuum unit pulls the trash into the unit where it is shredded and bagged for disposal. "Vac-n-Bag" simultaneously mows the grass and collects the clippings, to boot.

The "Vac-n-Bag" is now being manufactured by the dozen new employees of Thornburg's new firm, the Burg Corp., in Sylacauga. It has been demonstrated for a number of municipal sanitation officials and for the Alabama Department of Transportation. Six "Vac-n-Bags" already have been sold and—at $9,995 per unit—the new firm is cleaning up in more ways than one.

The work done to assist the new enterprise is part of a continuing NASA-wide effort to facilitate the private sector's accessing of research and development expertise derived by the nation's space Agency and its contractors. When appropriate, the resources of the entire 750-member Federal Laboratory Consortium can be accessed through the Marshall Center Technology Transfer Office.

Firms and individuals interested in receiving Federal technology transfer are encouraged to call 1-800-USA-NASA.

Sponsor: Office of Commercial Development and Technology Transfer

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NASA Technology Gives Montana Students a Helping Hand Into Industry and Amputees a Helping Hand in Life

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NASA technology may soon be providing tens of thousands of below-the-elbow amputees with a helping hand—literally.

Montana Hands, Inc., is a new company set up by engineering students at Montana State University in Boseman to manufacture and distribute a new prosthetic device they've designed for below-the-elbow amputees. As they graduate, the students will step directly into the world of industry via their own company.

The basis for the students' forearm torque actuated terminal device's design lies in a similar device developed in 1986 at the Marshall Center. James Carden, a NASA engineer at Marshall, lost his lower left arm in a home woodworking shop accident. Carden was fitted with a commercially

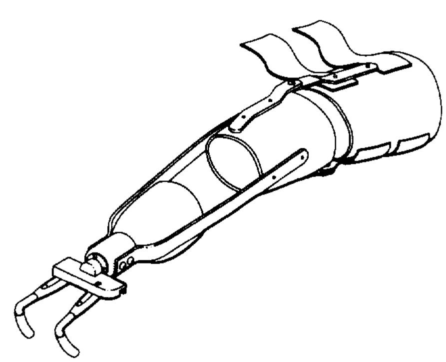

FIGURE 197.—The cheaper, smaller, lightweight design appears to offer a greater range of motion and mobility.

FIGURE 198.—Sandra Rossi, an early recipient of a NASA-designed prosthesis.

available prosthesis after his injury had healed, but he found that it was clumsy and didn't allow him to handle heavy lumber or pursue his favorite pastime, fishing.

Hearing of Carden's injury, a team of coworkers and friends at MSFC banded together to offer their help. Carden accepted.

According to Carden's long-time friend and coworker Jewell G. "Pete" Belcher Jr., an MSFC engineer and a member of the team formed to help Carden, "Studies have shown that the work we proposed to do for Jim could benefit many thousands of other Americans as well as uncounted others around the world."

One of the team's designs was a grasping device which can be opened and closed by the amputee twisting his or her lower arm. This design has been adapted by the students at Montana State University into their own design, assisted in the process by George Studor, a NASA engineer assigned to the university to facilitate the transfer of NASA technologies.

Unlike conventional body-powered prostheses that use a cable and harness or battery-powered myoelectric devices, the new design attaches directly to the amputees arm. The cheaper, smaller, lightweight design appears to offer greater range of motion and mobility, opposing hooks which open and close for grip and dexterity, an ability to grip various sized objects, and freedom from cables, harnesses and batteries. The new firm's device should be commercially available early in 1997.

In its charter, NASA is charged with facilitating the transfer of technology it and its contractors derive to the benefit of American businesses, schools and individuals. A NASA survey has shown that the improved below-the-elbow prosthesis could be used by 49,800 amputees in the United States alone. Headquarters endorsed the Center's work on the improved prostheses as authorized under this clause of the Agency's charter. NASA considers the work part of its overall technology transfer program as a biomedical applications project.

Sponsor: Office of Commercial Development and Technology Transfer

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Technology Transfer Alliance Industrial Outreach Effort Helping Louisiana Firm to Recycle Used Tires

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The Southeastern Regional Technology Transfer Alliance's industrial outreach effort has scored another success in working with Cryopolymers Inc., of St. Francisville, LA, to recycle the materials in worn-out vehicle tires.

Identified as a candidate for NASA technology transfer assistance by an industrial outreach team from the Marshall Center, a member of the alliance, a tire recycling system was devised in cooperation with engineers from Lockheed Martin's operation at the Stennis Space Center in Mississippi. They worked with Johnson Controls World Services, Inc., also at the Stennis Center, to take shredded vehicle tires, freeze them, and separate the rubber from the reinforcing steel belts and polyester fibers. The rubber which is recovered, called "crumb," is used in asphalt road beds and other items.

Anne Johnson, Technology Transfer Officer at Stennis, said, "The Cryopolymers project is a prime example of how NASA technology and expertise can benefit the public. The results of such collaborations (between NASA and private industry) can create jobs, increase profits and enhance economic competitiveness for the United States."

NASA personnel have been working with Cryopolymers to incorporate cryogenics (super-cold fluids such as liquid nitrogen and liquid hydrogen) into its recycling process. Stennis, as NASA's Center of Excellence for large propulsion engine testing, uses about 70 percent of all liquid hydrogen used by NASA.

Joe Kelley, director of community affairs for Cryopolymers, said the assistance from the Southeastern Alliance members has been "a blessing. The technology is there and we are purchasing equipment based on (alliance members') recommendations."

The most practical method of making "crumb" involves using liquid nitrogen to freeze the rubber to a temperature of –225 degrees Fahrenheit. Since the company has only been in business for a few months and the liquid nitrogen used in the process is extremely expensive, Cryopolymers was anxious to learn how to reduce the amount of liquid nitrogen needed to process the worn-out tires. Stennis helped Cryopolymers adapt its equipment to work in very cold temperatures and to better use cryogenic materials.

The "crumb" that is created from the cryogenic process can be broken down into various grades according to particle size. The largest particles are used to improve the wearability of road surfaces and can be reprocessed to mold products which must be weatherproof. Finer particles can be recycled to make new tires, agricultural hose, or mixed with plastics to produce culvert linings or beds for trucks. For each pound of rubber that is processed, 60 percent is reduced into crumb. The scrap metal and polyester residue also can be recycled into new products as a reinforcing fiber.

The importance of this recycling effort is best reflected in these statistics: More than 300 million tires wear out worldwide every year creating an enormous environmental disposal problem. Recycling techniques such as those developed for Cryopolymers are expected to recycle about 4,800 tires each day, recovering 4,000-lb of rubber every hour the plant is in operation.

Dr. Elizabeth Rodgers at the Marshall Center Technology Transfer Office is the primary NASA contact for Louisiana firms seeking assistance. She may be reached at Mail Code: LA20, MSFC, AL 35812; by telephoning 1-800-USA-NASA; or on the Internet by accessing http://techtran.msfc.nasa.gov. She coordinates her efforts with Andy Bush at the Louisiana Department of Economic Development's Technology Transfer Office, operated by the Louisiana Business and Technology Center at Louisiana State University; and Gordon Dyer of Lockheed Martin Manned Space Systems in New Orleans. Through this team, Louisiana firms can access the technological expertise and resources of all 752 members of the Federal Laboratory Consortium. The alliance will provide up to 40 hours of technical assistance, free of charge.

Sponsor: Office of Commercial Development and Technology Transfer

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Portable Seat Lift Benefits the Disabled

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Persons who cannot sit down or stand up easily are getting a boost—literally—from the American space program.

A portable lifting seat developed and patented by the Marshall Center, is now being manufactured by TQM, Inc., in Merrimack, NH. For individuals with degenerative knee or hip joint diseases or injuries, the easily carried device offers them a new degree of freedom. With it, they will be able to attend movies, go out to dinner, and do other things which involve sitting and standing without the need for a companion to help them sit or rise.

Development of the portable lifting seat was begun in 1990 by Bruce Weddendorf, Pete Rodriguez and Richard Smith, all from the structural development branch of Marshall's Structures and Dynamics Laboratory. Dr. David W. Gaw, an orthopedic surgeon at the Southern Hills Medical Center in Nashville, Tenn., provided professional medical guidance to the team. While the MSFC team members are more commonly involved in helping lift space shuttles to orbit, their expertise found a welcome application in developing the portable lifting seat.

Using funds provided by the Marshall Technology Utilization Office, the three developed what they call "an upholstered aluminum box"—a lightweight, battery-powered lifting device capable of assisting individuals weighing up to 300 lb with severe degenerative conditions in their knees, hips and/or backs with sitting down or standing up. It was estimated when work began in 1991 that up to eight million individuals could benefit from the device, if it could be developed. Most afflicted individuals have devices such as powered

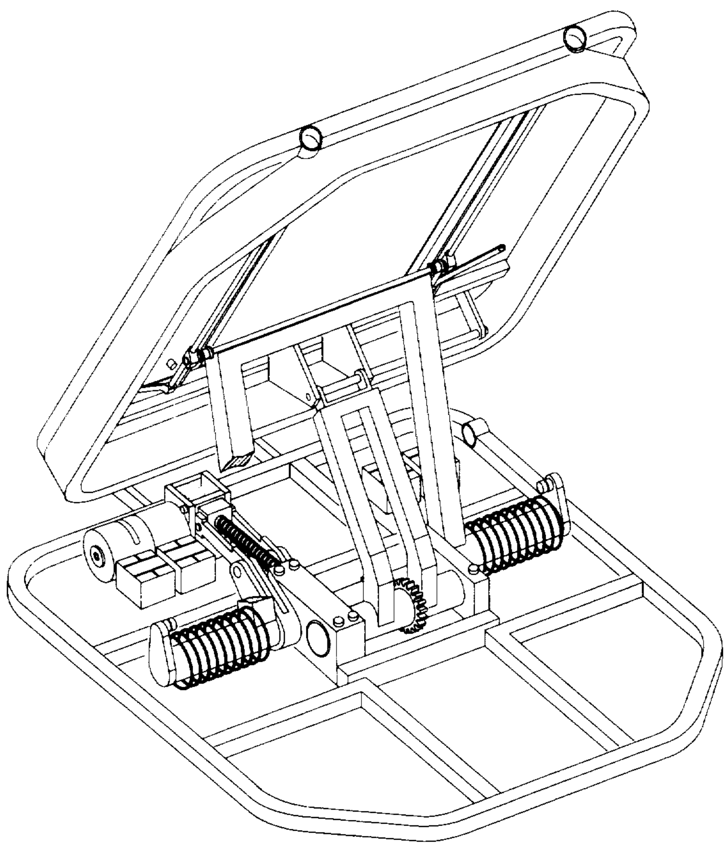

FIGURE 199.—The battery-powered portable lifting seat can help people who need assistance sitting and standing to lead more independant lives.

chairs in their houses, but require assistance when away from home. If no one is available to assist the individual, they often cannot leave home. With the portable seat lift, these persons may soon be able to carry the help they need as easily as a person carries a briefcase.

The device consists of a battery-powered motor which drives a gear train and crank assembly. The gears and crank lift up and push forward simultaneously, ensuring the padded seat remains at a proper angle to maintain contact with the individual being assisted. The individual being lifted controls the device via a three-position switch to raise, lower or stop the seat. A carrying handle completes the device.

By placing the powered lifting seat on a chair in a restaurant or on a theater seat, the individual needing assistance can sit down or stand up with ease, thereby experiencing a fuller, more normal lifestyle.

Nurses and orderlies in hospitals and nursing homes also may find the device useful in protecting themselves from back strain incurred lifting patients or residents and in assisting them to sit down. The powered seat would carry the weight of the patient with the nurse or orderly safely guiding and steadying the patient.

Sponsor: Office of Commercial Development and Technology Transfer

Biographical Sketch: Bob Lessels is the technical writer/editor (physical sciences) for the Technology Transfer Office at the Marshall Space Flight Center. A graduate of the University of Nebraska, he has been a professional journalist for the past 30 years. He joined NASA in 1986.

Marshall Center Book Lists Patents Available for Licensing

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Need information on welding innovations? Advances in bearing technology? How about medical advances or new uses for materials?

"NASA's ImagiNation," a new book produced by the Technology Transfer Office at the Marshall Center may provide just what you need.

Now, necessity may be the mother of invention, but the patent process is its legal guardian. The 76-page book lists and describes 38 of the best inventions patented by scientists and engineers of the Marshall Center. The 38 inventions were selected as they seem to offer the most potential for commercial application—a technology "spinoff," in NASA-ese—and because they are representative of the kinds of technology assistance available from the northern Alabama space center.

The technologies range from the exotic to the "why didn't I think of that!?"

Perhaps the longest title is "Control Circuitry Using Electronic Emulation of a Synchro Signal for Accurate Control of Position and Rotation for Shafts." The patent, in short, describes a digital circuit that improves the operation of robotic arms. Some of the shorter titles include a new design for a "Slip Joint Connector" and a "Prosthetic Elbow Joint." A "Quick Connect Nut and Bolt" device offers speed and security in building a space station—or in making emergency repairs here on Earth.

As NASA's leading center for the development of spacecraft propulsion systems, many of the patents included in the publication stem from work performed in developing the Saturn series of launch vehicles for the moon landing, the present Space Shuttle, and the next generation of propulsion systems for American space launch systems. Many of these patents deal with innovations in welding technology or equipment, development and testing of roller bearing assemblies and hydrostatic bearings used in rocket engine turbopumps, and the use of x-ray technology in nondestructive testing. The welding technology, for example, already has seen spinoffs into recycling 55-gal oil drums and in improving the manufacture of deep fat fryers and air-conditioning compressors.

A Centerwide interest in biomedical technologies has resulted in prostheses for amputees and an x-ray system for imaging soft tissues.

Research into uses for composite materials is extensive at Marshall and patents have been issued for breakthroughs in devising new methods of making composite structures. Metallurgy is another area of interest at Marshall, particularly as regards alloys and superalloys which are tolerant to rapid temperature changes.

The new publication provides but a brief overview of some of the thousands of patented developments stemming from the nation's space program which are now available for licensing to American business and industry. For more information on NASA-patented technologies or to obtain a copy of the publication, call 1-800-USA-NASA.

Sponsor: Office of Commercial Development and Technology Transfer

Biographical Sketch: Bob Lessels is the technical writer/editor (physical sciences) for the Technology Transfer Office at the Marshall Center. A graduate of the University of Nebraska, he has been a professional journalist for the past 30 years. He joined NASA in 1986.

Computational Fluid Dynamics, Not Crystal Balls, Help in Predicting the Future at Marshall Space Flight Center

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For centuries, mankind has sought to predict the future, but at MSFC, its computers, not crystal balls, and mathematics, not magic, are helping rocket scientists predict successful designs of future American spacecraft and propulsion systems.

The Computational Fluid Dynamics (CFD) Branch, led by Dr. Paul K. McConnaughey, is part of the Fluid Dynamics Division of the Structures and Dynamics Laboratory at MSFC. Using both desktop computer work stations and the Cray supercomputer at the Marshall Center, the men and women in the CFD branch use a variety of software to model the flow of liquids and gasses critical to the design and development of current and future spacecraft and propulsion systems. Both liquids and gases are considered fluids for the purpose of computational analysis of their dynamic properties.

McConnaughey said, "CFD is an analytical tool which helps speed design and guide development while reducing costs and saving time. CFD does not replace wind tunnel testing of aerodynamic designs or 'hot firing' of rocket engines. It does help to make such activities more time- and cost-effective through early identification of probable 'dead-end' designs, mathematical evaluation of alternative approaches to problem solving, and appreciation of potential improvements early in the design process. CFD enables us to look at design options up front, early in a program's

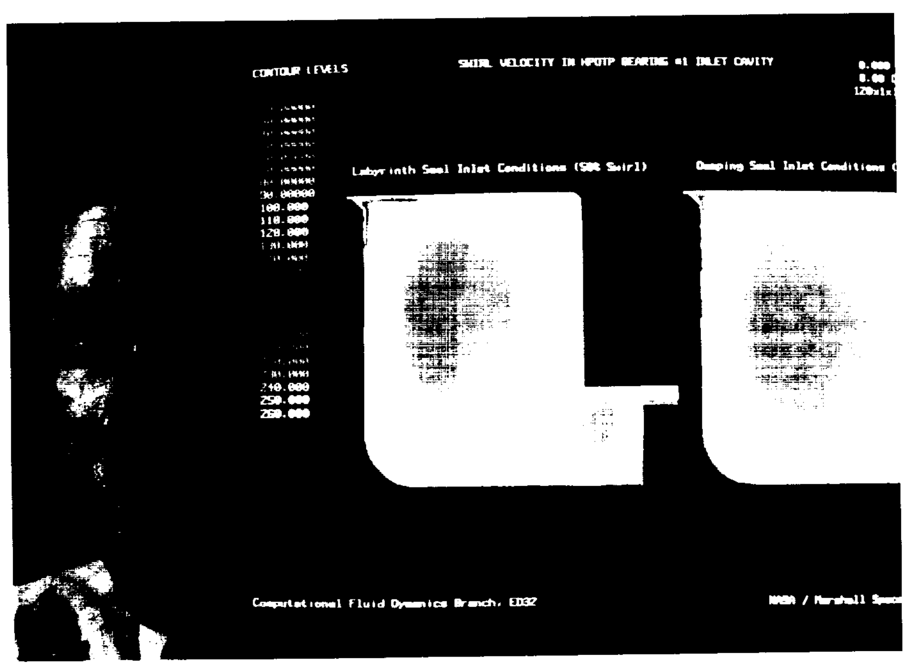

Figure 200.—Dr. Paul McConnaughey was a RTOP award winner with the implementation of state-of-the-art CFD codes at MSFC.

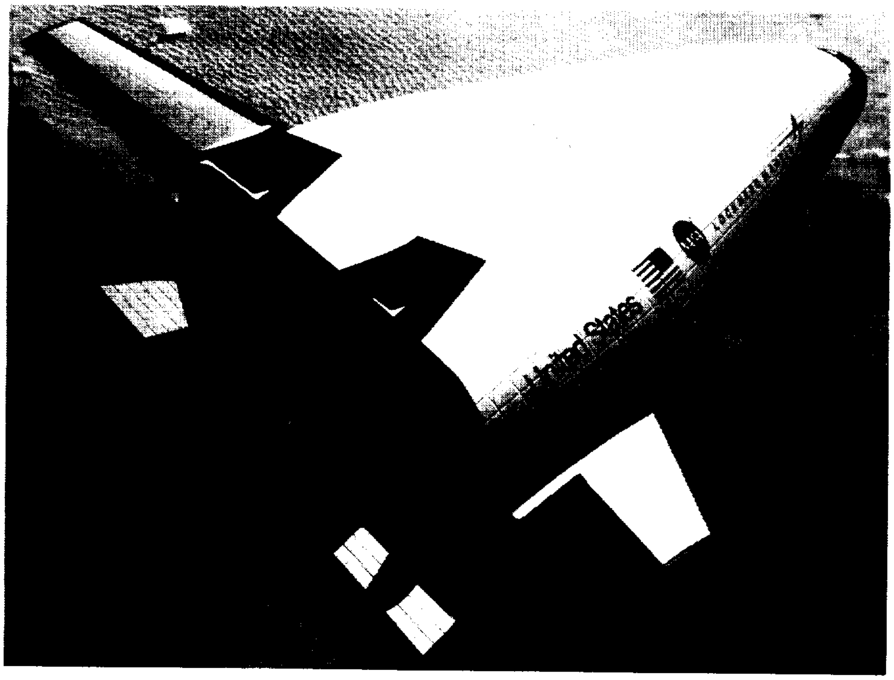

Figure 201.—An X-33 configuration which may replace NASA's Space Shuttle.

development, ensuring NASA and NASA-contractor engineers identify and pursue optimum solutions in the most efficient way possible."

The branch has initiated work on the X–33 and X–34 spacecraft with which NASA hopes to replace its current fleet of Space Shuttles in the next century.

"We're beginning work on mathematically modeling both the propulsion system and the vehicle itself," McConnaughey said. "This will be the largest, most complex task ever undertaken by the CFD branch. We're seeking to understand how various spacecraft shapes will behave operating in the Earth's atmosphere at high speeds where the gases which comprise the atmosphere ionize around the surface of the craft. Since NASA plans to use a hybrid propellant system—a solid fuel and a liquid oxidizer—we must ensure we fully understand the fluid mechanics and dynamics of candidate fuels and oxidizers, both as liquids on their way to combustion and as gasses during and after combustion in the rocket nozzles. We also are seeking to understand the effect of the thrust of the hybrid engines on the body of the vehicle, particularly on the couplings which hold the engines to the spacecraft. We will provide our mathematical models to materials scientists, engineers and others as we combine our efforts to develop a safe, efficient hybrid propulsion system."

The CFD figures also will be used to assess the impact of hybrid-propellant engine testing and operation on the environment. As an example, McConnaughey told of a study which involved disposing of liquid nitrogen. CFD was used to ensure the nitrogen would disperse safely as it evaporated without posing any dangers.

The Marshall Center has been NASA's principal field center for the development and evaluation of spacecraft propulsion systems since the beginning of the nation's space program in the 1950's.

Turning technologies developed through the national space program to the benefit of American industries is a major goal of NASA. Data concerning fluid dynamics is already being used in the new marine jet engine being built in Arkansas, and there is work underway to study using liquefied natural gas (LNG) as a fuel for the family car of the future and for commercial transportation systems. Aircraft and helicopters have already been test flown using LNG as a fuel. Other efforts to commercialize NASA technology in which CFD has played a developmental role include a human bone marrow implant, a cleaning nozzle, and a new design for a valve seat.

As regards assisting the Arkansas firm, the CFD branch was called upon to evaluate a proposed improved impeller blade for a medium-sized powerplant. The CFD branch's Robert Garcia used analytical systems to show that the proposed design would not meet desired performance requirements. Garcia and the firm's design team then discussed modifications to the shape of the impeller blades, which Garcia then analyzed via computer. His figures correctly predicted the new design would meet or exceed all the firm's requirements, resulting in the creation of a new product line for the firm. The marine jet-propulsion engine market is dominated by manufacturers in Europe and New Zealand; however, the Arkansas firm feels NASA's assistance will help it to compete successfully in the international market.

Improving impeller technology is particularly important to NASA as these devices are used to move liquid hydrogen and liquid oxygen from the Space Shuttle's external tank to the three main engines at the tail of the orbiter. A substantial improvement in impeller performance could enable the engine system to be modified to reduce weight of the propulsion system, increasing payload-to-orbit capabilities.

The transfer of technologies developed through the U.S. space program to benefit American industries is a responsibility given NASA in the Space Act of 1958 which established the agency. Firms interested in receiving NASA technological assistance to resolve manufacturing problems are encouraged to call 1–800–USA–NASA.

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NASA Composites Technologies Available to Industry

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Work at the Marshall Center to develop composite materials and technologies for use in the space Agency's Space Shuttle follow-on vehicle program should pay a number of dividends for American industries.

According to John Vickers, an engineer in the Materials and Processes Laboratory's Nonmetallic Materials Processes Branch, manmade composite materials technologies can offer significant advantages over metals when applied to structural programs and to programs where thermal problems are anticipated. Because composite materials are light and strong, they have already found their way into sports equipment. Tennis racquets, fishing rods, skis, boat hulls and golf club shafts are but a few examples.

"Various composite materials have different properties which can be tailored to suit the needs of the user," Vickers explained. "For structural applications where high strength and stiffness are most desirable, carbon or graphite fibers are combined with resins to achieve the desired results with the least weight. This, however, is the most costly approach. In situations where damage resistance is paramount and weight is not a major concern, Kevlar may be substituted for carbon or graphite. The most economical material is fiberglass, but it normally has the lowest strength-to-weight ratio. Being silica-based, fiberglass is very good for work involving thermal extremes as it has a low coefficient of expansion. The resins may be preimpregnated into the strips of fibers or the design engineer may elect to apply the epoxy or polyester resin later or during the manufacturing process."

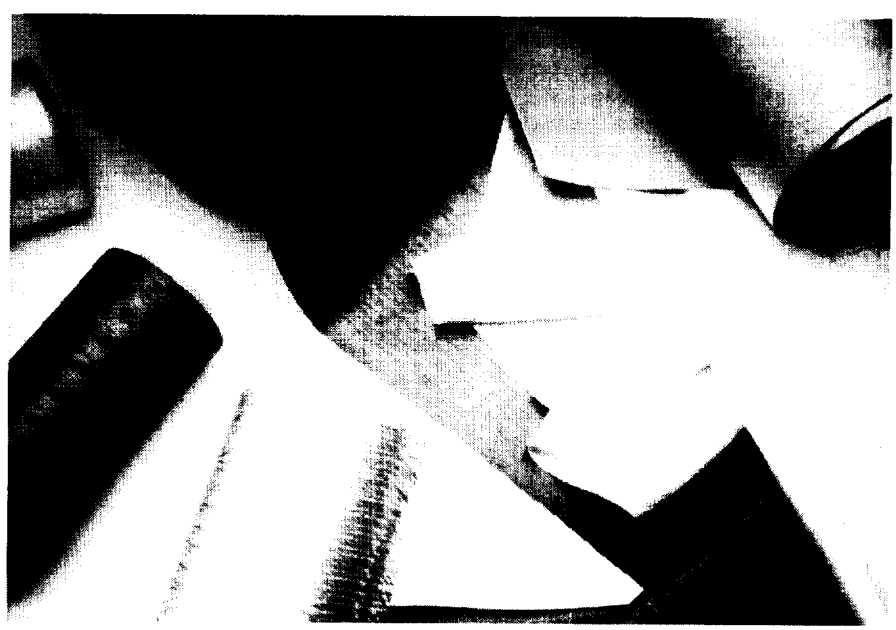

FIGURE 202.—Various composite materials have different properties that can be tailored to suit the user.

Regardless of the type of fiber selected, all are combined with a polymer resin such as epoxy or polyester which holds the fibers in place. A number of advanced resins have been developed for use in high-heat/cryogenic applications. Most epoxy and polyesters are thermoset resins which require elevated temperatures to completely cure.

According to Vickers, "The Reusable Launch Vehicle (RLV) Program is receiving a lot of attention from materials engineers and scientists as NASA seeks a follow-on craft for the present Space Shuttle. We've already used composites to fabricate cryogenic fuel pressure vessels for the RLV. These technologies may soon show up in the family automobile as attention is given to using liquefied natural gas as a low-emission fuel. Being extremely cold in its liquid state, liquefied natural gas will require an insulated, pressurized fuel tank. Insulation will probably be similar to the spray-on foam insulation now in use on the Space Shuttles' external fuel tank. We've already done some work, through the Marshall Center's Technology Transfer Office, with Thiokol Corp. in developing a compressed natural gas fuel tank for use on a minivan. We're also looking at composites for use in the Chrysler Corporation's proposed Patriot II formula one racing car, which also is expected to use liquefied natural gas as a fuel contained in an insulated, pressurized tank made of composite materials."

Marshall's work in developing composites technologies involves employing a number of specialized machines.

The filament winding machine lays down resin/fiber composite "ribbons" which are built up layer by layer until the desired thickness and degree of strength is achieved. Computer directed, the device is used to make pressure vessels and similar items which have symmetrical shapes. "As with many metal-working machine tools," Vickers said, "the filament winding machine was designed to do one job but has been adapted to perform others."

The pultrusion machine is similar to an extrusion machine. "Unlike metals, resin fibers can't be pushed through a machine. It's like trying to push a rope. The strand of epoxy-impregnated resin must be pulled through the die to shape it. Pultrusion technologies lend themselves to making long, continuous geometry shapes. This is a continuously operating machine in that, once set up, can be run for long periods. Pultrusion techniques have a number of structural applications," Vickers explained. "All types of fiber—carbon/graphite, Kevlar, or fiberglass—can be used depending on the desired physical properties of the finished composite item."

The laboratory's tape laying machine enables engineers such as Vickers to fabricate very large, somewhat contoured structures with asymmetrical geometries.

The lab's Viper CNC Fiber Placement System is the first of its kind. Built by Cincinnati Milacron Inc., the machine was initially used to make inlet ducts for experimental jet fighter prototypes. "Even now, there are only 10 or so of these systems in the entire world," Vickers said. "Marshall has been a leader in testing its potential applications in manufacturing composite parts with extremely complex geometries. The resin/fiber tools can be applied in patterns which can be narrowed or expanded to maintain a constant cross-sectional thickness. This is a very sophisticated, computer-controlled system whose uses are only beginning to be discovered and exploited. Possibly the most unusual application has been to fabricate from epoxy resin and graphite a human-powered submarine for a national student engineering competition in which the University of

Figure 203.—The filament winding machine lays down layers of resin/fiber composite ribbons until the desired thickness and strength is achieved.

Alabama in Huntsville is an annual participant.

The lab's tape wrapping machine was designed to build solid rocket motor nozzles, simulating those used for the solid rocket motors on the Space Shuttle. It has been adapted to make nozzles for engines which burn hybrid (solid fuel/liquid oxidizer) propellants and liquid fuels. Using carbon composites for the nozzles has a number of benefits. As the motor operates, gases from the composite resin evolve from the inside of the nozzle, acting as a passive cooling system. A carbon char layer builds up on the inside of the nozzle which also protects the nozzle from the heat of the motor's flame. In fabricating some nozzles, engineers replace the carbon with silica, Vickers explained, especially when the nozzle will be operating in a high-oxygen environment.

The lab's final capability involves resin transfer molding. "We have very limited capabilities in this at Marshall since this technology is more suited to being used in producing high-quantity precision components in a commercial manufacturing set-up," Vickers explained.

The laboratory is heavily involved in pushing the strength envelope of candidate composite materials for development of the Reusable Launch Vehicle for the nation's space program. Still, Vickers said, the lab is available to support less time-consuming projects on a time- and equipment-available basis. As examples of this, the lab is developing an instrumented obstetrical forceps to enable physicians to more safely position fetuses in the womb in instrument-assisted deliveries. Gauges on the instrument will enable the physician to avoid placing too much pressure or stress on the infant. Vickers was one of several materials engineers who recently worked on development of a racing wheelchair design, made of composites, that is now being manufactured commercially.

Research into high-strength, high-durability, low-cost composites at the Marshall Center is creating a technology data base which should benefit American industries and which is available to them under NASA's technology transfer program. Up to 40 hours of technical assistance can be provided by NASA's Marshall Center to U.S. firms, free of charge. For further information, call 1–800–USA–NASA.

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Marshall Begins Testing Hybrid Rocket Motor Technology

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The Marshall Center is preparing to test a new rocket motor that will combine the safety features of a liquid-propulsion system with the cost savings of a solid-propulsion system.

The hybrid system will combine a liquid oxydizer with solid fuel in a full-scale, 250,000-lb thrust hybrid rocket motor. It will be designed, fabricated, and tested under a multipartner effort called the hybrid propulsion demonstration program. Developmental testing of the hybrid motor will be performed at MSFC's Test Stand 500 beginning in December 1996.

"The goal of the new hybrid motor program is to develop a flight-like 250,000-lb thrust hybrid motor to demonstrate critical hybrid propulsion technologies and enable manufacturing of large hybrid boosters for current and future space launch vehicles," said Roger Harwell of Marshall Center's Propulsion Technology Office. Preliminary concepts show promise for application on both the X–33 advanced technology demonstrator and the Atlas launch vehicle.

The hybrid motors may be used independently, such as for a sounding rockets, or for thrust augmentation on an expendable or reusable launch vehicle.

"Safety, the most critical factor for any propulsion system, is the hybrid rocket motor's most notable feature," explained Harwell. "Hybrid motors employ an inert solid fuel and a liquid oxidizer which is physically separated until ignition. More importantly, the motor throttle can be controlled to enable on-pad check out, thrust tailoring and abort options."

Marshall Center's role will include providing test facilities, test operations support and test analysis. "Modifications to Test Stand 500 are being made to accommodate motor development," explained Jerry Cook of MSFC 's Propulsion Laboratory. "Expansions in the feed, ignition, pressurization and purge systems are expected at the test stand over the next year."

"The hybrid motor program is an excellent example of the partnership between Government and industry working to enhance and mature technologies for future applications," said Harwell. The program combines the efforts and funding of NASA, the Advanced Research Project Agency (ARPA) in Washington, D.C., Phillips Laboratory at Edwards AFB, CA, and members of an industry consortium. The consortium consists of Lockheed Martin, Thiokol, United Technologies, Rocketdyne, Allied Signal, and Environmental Aerosciences.

Marshall Center and industry have teamed in the past to develop subscale, hybrid rocket motors. An industry consortium, consisting of Thiokol, the Chemical Systems Division of United Technologies, the Rocketdyne Division of Rockwell International, Lockheed-Martin, and the American Rocket Company, joined with Marshall Center in 1989 to develop and test 11-in- and 24-in-diameter hybrid rocket motors for space vehicle applications. "Tests on the subscale motors were performed at Marshall," said Cook. "The tests have provided valuable data for the new hybrid rocket motor program."

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FIGURE 204.—A subscale hybrid rocket engine is demonstrated for one of the more "unusual" visitors to the 1996 Star Trek 30th Anniversary celebration in Huntsville, AL. The visitor agreed the new technology was out of this world—and it should know!

NASA Program May Revolutionize Rocket Propulsion and Air-Conditioning

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Application of hydrostatic bearing technologies may well revolutionize the world commercial air-conditioning industry, eliminate a source of environmentally hazardous chlorofluorocarbons, and speed the development of the next generation of military and civilian spacecraft.

The dual-use hydrostatic bearing program is a Federal technology reinvestment project under the Advanced Research Projects Agency (ARPA). The Marshall Center is NASA's Center of Excellence for the development of rocket propulsion systems. Chris Bramon, a mechanical engineer in MSFC's Technology Transfer Office, is the project's facilitator. In addition to MSFC, the project team is comprised of rocket engine manufacturer Pratt & Whitney of West Palm Beach, FL; world air-conditioning industry leader Carrier Corp., headquartered in Syracuse, NY, and the U.S. Air Force's Phillips Laboratory at Edwards AFB, CA.

In addition to being a world leader in spacecraft propulsion systems, the Marshall Center has one of the world's foremost tribology laboratories, specializing in finding ways to reduce mechanical friction through the use of improved bearings and lubricants.

In this dual-use technology effort—meaning that the results will have applications in the public and private sectors—engineers from both sectors are working together to replace the current rolling element bearings used in rocket engines and hydrodynamic journal bearings used in air-conditioner chiller units with hydrostatic bearings. In rolling element

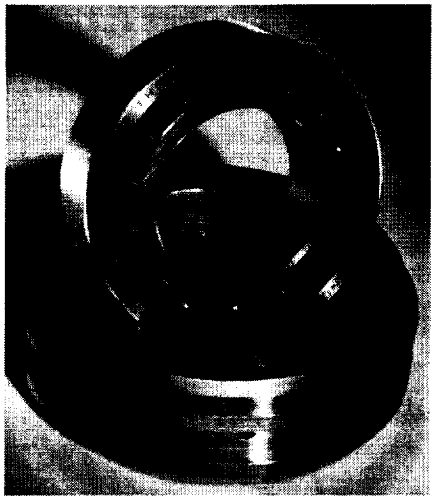

FIGURE 205.—Advanced hydrostatic bearings are being developed to replace existing bearings in rocket motors and air-conditioning chiller units.

bearing systems, the bearing's elements are in contact with the rotating shaft. This results in heat and drag in high-speed systems such as rocket engine turbopumps, which decreases the bearing's useful lifetime.

Hydrostatic bearing systems use the fluid being pumped as a means of keeping the rotating turbopump shaft centered in the pump and reducing friction. The fluid enters the small clearance between the bearing and shaft under pressure from six or more openings around the perimeter of the rotating shaft. This keeps the shaft centered.

Adoption of hydrostatic bearing pumps for future military and NASA rocket engines will reduce launch costs. A pump with typical rolling element bearings has up to 10 times as many parts as its hydrostatic bearing counterpart and is much heavier. Successful development of a hydrostatic bearing turbopump for rocket engines also will enhance launch-on-demand capabilities, reduce the weight of launch vehicles, permit the carrying of heavier payloads to orbit, reduce or eliminate propulsion system maintenance, and extend engine life of future reusable launch vehicles. Engines with the hydrostatic bearing technology also could be retrofitted into existing launch vehicles to reduce costs there.

Improvements to the turbopump component of the rocket engines include elimination of steady-state wear, removal of the rolling element bearing speed limitations (permitting smaller, lighter-weight turbopumps), fewer parts (leading to lower manufacturing and assembly costs), reduced complexity (resulting in higher system reliability), greater durability and longer service life.

In the commercial cooling and refrigeration industry, the use of hydrostatic bearings combined with nonozone-depleting refrigerant will have significant environmental advantages. Currently, oil is used to ensure proper lubrication of the refrigerant compressor's gears and bearings. Although essential for existing systems, oil contaminates the refrigerant, reducing heat transfer efficiency. The adoption of hydrostatic bearings, which operate with a nonozone-depleting hydrofluorocarbon coolant such as HFC–134a, would eliminate the need for about 72,000 gal of lubricating oil annually. Used oil is considered to be a hazardous waste.

The adoption of hydrostatic bearings in commercial water chillers also improves heat transfer performance, thus reducing unit cost, lowering the user's annual power costs, and extending the in-service life of the unit. Jonathan Shaw, manager of communications for Carrier Corp., believes new jobs may be created as manufacturing facilities for hydrostatic bearing air conditioners come on line before the end of the century. The technology also will enable the U.S. firm to remain on top in the world's air-conditioning and refrigeration equipment market, Shaw said.

Use of hydrostatic bearings in the air-conditioner's compressor system eliminates mechanical energy losses in the unit's gearbox, eliminates the contamination of the refrigerant by the unit's lubricating oil, reduces fabrication and assembly costs, and improves cost and reliability of the chiller through elimination of the lubricating oil management system's components.

There is an additional advantage for NASA, the U.S. Department of Defense and the nation's rocket engine industry: HFC–134a is an excellent surrogate fluid for testing hydrostatic bearings in those rocket engines' fuel pumps which are designed to use liquid hydrogen as a fuel. Like hydrogen, HFC–134a is a compressible liquid. However, unlike hydrogen, HFC–134a is not combustible, thus increasing safety for surrogate fuel testing.

For more information about NASA's Technology Reinvestment Program and the Federal Government partnering with industry, call 1–800–USA–NASA.

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NASA Helps Invent Revolutionary X-Ray Instrument

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A 3-year collaborative effort by NASA, industry and university researchers has resulted in the development of an instrument which can generate the world's most intense source of commercial x-rays.Capable of generating beams that are more than 100 times the intensity of other conventional x-ray sources, the new instrument is expected to lead to improvements in biotechnology research and have a wide variety of applications in scientific research, medicine and industry.

The revolutionary invention was developed by researchers at MSFC; X-Ray Optical Systems, Inc., Albany, NY; and the Center for X-Ray Optics of the State University of New York at Albany.

"This new optical instrument provides something never before possible: a capability to control the direction of x-ray beams," explained Dr. Walter Gibson, professor of physics at the State University of New York at Albany.

At the heart of the instrument is a new type of optics for x rays called "capillary optics." "The x rays are controlled by reflecting them through tens of thousands of tiny curved channels or capillaries, similar to the way that light is directed through fiber optics," said Gibson. "Thus, we are able to concentrate the beams to suit the particular needs of the intended research or medical procedure." Researchers at Marshall are using the newly developed x-ray instrument to determine the atomic structure of important proteins which are the targets for drug design by leading pharmaceutical companies. "Our current research efforts focus on many difficult public health problems such as cancer, AIDS and heart disease," said Dr. Daniel Carter of Marshall's Laboratory for Structural Biology.

"This new capillary x-ray technology will allow us to pursue more challenging research problems in our own laboratory with a speed and effectiveness never before possible," said Carter. "These and future applications should have a profound impact on many areas of science and medicine.

"We expect this new technology to significantly accelerate the ability of researchers to gather the information necessary to design entire families of highly effective, disease fighting drugs," said Carter. The new x-ray lens system, designed by the University of New York at Albany under NASA contract, incorporates the special optics manufactured by X-Ray Optical Systems.

"As a result of working with NASA and the State University of New York at Albany, we have developed x-ray optics which will provide important commercial benefits to a broad range of industries," said David Gibson, president of X-Ray Optical Systems, Inc. "Many commercial applications of this new technology are possible, including better manufacturing control for semiconductor circuits, better medical imaging, such as in mammography, and improved forensics."

The high intensity x-ray beams will permit scientific and medical research to be performed in less time with higher accuracy. In some cases the research was not feasible in standard x-ray laboratories. Also, the instrument could permit the use of smaller, lower cost and safer x-ray sources.

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Sometimes It Does Take A Rocket Scientist...

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Georgia firms with out-of-this-world technical problems may soon find that NASA can help them find some down-to-Earth solutions.

Working with Georgia Tech's Economic Development Institute, MSFC has established a new video conferencing center at Georgia Tech's Center for Manufacturing Information Technology (CMIT) in Atlanta. NASA's goal is to help Georgia industrialists, educators and entrepreneurs discuss technical problems directly with NASA scientists and engineers at Marshall and—it is hoped—find a solution.

Videoconferencing technology allows voice and video interaction so groups can communicate live over long distances. Establishment of the videoconferencing center eliminates the need for Georgia business persons to travel to MSFC in Alabama. Collaboration between Georgia businesses and NASA can now take place at the videoconferencing center, making optimum use of their time for the least cost. Georgians can arrange to use the video teleconferencing center to speak face to face with those NASA scientists or engineers at MSFC who are best qualified to provide technical assistance or recommendations.

The CMIT frequently hosts visits by business and industry leaders from across the state and serves as a convenient location for videoconferencing. It showcases the latest in manufacturing information technologies available to Georgia firms. Visitors can learn about the latest computer and communications technologies by participating in training classes and trying out some of the latest software to enhance their businesses' competitiveness at home and abroad.

Harry G. Craft, Jr., manager of MSFC's Technology Transfer Office, arranged NASA's loan of the video teleconferencing equipment necessary to establish the link between Georgia and the space agency. Craft said, "The establishment of the videoconferencing center provides an efficient, economical way to transfer of Federal technologies and expertise to industries across Georgia. NASA seeks to return taxpayer-funded technologies to U.S. business; a service the public rightly expects to receive from this nation's space program. The Marshall Center often will provide firms with technical assistance free of charge."

On September 19, 1996, the videoconferencing center hosted a special program from NASA. Business leaders electronically met NASA personnel and learned, firsthand, how to participate in the NASA technology transfer program. Demonstrations and information on NASA's materials science and plasma spray process were included. Instead of the one-way communication of regular video programming, the participants were able to ask questions on the spot and interact with NASA scientists.

NASA technology transfer makes available thousands of items developed for use in space that have down-to-Earth industrial applications. Lightweight materials, heat resistant shielding, remote sensing, cryogenic technologies, insulating foams, welding technologies, computer software, and a host of other inventions, developments and innovations from the space program are finding commercial applications each day. By mid-summer 1996, more than 5,000 U.S. firms had benefited from NASA assistance. A survey of NASA technology transfer's economic impact on Georgia from January 1993 to May 1996 showed assistance provided more than $42 million in economic benefits, with 492 jobs saved or added to the state's work rolls. More than 60 new or improved products were being manufactured in the state, all thanks to technology transfers from the nation's space program.

To arrange a video conference with NASA, Georgia business persons should contact the CMIT's Margi Berbari at 1–404–894–0357.

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NASA, USBI Engineers Turn Into "Roads" Scholars

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A process developed by MSFC and United Technologies' USBI to apply heat-resistant coatings to the Space Shuttle's solid rocket boosters is finding a new use. It has been successfully used to apply a new, skid-resistant surface to an interstate highway bridge south of Huntsville, AL.

The demonstration, conducted with the cooperation of the Alabama Department of Transportation, successfully resurfaced a bridge on Interstate 65 (I–65) between Huntsville and Cullman, AL. Using the new process—called convergent spray—the coating was applied in less than 1 hour. Four hours after the application was completed, the roadway was reopened to traffic. This is a fraction of the time such a resurfacing normally would require. In addition to being faster, the cost of the resurfacing was considerably less than it would have been using conventional methods.

FIGURE 206.—This roadway was reopened just 4 hours after the skid-resistant coating was applied.

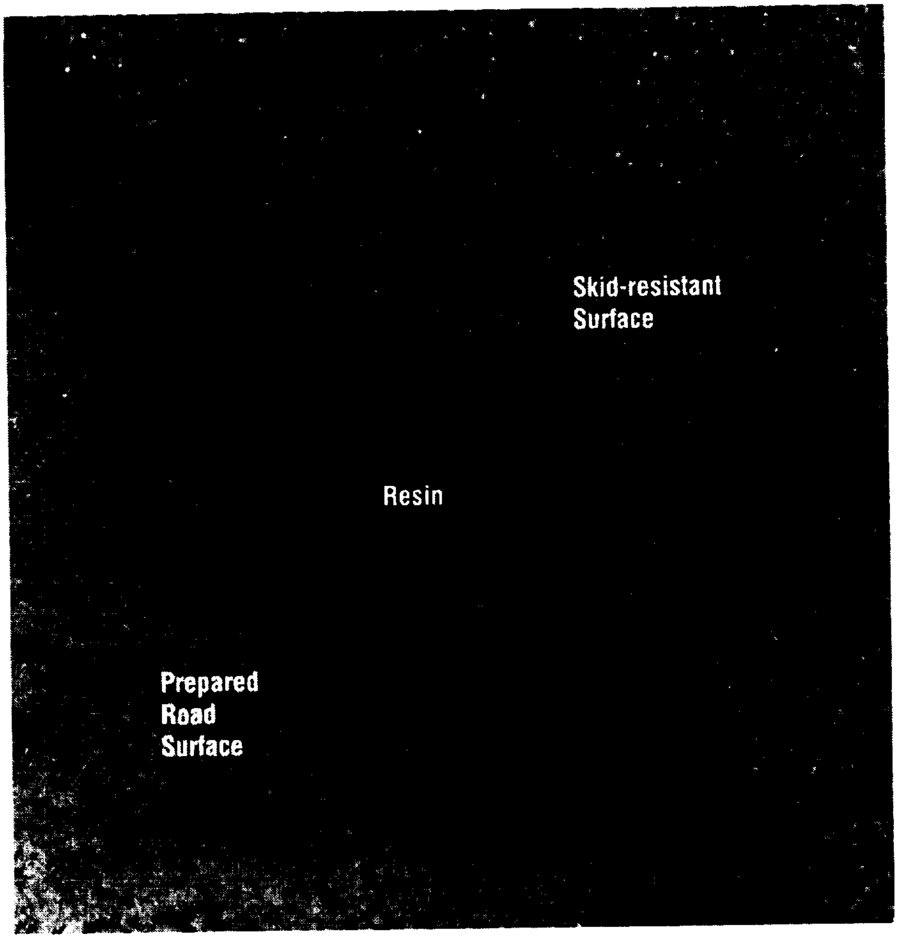

FIGURE 207.—A close-up of the I–65 roadway resurfacing project, ground flint and resin was used providing a higher degree of traction and better protection from erosion.

Once the surface is prepared, the conventional method requires workers to apply a coat of resin to the roadway, manually lay down a coat of gravel or skid-resistant material, then apply a second coat of resin. The new space-age process does the entire job in one pass.

"Not only does it shorten the job, the process does not harm the environment," Kyle Hamlin, a materials engineer at USBI said. The tool uses a solvent-free spray which significantly reduces the hazardous waste normally associated with most spraying processes.

Another environmental plus is that recycled filler materials and common resin systems can be used in the device.

For the I–65 bridge roadway resurfacing project, these space-age roads scholars used a mixture of ground flint and resin. The new coating provides a higher degree of traction and will better protect the bridge from erosion than do traditional roadway coatings.

Vernotto McMillian, technical manager in the Marshall Center's Technology Transfer Office, said, "The project afforded us the opportunity to evaluate a new pollution-preventing technology as well as to test different resin systems and filler materials which might be used for other NASA programs. We took an existing NASA technology, developed it for use in other NASA and commercial projects, and demonstrated that its use would afford a cheaper, better product that saves time," he said.

The bridge resurfacing project is the result of a 1994 agreement between Marshall and the Federal Highway Administration's office for the southeastern United States. Marshall and its contractors agreed to provide innovative technology derived from the space program and put it to use for a variety of highway applications, including corrosion-resistant coatings for metal bridges and skid-resistant surface treatments for pavement.

The new process may have a number of other applications. It is currently being used to apply a roof coating to two commercial buildings. Investigators also are working with a food company to spray toppings on snack foods.

"The successful commercial adaptation of this space program technology is yet another example that shows America's space program is paying off for American business and industry. Technologies, developed for the nation's space program by NASA and its contractors, are now at work in thousands of American firms, benefiting millions of Americans," said Harry G. Craft Jr., manager of the Technology Transfer Office at the Marshall Center. American firms wishing to discuss ways in which NASA technical assistance programs might benefit them are encouraged to call 1–800–USA–NASA.

Sponsor: Office of Commercial Development and Technology Transfer

Biographical Sketch: Bob Lessels is the technical writer/editor (physical sciences) for the Technology Transfer Office at the Marshall Center. A graduate of the University of Nebraska, he has been a professional journalist for the past 30 years. He joined NASA in 1986.

Space Shuttle Engine Technology Research Benefits American Jet Engine Manufacturer

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NASA Space Shuttle technology is paying big dividends for one of the nation's largest manufacturers of jet engines for aircraft, Pratt & Whitney (P&W) of East Hartford, CT.

As a spinoff of an experimental investigation conducted at MSFC, significant improvements have been incorporated into the design of a P&W jet engine. The technological enhancements are applicable to other turbine designs, as well.

In 1992, a series of tests were conducted to experimentally investigate the settings of the blades and vanes of the turbine components on Pratt's high-pressure fuel turbopump for the Space Shuttle Main Engine. These tests were part of a cooperative program between NASA and P&W, one of America's premiere jet engine/rocket engine manufacturers, to experimentally study performance improvements possible by repositioning turbine blades relative to one another.

In the test rigs there were two sets of rotating turbine blades, called rotors, and two sets of stationary vanes, called stators, which direct the flow of hot combustion gases. The 50 airfoil-shaped blades on each of the 2 rotors and 54 vanes on the 2 stators are aligned consecutively, one after the other.

The Marshall and P&W engineers studied the effects of slightly rotating the vanes on stator two relative to their upstream counterpart. The vanes were thus slightly out of direct alignment. Tests also studied similar rotational adjustments on the blades of rotor two relative to those on rotor one. P&W engineers were later able to apply the experimental test data obtained in the Marshall Center tests to modify turbine rotor designs in the PW–4084 engine for the Boeing 777.

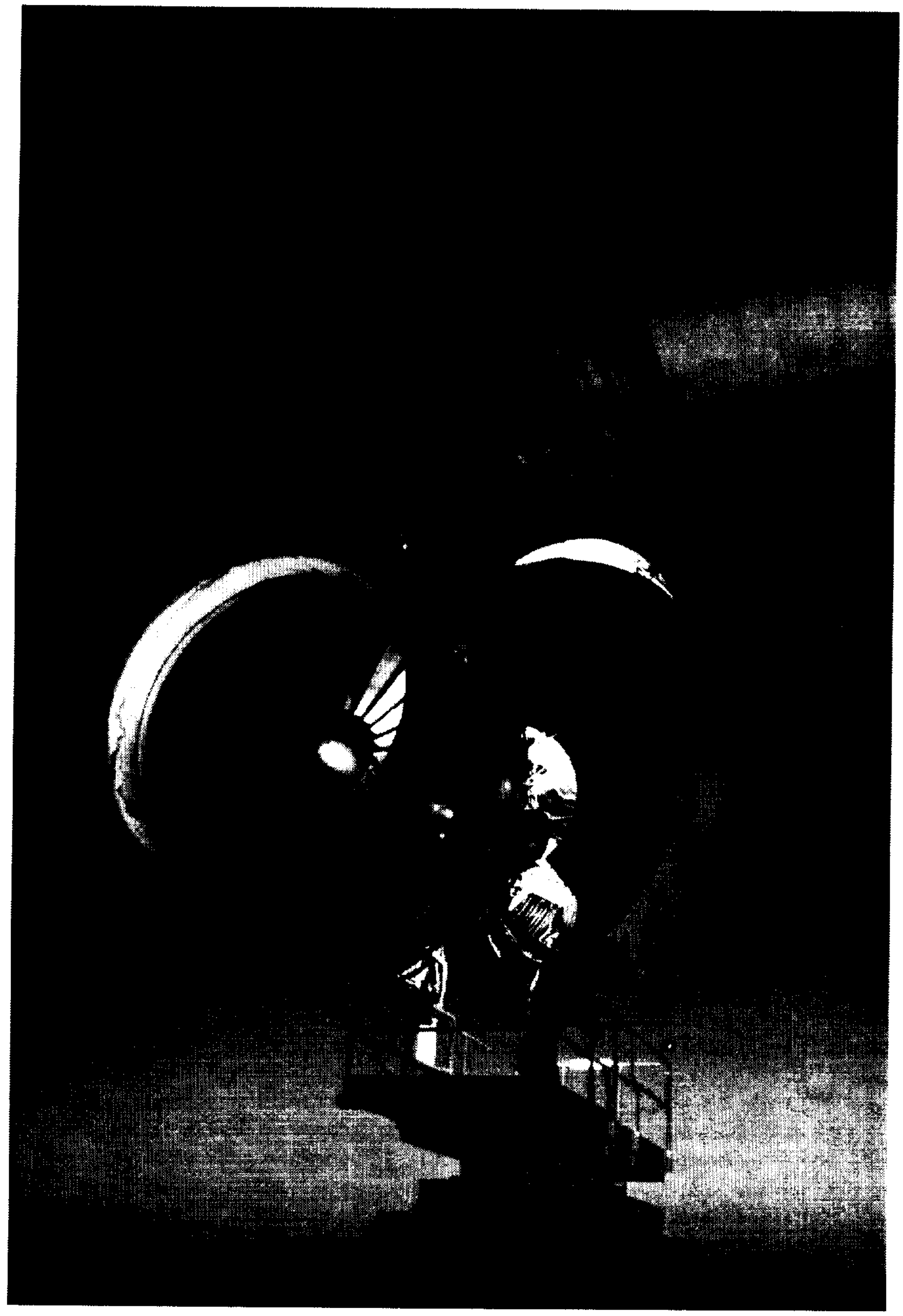

Figure 208.—A spinoff of an experimental investigation produced significant improvements to the design of a Pratt & Whitney jet engine.

Researchers at Marshall included: Stephen Gaddis and Lisa Griffin of the Structures and Dynamics Laboratory. Supporting them were John Heaman, William Neighbors, and William Kauffman of the Structures and Dynamics Lab and Richard Branick of Dynamic Engineering Inc., of Laceys

Spring, AL, the support contractor for the lab. They worked with F.W. Huber, P.D. Johnson and A.K. Finke of P&W's West Palm Beach, FL, facility, and O.P. Sharma from P&W's jet engine facility in East Hartford, CT.

The research team learned that a significant improvement in engine efficiency could be attained through the application of this innovative alignment of turbine rotor and stator blades. By applying this concept to the new P&W engine's rotors, they were able to improve its efficiency by a full half-percent. This is a significant improvement.

A twin-engined Boeing 777 aircraft using improved P&W–4084 engines flying a round-trip between Los Angeles and Hong Kong—a total distance of about 12,500 miles—would save about 400 gal of fuel. For shorter, transatlantic flights of about 6,000 miles round-trip, the savings would be about half that for Pacific operations. On an average, transoceanic airliners fly their routes three times a week. Extrapolating the fuel savings for the entire projected airline industry fleet of 92 Boeing 777 jets equipped with improved P&W–4084 engines over the course of a year of operations, shows an anticipated savings of more than 4 million gal of fuel—the equivalent of more than 650,000 barrels of oil.

The Pratt & Whitney engine is one of three being offered by Boeing for customers of the 777. The new Pratt & Whitney engines are projected to be installed on 40 percent of all Boeing 777's manufactured.

Some other benefits will accrue to the U.S. economy from these new engines besides greatly improved airline efficiency. U.S. airplanes and the new fuel-efficient engines will gain an important competitive edge in the international aircraft marketplace.

As a result of the tests conducted at MSFC, the fine tuning of the airfoil blade settings also may find an application in the large electricity-generating turbines used by America's utilities. By increasing generator turbine efficiency, electric utilities could achieve significant operational cost savings. In the case of electric turbines run by fossil fuels, greater efficiency of operation means lower fuel costs and the possibility of reduced pollution.

With America's electric utilities moving rapidly toward deregulation and increased competition, this means there will be great pressure to pass the savings on in the form of lower electric rates to the consumer.

"NASA efforts working with U.S. firms in transferring technologies from the Nation's space program to the public sector are proving to be very effective," said Harry Craft, manager of the Marshall Center Technology Transfer Office. "NASA is actively returning to U.S. industry the technologies for which the American taxpayer has paid and rightly expects to receive from this Nation's space program."

NASA will provide up to 40 hours of free technical assistance to U.S. businesses and industries. For further information on NASA Technology Transfer activities, call 1–800–USA–NASA.

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Abbreviations and Acronyms

AADSF	advanced automated directional solidification furnace
ADIS	anomaly detection and identification subsystem
AEDC	Arnold Engineering and Development Center
AEOLUS	autonomous Earth orbiting lidar utility sensor
AFIS	automated fluid interface system
AITP	Aerospace Industry Technology Program
AMI	analytical model improvement
ARPA	Advanced Research Products Agency
ARRT	Advanced Reusable Transportation Technology
ASAL	Advanced Signal Analysis Library
ASPS	automated signal processing subsystem
ASTEX	Atlantic stratocumulus transition experiment
ASTP	Advanced Space Transportation Program
AT	advanced turbopump
ATM	Atmospheric Tether Mission
ATMS	analysis topographical mapping system
AXAF	Advanced X-Ray Astrophysics Facility
BATSE	burst and transient source experiment
BET	beamed energy transportation
BLAST	beyond LEO advanced space transportation
BSMT	bearing seals and materials tester
C-STAR	conically-scanning two-look airborne radiometer
C/SiC	carbon/silicon carbide
CADDMAS	computer assisted dynamic data monitoring and analysis system
CAVE	computer applications and virtual environments
CBLISK	composite integrally bladed disk
CBM	common berthing mechanism
CCD	charged couple device
CCN	cloud condensation nuclei
CDDF	Center Director's Discretionary Fund
CER	cost estimating relationship
CFD	computational fluid dynamics
CFM	cryogenic fluid management
CGEL	Ground Control Experiment Laboratory
CGF	crystal growth furnace
CMC	ceramic matrix composite
CoFlo	compressible flow
COTS	commercial off-the-shelf
CPU	central processing unit
CW	continuous wave
DBC	differential box mounting
DC-X	Delta Clipper Experiment
DCAM	diffusion controlled crystallization apparatus for microgravity
DOE	diffractive optical elements
DOF	degree of freedom
DTA	differential thermal analysis
ECLSS	environmental control and life support system
EDIFIS	engine diagnostic filtering system
EMA	electomechanical actuator
EMI	electomagnetic interference
ENA	energetic neutral atoms
EPDM	ethylene propylene diene monomer
EPRI	Electric Power Research Institute
ERBS	Earth Radiation Budget Satellite
EUV	extreme ultraviolet
EVA	extravehicular activity
EXVM	experimental vector magnetograph
FCCC	framing convention on climate change
FDM	fused deposition method
FM	frequency modulation
FMLI	foam/multilayer insulation
FOV	field of view
FPB	fuel preburner
FSM	flight support motor
FSW	friction stir welding
FTIR	fourier transform infrared
FTTS	flight test telemetry system
GCM	general circulation model
GEO	geosynchronous-Earth orbit
GFFC	geophysical fluid flow cell
GHCC	Global Hydrology and Climate Center
GOES	Geostationary Operational Environmental Satellite
GQE	generalized quadratic equation
GRO	Gamma-Ray Observatory
GSE	ground support equipment
GUI	graphical user interface
HDFTP	high-pressure fuel turbopump
HEDS	Human Exploration and Development of Space
HENA	high energetic neutral atom
HIRS	high-resolution infrared sounder
HLR	Human Lunar Return
HOE	holographic optical elements
HRMA	high-resolution mirror assembly

HRST	Highly Reusable Space Transportation program
HST	Hubble Space Telescope
HTML	hypertext markup language
IMAGE	Imager for Magnetopause-to-Aurora Global Exploration
IMSL	International Math and Statistics Library
IPTD	integrated propulsion technology demonstrator
I_{sp}	specific impulse
ISS	International Space Station
ISTP	International Solar Terrestrial Physics program
ISWE	international space welding experiment
IVHM	integrated vehicle health management
JANNAF	Joint Army-Navy-NASA-Air Force
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KB	knowledge base
KSC	Kennedy Space Center
LAD	liquid acquisition device
LaRC	Langley Research Center
LCF	Laser Characterization Facility
LDSP	large-scale digital signal processing
LEEIF	low-energy electron and ion facility
LEO	low-Earth orbit
LIS	lightening imaging sensor
LO	local oscillator
LOI	lunar orbit insertion
LOM	laminated object manufacturing
LOPC	laser optical particle counter
LOS	line of sight
LWCS	longwave clear-sky radiation
MAC	modal assurance criteria
MACAWS	multicenter airborne coherent atmospheric wind sensor
maglev	magnetically levitated
MAMS	multispectral atmospheric mapping sensor
MAPO	magnetically actuated propellant orientation
MET	mission elapsed time
MGA	multigraph architecture
MGM	mechanics of granular materials
MHD	magnetohydrodynamics
MHTB	multipurpose hydrogen test-bed
MIC	microprocessor
MLI	multilayer insulation
MMA	method of moving asymptotes
MMC	metal matrix composite
MRECS	modular rocket control software
MSA	Marshall sprayable ablator
MSAD	Microgravity Science and Applications Division
MSG	microgravity science glovebox
MSM	magnetospheric specification model
MSU	microwave sounding unit
MSV	mechanisms of solar variability
MTF	modulation transfer function
MTPE	Mission to Planet Earth
NAFCOM	NASA Air Force cost model
NBS	Neutral Buoyancy Simulator
NDE	nondestructive evaluation
NGST	Next Generation Space Telescope
NLO	nonlinear optical
NOAA	National Oceanic and Atmospheric Association
NRA	NASA Research Announcement
NTC	NASA Teleconference Center
NTR	nuclear thermal rocket
OBCS	on-board computer system
OBVCU	on-board bias and vent control unit
OEA	operations execution assistant
OISPS	operator interactive signal processing system
OLMSA	Office of Life and Microgravity Science and Applications
OMS	orbital maneuvering system
OPAD	optical plume anomaly detection
ORNL	Oak Ridge National Laboratory
OSSE	observing system simulation experiments
OTD	Optical Transient Detector
OVRO	Owens Valley Radio Observatory
PCAM	protein crystallization apparatus for microgravity
PCTC	Payload Crew Training Complex
PDA	polydiacetylene
PDE	pulse detonation engine
PDT	product development team
PEC	Productivity Enhancement Complex
PEEK	polyetherether ketone
PGSC	payload general support computer
PIVI	pinhole ion velocity imager
POCC	Payload Operations Control Center
PPPOA	product and process plan of action

PSI phase shifting interferometry
PSU Penn State University
PSW physical split window
PTA propulsion test article
PVT physical vapor transport
PWI plasma wave instrument
PWR power
R&D Research and Development
RBCC rocket-based combined cycle
RBF radial basis function
RCS reaction control system
RIMS retarding ion mass spectrometer
RLV Reusable Launch Vehicle
RMF rotating magnetic field
RMS remote manipulator system
ROSETA range over standard deviation experimental trend analysis
RP rapid prototyping
RPI radio plasma imager
RRTT revolutionary reusable technology turbopump
RSM reference stress method
RSRM reusable solid rocket motor
SAIC Science Applications International Corporation
SBIR Small Business Innovative Research
SDT Science Definition Team
SEDS small expendable deployer system
SEE Space Environments and Effects program
SIF sensor interface
SIFTER scintillation fiber
SINDA systems improved numerical differencing analyzer
SLD semiconductor laser diodes
SPIE Society for Photo-optical Instrumentation Engineers
SRB solid rocket booster
SRCF X-Ray Calibration Facility
SSC Stennis Space Center
SSE shooting star experiment
SSFF Space Station furnace facility
SSME Space Shuttle Main Engine
SST sea-surface temperature
SSTO single-stage-to-orbit
STEPS Station-tethered express payload system
STICS scanning thermal ion composition spectrometer
STTR Small Business Technology Transfer
STUSTD solar thermal upper stage demonstrator
SVD singular value decomposition
SXT Soft X-Ray Telescope
TCM thermal conditioning module
TCS thermal control system
TEI trans-Earth injection
THM traveling heater method
TLI trans-lunar injection
TLM telemetry
TLP tension leg platforms
TMA technology mirror assembly
TOMS total ozone mapping spectrometer
TPS thermal protection system
TRAYS thermal radiation analysis system
TRN thermal response number
TSS-1R Tethered Satellite System Reflight
TTB technology test-bed
TTO Technology Transfer Office
TVS thermodynamic vent system
TWI The Welding Institute
UAH University of Alabama in Huntsville
USBI United Space Boosters Inc.
USML United States Microgravity Laboratory
USMP United States Microgravity Payload
UV ultraviolet
UVI ultraviolet image
VEDM volume elements damage
VOF volume of fluid
VPPA variable polarity plasma
VR virtual reality
VSLM virtual Spacelab module
WIC wideband imaging camera
XTM x-ray transmission microscope

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