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Materials in Space

How Air Force Research is Maintaining America's Advantage in Space

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Editorial: Seizing the High Ground

History is replete with examples of armies and empires whose military success was a direct result of their technical supremacy. The Roman Empire's expertise in road building allowed them to keep their armies supplied during campaigns. Half of the world's people were subjects of the British Empire at its pinnacle; due in large part to their ships, which enabled them to project force around the globe. Most recently, America assumed the promontory of military superiority at the beginning of the twentieth century. This was a direct product of America's industrial and technology edge over competitor nations; and was concurrent with the ascendancy of our air power. This first became apparent in World War I, and then again in World War II, when the Army discovered it could greatly extend its reach into enemy territory using the Army Air Corps. The Navy experienced similar success in the Pacific War when it shifted its emphasis from battleships to aircraft carriers, which helped turn the tide against Japan.

In the years following the Second World War, the arrival of the Space Age was highly anticipated. The pioneering work by the US Military and Werner Von Braun in the 1950s (along with Sergei Korolev's parallel efforts in the Soviet Union) was performed to be the "first to space." Even before the first successful launch in 1957, the strategic value of space was understood.

Commanding the high ground of space has long been an Air Force priority. Shortly after the launch of Sputnik, Air Force Chief of Staff General Thomas D. White declared that the Air Force "must win the capability to control space." Since that time, space systems have played an increasingly larger role in the Air Force's overall mission, culminating with the establishment of the Space Command in 1982.

The Space Command, and by extension much of the Air Force's space technology got its first "test under fire" during the 1991 Persian Gulf War; when its satellites provided critical communications for the US Central Command, both in-theater and with the Pentagon. Global Positioning Satellites (GPS) were able to provide our armed forces with precise position information of key targets. Furthermore, Space Command's GPS and weather satellites guided ground units across the featureless expanses of the Iraqi desert in all weather. In addition, the Air Force's early warning satellites gave a much needed "heads-up" to Army Patriot missile batteries repelling incoming Scud attacks. Space technology had come of age – the Gulf War was truly the "First Space War."

This brings us to the present day – the impact and versatility of military space systems continue to grow, and just in time. If the Gulf War was the first space war, then the current Global War on Terror is most certainly the second. In addition to the functions of weather, navigation, communications, and early warning, the latest generation of tactical satellites are also capable of providing guidance, and even *control* of certain military systems. The new wave of unmanned aerial vehicles, such as Predator and Global Hawk, utilize satellites for guidance and communications. The same is true for weaponry; like the new Joint Direct Attack Munition (JDAM), recently used in Afghanistan and Iraq. American Special Forces depend on satellites to provide navigation, surveillance, communication, and intelligence while on missions. In the past decade, military space capabilities have evolved from a supporting role to an indispensable part of the warfighter. In the future, some space systems may even *become* the warfighter.

How will America maintain its 'Space Superiority' in the future? The best way is to preserve the technology edge that has brought us to this point. The Air Force Research Laboratory's Materials and Manufacturing Directorate (AFRL/ML) has demonstrated its value as the focal point for originating new materials technologies for space applications. While war tends to draw our attention away from technology development, it also makes us thankful for those same technologies, which have now been called upon to protect the nation. It is only through the continued development of new and enabling technologies that we will continue to command the high ground in the space wars to come.

Christian E. Grethlein
Editor-in-Chief

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Issue Focus: Air Force Research Enables Enhanced Launch and Space Systems

Section IV: Technology Development for Satellite Applications

Systems that operate in the extremes of space have robust and innovative materials and manufacturing processes to thank for their success. AFRL/ML has been a leader in developing, testing, and fielding the state of the art materials and processes needed to fabricate the myriad of subsystems that make up the modern military satellite.

Acknowledgements

Does our cover look familiar? It should to many of our readers. It also happens to be the poster artwork for this year's National Space and Missile Materials Symposium (see the announcement later in this issue). We would like to thank the Anteon Corporation for allowing us to use it, and more specifically, to Ms. Rae Parks who created it.

We would also like to thank the following AFRL personnel for their support and guidance in the preparation of this issue: Mr. George Schmitt, Chief of the Integration and Operations Division; Mr. Fredrick Coleman at the Materials and Manufacturing Directorate's Technology Information Center; and Mr. Dan Cleyrat at the Materials and Manufacturing Directorate's Space Office.

Lastly, AMPTIAC would like to extend our sincere appreciation to all our authors and contributors who helped to make this another great issue!

Defending the Nation through Excellence in Space

A Conversation with AFRL/ML's Director

Recently, Dr. Charles Browning, the Director of the Materials and Manufacturing Directorate, at the Air Force Research Laboratory (AFRL/ML), was able to share with AMPTIAC *some of his reflections and insights on the contributions of AFRL/ML (and to a greater extent, that of the Air Force) to space technology. Our conversation with Dr. Browning delves into the various aspects of ML's history, philosophy, accomplishments, and strategies to meet and surmount the challenges of prevailing in the space environment; and how these technologies are critical to national defense.*

AMPTIAC *would like to thank Dr. Browning for his time and consideration in consenting to this interview. After reading this interview and the rest of this issue of AMPTIAC Quarterly, we believe that our readers will take away a greater appreciation of the critical role that materials play in enabling space technology, and how AFRL/ML, as a technology leader, contributes to the nation's defense.* - Editor

Unlike aircraft applications where hundreds of systems might be procured, most space applications do not require many systems. Hence, far fewer numbers of components or structures are needed – yet materials are critical to those applications. How does ML balance the need for developing critical technologies intended for a single space system vs. a host of air vehicles or engines?

If a specific benefit greatly enhances, or in many cases enables a desired capability for the customer, then obviously we may want to pursue investment in the area. It can't be viewed strictly as a numbers game. The strategic or tactical value/impact of a space system can be immense: so much so that the return on investment is significant, even when there's only one system procured.

Materials are fundamental to a component's capability – that is, they endow components with the characteristics needed to meet the demands of the application. This is very evident in the case of spacecraft, which are produced in very limited numbers. When a required mission capability is determined to be dependent on new materials technology (and thus drives the need for improved materials), then further investment is justified.

DR. CHARLES E. BROWNING
Director of the Materials and Manufacturing Directorate

Again comparing to aircraft systems, ML has historically been involved in developing new manufacturing methods that help reduce the cost of structures for these applications. This is driven by the fact that production runs for aircraft are normally quite large. Do you have any manufacturing programs in-place to help reduce the cost of structures and components for space systems that will be procured in very limited quantities?

ML has been active in space materials since the days immediately after Sputnik was launched. Our past and present range of activities includes research and development of structural materials based on our expertise in composites, nonstructural materials such as thermal control coatings, lubricants, and polymeric films. In addition, it also includes electronic packaging and low cost manufacturing of space components, as well as sensor materials for surveillance systems. Our lean manufacturing initiatives to address affordable components and systems (when few are being made) are particularly well suited for space systems, although many are applicable to aircraft production as well.

Balancing limited resources is always a challenge, especially when multiple issues must be addressed. Within the space sector itself, what relative emphasis does ML place on launch, satellite, and force application technologies?

In the launch area, we have heavily invested in rocket propulsion materials for boost and orbit transfer. For liquids, this includes materials for turbopumps, combustion chambers, nozzles, and lines/ducts/valve. For solids, insulation and nozzles. Moreover, we have invested extensively in both chemical and electric on-board propulsion systems for spacecraft. The propulsion area represents the largest stake in a single area within ML's space enterprise. ML also supports spacecraft with investments spread across bus and payload technologies. In the force application area, ML has a long legacy in reentry thermal protection materials and continues to support the area with materials development, analysis, and testing.

To follow up on our last question, what are the critical material and process technologies that the Materials and Manufacturing Directorate is currently developing for space?

The Materials and Manufacturing Directorate has a robust technology development program that spans all materials classes for both satellite and space launch applications. ML is addressing many needs for the functional areas of satellites. For satellite propulsion, we are developing refractory metals, ceramic matrix composites, and carbon-carbon materials in both traditional and new propulsion systems. We are addressing the continued need for lightweight power generation and distribution. ML is supporting surveillance and reconnaissance missions with the development of a variety of sensor materials. We have a rich and ongoing history of providing materials for structures and mechanisms, including space lubricants. For communication applications, we are developing wide band-gap semiconductors and electro-optic polymers. Thermal management is increasingly difficult for satellite components with higher power densities. As such, we are continuing to develop highly thermally conductive materials and advanced thermal control coatings.

For launch vehicles, we are focusing our development efforts on the subsystems that will be enabled by advanced materials. For example, ML is developing a number of thermal protection materials such as carbon-carbon, ceramic, and metal matrix composites. Rocket propulsion is another area where materials will define the performance of various propulsion concepts. Cryogenic tanks will require lightweight materials that are compatible with liquid oxygen and hydrogen. The recent Shuttle disaster has highlighted the need for vehicle health monitoring and we are just beginning to examine the requirements of needed materials.

Over the past several years there seems to be a drive towards larger satellites, but at the same time micro- or nano-satellites are being considered. What emphasis does ML place on these dual trends?

Our program is well suited to support both areas, as materials are fundamental to all applications. Our historical and continued work in organic matrix composites has an area of emphasis to provide for lighter-weight stable structures, as well as multifunctionality. These developments will not only be of benefit to large spacecraft, but to smaller ones as well.

Additionally, we have efforts supporting large, lightweight deployable structures with application to mirrors or antennas. For small satellites, our work in thermal management materials is crucial. We are developing carbon-carbon materials that will provide improved thermal efficiency for thermal planes, heat sinks, and radiators. This has particular impact on denser electronic systems as spacecraft become smaller. Additionally, our work in advanced coatings and lubrication will provide added benefit to either.

Our biomimetics and nanomaterials research has great potential benefit to small spacecraft. Technology impact areas include smaller lightweight sensors, adaptive materials, room temperature IR detectors, EM shielding, and high performance tethers to name a few.

It seems as if obtaining material requirements for future aircraft systems would be a straightforward process, since the Air Force's aircraft program offices are located with you at Wright Patterson AFB. How do you successfully gather the requirements needed to establish new 'space' materials development programs when the program offices dealing with space related technologies are scattered among several locations around the country?

As you know, we established Integrated Application Areas (IAAs) that are in part charged with working closely with customers to obtain requirements. The Space IAA has initiated and fostered many initiatives to broaden communication and interaction across both customers and other technology development organizations. Some of these activities include the National Space and Missile Materials Symposium, the IHPRPT Materials Working Group, and the TPS Working Group. One of the common benefits of these activities is the opportunity to validate requirements and provide organizations with insight to formulate recommended strategies for materials development programs at large. There are also many other activities and organizations with whom the Space IAA and its extended team are engaged; such as the National Aerospace Initiative, AFSPC (Air Force Space Command) reviews, the AFRL Space Sector Office, sister directorates, Warfighter Technology Areas, etc. Additionally, we have ML collocates at Kirtland AFB (AFRL Space Vehicles Directorate) and Los Angeles AFB (Space and Missile Center) who continuously maintain a finger on the pulse of requirements.

As more nations begin developing space systems, rapid access to space becomes essential for our Nation's security. Can you project a single enabling technology that must be developed if the Air Force is ever to develop a single-stage-to-orbit (SSTO) system that can maintain aircraft-like operations?

With respect to materials impact, highly robust, operable thermal protection systems are the most enabling. Propulsion materials closely follow this, where we currently have a reasonably robust materials program. The development of highly durable materials and processes that will provide options for the advancement of the various vehicle TPS and hot structures is equally critical. The TPS must be capable of protecting the vehicle from not only high heat loads, but also other compromising environments associated with flight and ground operations. The TPS technology is applicable to both advanced access to space vehicles and high mach/hypersonic air breathing vehicles. Additionally, the technology has potential payoff to both rocket and air breathing engine components, such as nozzles. The temperature capability, service life, and turnaround time are the most critical for the TPS overall. The durability and damage tolerance of the TPS system will govern the ability of advanced reusable space vehicles to perform with aircraft-like operations.

Over the past several decades, ML has been responsible for developing many of the materials technologies that have enabled advanced space systems. A few examples that come to mind include carbon-carbon and polymeric matrix composites for high temperature and structural applications, and mercury cadmium telluride materials for infrared sensors. What technologies are you working on today that may provide similar advances in capabilities?

Much of the cutting edge work in photonic materials may provide space capabilities that do not exist today. For example, one application of photonics would provide for multi-gigahertz modulators; which due to their speed, weight, and size, could enable a space-based radar system. Another application might be

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for non-volatile memory. Our work in biomimetics and nanomaterials could potentially result in lighter, smaller, flat panel sensors or room temperature infrared detectors to name a few.

Maturing and transitioning technologies is a process that can sometimes take decades to accomplish. What actions does your organization take to accelerate the process so that your new technologies become recognized as viable approaches by industry?

Here are two examples: one for near or current technology, and the other a paradigm change in the insertion process of new materials technologies:

The Space Systems Support and Affordability Effort (S3AE) is a unique program that we initiated approximately six years ago to address materials and manufacturing issues of spacecraft, and provides an avenue for rapid transition. S3AE is a partnership between ML and major spacecraft prime contractors to address and resolve common issues in materials, processes and manufacturing. The project duration has a near-term focus, 12 - 18 months, to resolve key shop floor issues common across the industry. A major product is documentation on issue resolution and best practices available to the entire spacecraft community (non-proprietary). It provides a means for near real-time transition to spacecraft production lines. The program also provides a key connectivity between AFRL and spacecraft primes.

For new materials technology, we are working on a program with DARPA called Accelerated Insertion of Materials (AIM). The time required to procure new systems is often linked to the ability to make new materials and processes ready for implementation. Consequently, progress in the aerospace sector will to a large extent be driven by the development and insertion of new materials and more efficient manufacturing processes. The AIM program is establishing and validating new approaches for materials development that will accelerate the insertion of these materials into the production hardware for aerospace applications. The AIM program is showing that the time scale between development of a new material and its implementation into production can be significantly shortened. The resulting pay-off is a substantial reduction in the time required for the development of cost-competitive aerospace systems with higher performance and greater efficiency.

In these days of limited budgets, it seems as if collaboration and joint programs are possibly the only way that technologies can be developed quickly. We know that the Integrated High Payoff Rocket Propulsion Technology (IHPRPT) Materials Working Group and the Thermal Protection Systems Working Groups are ongoing DOD/NASA/industry initiatives to increase the rate at which new thermal protection and propulsion materials are developed. Do you see this approach being used in other areas?

Collaborative programs and joint organization sponsorship have been in effect for many years in ML, including examples such as the Integrated High Performance Turbine Engine Technology (IHPTET) program and the Composites Affordability Initiative, both of which include several government agencies, industry OEMs and materials suppliers. Many other programs are ongoing and ML develops and partners on new ones continually. Organizing and providing leadership for collaboration is a routine approach to doing business for us as we look to leverage resources, develop and transition the enabling materials technologies, and being able to afford these costly new developments in a world of ever limited resources.

Integrated Vehicle Health Monitoring (IVHM) might be a new candidate area. There are many aspects to IVHM that cut across numerous disciplines and must be tied together to form a working capability. Currently there is work ongoing within AFRL, NASA, the Army, Navy, and other agencies. Pulling together a working group to share common requirements and solutions is an initiative worth serious consideration. AFRL is currently addressing many of the constituent technology areas that would comprise IVHM. These include degradation processes of materials, vehicle damage caused by the assembly process, new and novel sensing technology development, miniaturized control and power-scavenging, modeling of NDE response, and dynamical systems engineering optimization. ML is also engaged in identifying critical failure modes that would be used to define material thresholds in TPS, beyond which the loss of the vehicle would be considered imminent. Any thrust in ML would be focused on structures, TPS, wiring, and propulsion in that order.

The Long Duration Exposure Facility (LDEF) launched by the Space Shuttle in April 1984 was initially planned to be in space for a year, but because of the loss of Challenger it remained aloft for nearly six years. When it was recovered, the results from exposure of the test specimens to the space environment were mixed. Some of the tests came out better than expected since the materials received extended exposures. However, other materials, such as the polymer thin film specimens, were severely eroded or even destroyed, which limited the amount of useful data that were gathered. Today we see a similar prospect occurring. In August of 2001, the Materials International Space Station Experiment (MISSE) was attached to the International Space Station (ISS), where it was scheduled to return to Earth last year. Because of the grounding of the Shuttle fleet, it will be spring 2005 at the earliest before MISSE can be returned. Are you worried that the some of the materials currently being tested on MISSE may see a similar fate as those on LDEF?

We are somewhat concerned, mainly because atomic oxygen (AO) erosion is a very severe problem for some materials. However, the fluence of AO which the specimens on the ram side of LDEF experienced was significantly greater than that anticipated on the MISSE experiment. LDEF's orbital configuration was designed to maximize the AO exposure for the ram-facing specimens, while totally shielding those on the wake side of the satellite. Because MISSE is attached to the ISS, we were not afforded that same luxury, thus none of the MISSE specimens are either constantly exposed to or constantly shielded from AO. Additionally, LDEF was on-orbit for 5.7 years and its altitude had decayed from 275 to 175 nautical miles, and was about a month away from reentry when it was recovered. Thus, most of LDEF's AO exposure actually occurred in its last 6-12 months of orbiting the earth. The ISS is in a stable orbit at about 217 nautical miles and if things go as planned, MISSE will have been in orbit for about 3.5 years. Thus, the possibility of totally destroying specimens is not as likely to be a concern when compared to LDEF.

Two other thoughts concerning this question: First, MISSE was originally planned to be a two part experiment with one set of PECs (passive experimental carriers) being on-orbit for 1 year while a second identical set were to be on-orbit for 3 years which is about what the current PECs are anticipated to receive. Thus, we may just be able to reverse the experiment plan without as significant of an impact to the specimens as might be expected. Second, a lot of work has been done to improve the AO resistance of various polymeric materials since LDEF. While MISSE still is utilizing polyimide materials as AO reference materials and monitors, the newly engineered polymers on MISSE should not be as impacted by the AO environment as those on LDEF.

Over the past ten years or so, ML has increased its efforts in researching materials for space applications to the levels seen today. Barring any unforeseen circumstances, do you envision that this focus will remain for the foreseeable future?

Most likely. AFRL as a whole plans to increase its percent investment in space technology to the 25-30% level by 2009. Given the importance of space capabilities in the last two conflicts, a sustained or increased investment in space is justified.

Since many of the engineers and scientists involved in the early days of space research have already retired, do you find it much of a challenge to obtain the experienced technical support needed to foster the technology areas the lab is pursuing?

The availability of experienced technical support as well as new scientists and engineers to train to be experts in space materials and other disciplines is a national issue. Senior leadership in the DOD, other government agencies such as NSF and NASA, as well as those in academia have identified the need for promoting technical careers to entice student to pursue courses of study to enter those fields. Materials science and engineering are fundamental across the space sector so that we share these needs for bright young people. We are attracting them and in many cases are growing our own by training and providing exciting opportunities in space materials research.

Considering that the space environment is so different than that facing aircraft, do you find it difficult to train the engineers that transition into space research?

From a technology perspective, space can be broken into three major sectors, spacecraft, space access vehicles, and missiles. Each sector has its own set of customers, processes, and requirements. Additionally, each sector is at a different level of maturity. Currently, major platforms of each of these sectors are either one-time use or not recoverable. These aspects inherently present a major challenge for anyone working in the space sector. The air area provides somewhat of a more comfortable environment for engineers, as customers and requirements are more straightforward. Conversely, the space sector is relatively in its infancy and has very diverse customers and requirements spread across the three major sectors mentioned above.

ML's Space IAA Office leads or offers many opportunities for educating ML personnel in space and missile systems. These include classes, symposiums, workshops, and meetings. It developed and offered several classes on spacecraft systems taught by renowned experts. The IAA Office leads the National Space and Missile Materials Symposium that is held every June. Part of this forum includes tutorials and workshops, including presentations by Nobel laureates. Tutorials include subjects such as nanotechnology, spacecraft design, smart materials, space environments, etc. Workshops on propulsion materials and thermal protection are also held annually. The IAA Office also holds a bi-weekly meeting at the Directorate to keep personnel abreast of events in the space arena. As an additional part of that meeting, cameo presentations are offered on various materials technologies and activities.

Recently, President Bush proposed extending manned space flight further into our solar system, including returning to the moon and eventually going to Mars. During the early days of manned space flight, ML was quite involved in space technology development. A notable example of Air Force technology that transitioned to manned space flight was the heat shield technology used to keep the capsules from burning up during reentry. Do you see a role for ML in developing technologies to enable systems to meet the president's challenging goals?

ML has many technologies that would be applicable to the President's new space vision. For example, all of our materials work for spacecraft would be applicable, as we discussed earlier. Depending on the concepts that are ultimately identified, many of the ML programs for space access vehicles could also be enabling, particularly in propulsion and thermal protection. Additionally, our cutting edge work in biomimetics and nanomaterials for transformational capabilities would definitely support the new space vision. What has been true historically is still true: materials are the principal enablers of emerging technologies.

Dr. Charles E. Browning, a member of the Senior Executive Service, is Director, Materials and Manufacturing Directorate, Air Force Research Laboratory, Air Force Materiel Command, Wright-Patterson Air Force Base, OH. Dr. Browning is responsible for the planning and execution of the Air Force's advanced materials, processes, and manufacturing and environmental technology programs to support all elements of Air Force acquisition and sustainment. He is also responsible for interfacing these specific areas throughout the corporate Air Force and Department of Defense. He leads an organization of approximately 530 government employees with a yearly budget of nearly $250 million.

Dr. Browning began his career with the Air Force in 1966 and has held various senior technical and management positions within the laboratories. He was appointed to the SES in 1998.

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Materials for Spacecraft Propulsion Systems

- High durability catalyst materials, such as advanced nanocomposites and hexaluminates with various coatings, IR Platinum etc.
- Oxidation resistant chambers - Rhenium/Iridium alloys and processing; cost effective manufacture of combustion chambers, and powder metallurgy.
- Hall Thrusters – Alumina, Aluminum Nitride, and Silicon Nitride used to make erosion resistant chambers with rapid prototyping operations.
- Electrostatic carbon-carbon ion engine grids.

Materials for Electric Power

- Currently conducting industrial base analysis of solar cell manufacturing.
- Polymer wiring – Polymer embedded with metal (copper and nickel coating). Currently with application to aircraft but potential for space.

Sensor Materials

- High performance mercury cadmium telluride (MCT) materials for long wave infrared detection.
- Early efforts to develop materials growth and processes for quantum dots and carbon nanotubes for future hyperspectral systems.
- Wide band-gap semiconductors; Gallium nitride (GaN) for SSPAs (Solid State Power Amplifiers) and LNA (Low Noise Amplifiers) for radar and communications.
- Developed electro-optic polymer modulators enabling high bandwidth data links and straightforward solutions to data fusion.
- Developed laser source materials for space-based Light Detection and Ranging (LIDAR).

Spacecraft Structures and Assemblies

- Developing advanced lubrication formulations for application to control momentum gyros (CMGs) that will result in their meeting 15-year satellite life and for application to moving mechanical assemblies.
- Developed high speed bearing races and pennzane formulation to provide longer lifetimes for future satellites. TiCN coated races outperformed the state of the art.
- Developing lubrication techniques for micromechanical systems (MEMS).
- Applying nanocomposite research to the development of multifunctional materials for improved electrical/thermal conductivity, reduced CTE, and microcracking.
- Developing advanced polymer materials for application to space-deployable structures and membranes. Researching nano-processing techniques for ultra-light structures.
- Collaborating with other DOD agencies, NRO, NASA, and industry for the development of advanced mirror and optics technology. The thrust of the program is to develop structural substrates, optical surfacing techniques, and processing tailorability.
- Manufacturing: A partnership (S3AE) was developed between ML and major spacecraft prime contractors to address and resolve common issues in materials, processes, and manufacturing. The project duration has a near-term focus, 12 to 18 months, to resolve key shop floor issues common across the industry. A major product is documentation on issue resolution and best practices available to the entire spacecraft community (non-proprietary). The program provides a key connectivity between AFRL and spacecraft primes. Embedded heat pipes are an example of recent work.

Hardening

- AFRL/ML is developing a number of technologies that provide filtering and limiting of energy from laser irradiation on optical systems.

Materials for Communications, Power Control, and Microwave

- Developed electro-optic polymer modulators for high-bandwidth optical communications. Working for even higher performance modulators for the photonic control of phased array radar for weight and power savings.
- Developing improved wide band-gap semiconductor materials (silicon carbide), which will enable compact megawatt power switching devices for on-board power management and distribution.

Thermal Management Materials for the removal of heat from on-board components and structures

- Developing advanced coatings; conducting space environment testing.
- Developing materials for thermal planes and radiators.
- Developed C-C radiator material and transitioned to Earth Orbiter 1 (EO-1) satellite, now in orbit. (Completed)
- Developing carbon-carbon thermal planes and heat sinks for heat removal in advanced electronics.
- Developing carbon-carbon heat pipes for radiators.
- Developing higher conductivity carbon foams for advanced high performance heat exchangers and radiators.

In The Spacecraft Area

While many of the leading edge material and process technologies that the Materials and Manufacturing Directorate are currently developing for space are discussed in this issue of the AMPTIAC Quarterly*, the spectrum of covered topics is far short of exhaustive. For the sake of completeness, we offer this comprehensive directory of AFRL/ML's material activities related to space technology.*

In The Spacelift Area

Similarly, the full panorama of AFRL/ML's material development efforts for launch and re-entry vehicles far exceeds the scope (or capacity) of this issue of the Quarterly. Here is the complete array of activities.

Thermal Protection System Materials for protection of vehicle structures from high thermal loads.

- *Hybrid & Cooled Leading Edges:* A hybrid solution will involve the right combination of materials for management of thermal and structural loads. The hybrid concept being developed by ML is utilizing a structurally integrated non-parasitic approach with options for a novel combination of materials such as C-C, ceramics, metals, foams, aerogels, and/or phase change materials. The focus is on reliability, durability, and supportability, as well as cost and manufacturability. Another approach is heat pipe cooling, which is accomplished by converting the leading edge of an airframe component and a specified chordwise distance to the rear into a liquid metal heat pipe. This program's focus is also on reliability, durability, and supportability, cost, and manufacturability.
- *Highly-Operable Ceramic Acreage Panels:* ML has two cooperative programs with the Air Vehicles Directorate (AFRL/VA) to develop and demonstrate large C/SiC standoff thermal protection system panels. This approach provides for simplified removal that facilitates maintainability and operability of the vehicle system.
- *Carbon-Carbon Nosetips & Aeroshells:* ML is continuing advancement in C-C nosetips and aeroshells. The current focus is on materials for a modified C-C aeroshell for reentry, which is thermally efficient, structural, and low cost. The effort also has potential for transition to leading edges and heatshields. Current materials being investigated are carbon-carbon infiltrated with RTV resin.
- *Gamma Titanium Aluminide for Acreage Panels:* A metallic approach for acreage TPS is being worked by ML in collaboration with AFRL/VA and NASA. This work involves the processing and testing of gamma-titanium aluminide sheets for application to large, windward surfaces of a reusable launch vehicle.
- *High Temperature Ceramics for Control Surfaces:* ML has planning in place for process and composition development for fiber reinforced high temperature ceramics. It will include sub-element fabrication and test of monolithic and composite ultra-high temperature ceramics for durability assessment. Oxidation protection methods will also be addressed. Materials will be C/SiC.

Materials for Liquid Rocket Engines for the Integrated High Payoff Rocket Propulsion Technology (IHPRPT) program:

- *Turbopump Housing:* Nickel based super alloys for LOX. Mondalloy improved Ni based Ox compatibility over Haynes 214.
- *Rotating Turbomachinery:* Powder metallurgy super alloys. HIP bonded surface layering. Carbon steel tooling used to clad with HIP process and Ox resistant materials.
- *Lines, ducts, and valves:* Nanophase aluminum, LCP lined, graphite epoxy ducts, and PMCs for liquid hydrogen feedlines.
- Nozzles: Radiation and actively cooled approaches using CMCs. SiC/SiC, C/SiC coated with various materials. Open woven Ceramic for a dual bell.

Materials for Cryotanks, both organic matrix composites and metallic

- For organic matrix composites current efforts are focused on reducing microcracking, demonstrating liquid oxygen compatible OMCs, and assessing modeling/test methods.
- For metallic tanks, collaborating with NASA on the scale-up of an Air Force formulation (2099) of Aluminum-Lithium. Provides lighter weight and improved characteristics over current metallic formulations.

Vehicle Health Monitoring

- ML is engaged with AFRL in a teaming approach, to address issues associated with operable spacelift vehicles. ML is also engaged in identifying critical failure modes that define material thresholds in TPS with loss of vehicle consequences. ML is also part of AF oversight team on a DARPA Integrated health monitoring (IVHM) program for propulsion.

Materials for Airframe Structure and Subsystems

- ML is researching high temperature PMCs that are suitable for airframe applications capable of continued service temperatures beyond 450°F. Potential payoff is the reduction in the amount of TPS required on a vehicle.
- Thermal management – Applying higher conductivity carbon foams for advanced high performance heat exchangers and carbon-carbon thermal planes and heat sinks for advanced electronics.

A Legacy of Achievement

One Man's Recollection of AFRL's Accomplishments in Space Technology

Paul M. Propp, Private Consultant
Retired, Materials and Manufacturing Directorate
Air Force Research Laboratory

The Air Force Research Laboratory has been a leader in space technology since the beginning of the space race. Over the past four decades, many technical professionals have dedicated substantial portions of their careers to bring some of these technologies to realization. During this time span, many contributed to some number of these milestones, but few were fortunate enough to bear witness to the entire history of AFRL's space efforts. During the preparation of this issue, AMPTIAC was privileged to speak with Mr. Paul Propp, who is one of the few people to have gained that unique perspective. Mr. Propp worked at AFRL from the early 1960s through the mid-1990s. During the bulk of his tenure, he was the materials liaison for the Space Systems Division (now the Space & Missile Center), which afforded him a unique view of developments in both the materials and systems areas. Since his retirement almost 10 years ago, he has continued to serve AFRL and its technology programs as a private consultant.

Many staples of space technology can trace their roots to groundbreaking work at the Air Force's laboratories. Bringing some of these more notable achievements to light, Mr. Propp shares his recollections of the major strides AFRL has made in space technology over the last forty years. – Editor

Manufacturing Technology for Filament Winding Large Solid Rocket Motor Cases: 1960-65

Early Minuteman motor cases were constructed of steel and titanium. Research was aimed at replacing the Minuteman II (MM II) second stage metal motor cases with lighter-weight fiberglass filament-wound cases. Although the MM II system program office (SPO) did not adopt this technology, the work provided experience and confidence; which eventually led to the introduction of a composite third stage motor in the Minuteman III, and composites in all three stages of the Peacekeeper.

Fabrication of Large-Diameter Ablative Solid Rocket Motor Throats: 1964-70

This research was part of a series of programs to explore alternative designs and materials for very large motors. In the same timeframe, the Titan III system program had suffered repeated nozzle failures in its Solid Rocket Motor (SRM) development efforts. The results of this research and successful motor firings provided a capability and confidence that allowed the replacement of graphite nozzles in the Titan III SRM system and all subsequent designs.

Manufacturing Technology for Shear-Forming Large-Diameter, Metal Solid Rocket Motor (SRM) Cases: Mid 1960-70

Ring-formed and welded metalworking techniques produced the steel motor cases for the Minuteman and the first block of Titan III SRMs. Our research resulted in the design, assembly, and demonstration of a shear-forming machine capable of producing a Titan III-size motor case without welds. The program produced an expensive but capable, large shear forming machine for producing case up to 120 inches in diameter and demonstrated them in both D6AC and 9Ni-4Co steels. Although it never went into production, it motivated suppliers to develop shear forming processes that resulted in significant case cost savings, enhanced performance, and reliability.

Manufacturing Technology for Radiation-Hardened Integrated Circuits: Mid 1960's - Late 1980's

Early work in this area addressed the introduction of dielectric isolation into the fabrication sequences for hardened integrated circuit (IC) manufacture. As radiation effects became better understood, and circuits became more complex; circuit redesigns required the introduction of new and or modified circuit fabrication processes, which became the focus of several Manufacturing Technology (MT) contracts. Hardened memories, logic circuits, and mass storage were all subjects of MT contracts. Prior to the involvement of the Phillips Laboratory (now AFRL/VS) in hardened circuit design and fabrication; the MT program had produced the first hardened chip set that was MilStd compliant.

Infrared Detector Development: Late 1960's - Present

At the time of their early system application, certain important infrared (IR) responsive materials were known empirically, but not scientifically. The processes used to produce the materials involved a good deal of art. To help mature IR material technology, the mechanisms of photoconductivity in lead sulfide (PbS) were systematically studied by the materials laboratory (ML) to build a stable process that reduced manufacturing problems. However, ML believed that the ultimate answer lay in an alternate IR sensor material, namely mercury-cadmium-telluride (HgCdTe). A major accomplishment was the single-handed development of HgCdTe IR detectors for short wave

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infrared (SWIR), medium wave (MW), and long wave (LW) IR spectrums. ML-directed work resulted in HgCdTe becoming the detector for the second color DSP focal plane (a Defense Support Program's early warning satellite able to simultaneously detect at two different wavelengths) and subsequently replace PbS as the primary SWIR detector as well.

Advanced Composite Structures for Space: Late 1960's – Present

Following initial work in the use of fiberglass-reinforced polymer materials, ML sought fibers with better mechanical properties. Boron fibers, followed shortly by carbon and graphite fibers, became the basis for an Advanced Development Program (ADP). After early advancements directed at aircraft structures, the ML turned ADP attention to consider space and missile applications. Aluminum, beryllium, and titanium were the standard materials of construction at the time. Now, after many AFRL-programs supporting composite development, graphite reinforced composite materials have become one of the industry's basic materials of construction for space structures, dimensionally stable space structures, and propulsion tankage (for station keeping). Moreover, they have replaced fiberglass for filament wound motor cases and other missile structures in many Air Force systems, including Peacekeeper.

Temperature Compensated Rare Earth Magnets: Early 1970's

High strength, rare earth magnetic materials were an ML development. Recognizing the potential impact of these materials, ML was encouraged to seek out applications which would meet Air Force needs. MT followed the ML development of rare earth magnets with programs directed toward scaled-up processes and controls for producing these materials in reproducible and high quality volumes; and subsequently demonstrating them in critical design applications. MT programs directed at space applications were conducted on magnetic bearings and traveling wave tubes (TWTs). The TWT work was immediately successful. Rare earth-focused TWTs are today the standard in the industry. Magnetic bearings have found limited space applications, but have been used on DSP satellites.

3D Carbon Carbon Composites for Reentry Vehicle Nosetips: 1970's

Carbon-carbon (C-C) composites were an ML-conceived and sponsored development. The ML sought out and established a strong technology program in support of the Advanced Ballistic Reentry Systems Program (ABRES). The ABRES program was responsible for the advanced development of next generation ballistic missile reentry vehicle technologies. Great emphasis was placed on improved accuracy and reliability of the warheads reentering under extreme environment conditions. Bulk graphite (in many varieties) and pyrolitic graphite were the products of ML and others, but all were found inadequate for high precision reentry vehicle nosetips. ML focused on a coordinated effort across the Lab and in conjunction with ABRES to develop C-C composites for this application. This technology was enabling to achieve precision ballistic reentry vehicles (RVs) for MIRV warheads. This was a totally successful effort which resulted in the redesign of the MK 12a (Minuteman III) and subsequent RVs.

High Performance, Lower Cost, Reproducible Carbon Carbon for Rocket Motor Throat Inserts: Mid 1970's - Early 80's

In the afterglow of the success of carbon carbon (C-C) for RV nosetips, ML turned to rocket propulsion applications. Large diameter solid rocket nozzles, as in the Titan SRM (note earlier), could accept the lower efficiency of ablative nozzles; while high performance tactical missiles motors could not. Frequent failures of graphite and ceramic throats, plus the inefficiency of ablative nozzles demanded a new approach to motor designs be

Space & Missile Heritage
Traditional and Current Research Areas

AFRL has a long, proud heritage of developing leading-edge space technology. As shown here, the Materials and Manufacturing Directorate (ML) has played a major role in this legacy.

Structural Materials
- Organic Composites
- Metal Composites
- Carbon-Carbon Composites
- Design Methods & Data
- Joining Technology

Electronic Materials
- Detector Materials
- Microwave & Microelectronic Materials
- Packaging

Missiles/Hypersonics
- Nose Tips
- Heat Shields
- Antenna Windows
- Rocket Motors
- Exit Cones

Thermal Control Materials
- Structural Coatings
- Multi-Layer Insulation
- Radiator Coatings
- High Conductivity Substrates

Industrial Base Issues
- Advanced Practices
- Process Optimization
- M&P Transition

Systems Support
- Failure Analysis
- Consultation
- Collocated Engineering

Space Environment
- Spacecraft Coatings
- Space Environmental Effects on Materials
- Space Effects Simulation/Modeling
- LDEF Materials Evaluation

Laser Hardened Materials
- Sensor Materials
  - Optical Substrates
  - Baffles
  - Coatings/Filters
- Antenna Materials
- High Temp Adhesives
- Hardened T/C Coatings
- Hardened Multilayer Insulation

Tribomaterials
- Solid Film Lubricants
- Advanced Liquid Lubricants
- Life Prediction Methods
- Bearings

Power Materials
- Long Life Battery Materials
- High Efficiency Solar Cell Materials
- Radiator

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taken. The Air Force's Rocket Propulsion Lab (RPL) had established advanced tactical missile technology as a thrust. ML advanced a plan to RPL to demonstrate C-C composites for high performance solid motors. A new basis for designing tactical missiles resulted from a coordinated program involving ML and RPL. ML led the efforts related to material development and characterizing MT for producibility, while RPL headed up the motor design and ground firing tests. This work also helped pave the way for C-C to be introduced into the Peacekeeper missile motor design and others to follow.

Propellant Compatible Elastomeric Seals and Bladders: 1970's - Early 80's

Spacecraft and missiles have a requirement for long-time containment of energetic propellant fluids. Expulsion of these fluids in the zero-g environment requires positive pressure to be imposed. Early approaches employed metal bellows or Teflon seals and surfaces, but both approaches had problems. ML pursued the development of propellant-compatible elastomers - first for fuels, and later for more aggressive oxidizers. The development of AFE332, a hydrazine-compatible elastomer solved that fuel containment need and became an industry standard used for seals and bladders. The subsequent development of AFE124 provided an elastomer to be used with nitrogen tetroxide (NTO). This material found use in Titan II missile seals.

Contamination and Optical Surface Material Data: 1970's - Present

Accurate data for the degradation of spacecraft thermal control surfaces and optical surfaces has a major influence on reliably predicting on-orbit lifetimes and sizing thermal radiators. Degradation of these surfaces results from radiation effects, and contamination from outgassing products from the satellite itself. In addition to supporting the development of space-stable thermal control coating materials, ML has sought to provide designers with accurate in-space performance numbers on many of the commonly used thermal control materials. Space experiments ML 101, ML 12 and very recently the MISSE experiment, have provided spacecraft designers with fundamental information that has become standard references in the industry. ML had also supported the definition of the first contamination effects model for the analysis of this phenomenon.

Manufacturing Technology for Nickel Hydrogen Space Batteries: 1980's

The relative cost of nickel hydrogen (Ni/H_2) space battery cells was cited as an obstacle to their broader usage. This MT program examined the design and fabrication of pressurized Ni/H_2 cylindrical battery cells with lower cost and enhanced reproducible performance in mind. At the successful conclusion of this program, the resultant redesign and assembly techniques enabled what was referred to for several years as the Air Force standard MT cell. This cell and others were entered into the national life test program ongoing at the time and became the initial baseline technology for the transition from NiCd to Ni/H_2 space batteries.

GaAs Solar Cells: Mid 1980-1990's

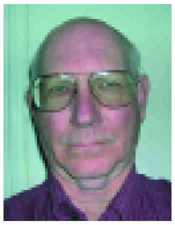
GaAs has long been recognized as a candidate solar cell material. The Aero Propulsion Laboratory (APL, now the Propulsion Directorate, AFRL/PR) began the development of GaAs for solar cell application and demonstrated its potential to significantly exceed the performance of the most advanced silicon cells. In a series of programs, MT met the demands of performance, quantity, and schedule on this classified program and established the industrial base for early GaAs solar cell production (for several years, the industry referred to GaAs solar cells as the "MT cell"). MT subsequently supported one or two additional programs dealing with multijunction cells that have advanced solar cell technology to the highest level of production cell efficiencies achieved to date.

MT for HgCdTe IR Detector Module Producibility: Late 80's - Early 90's

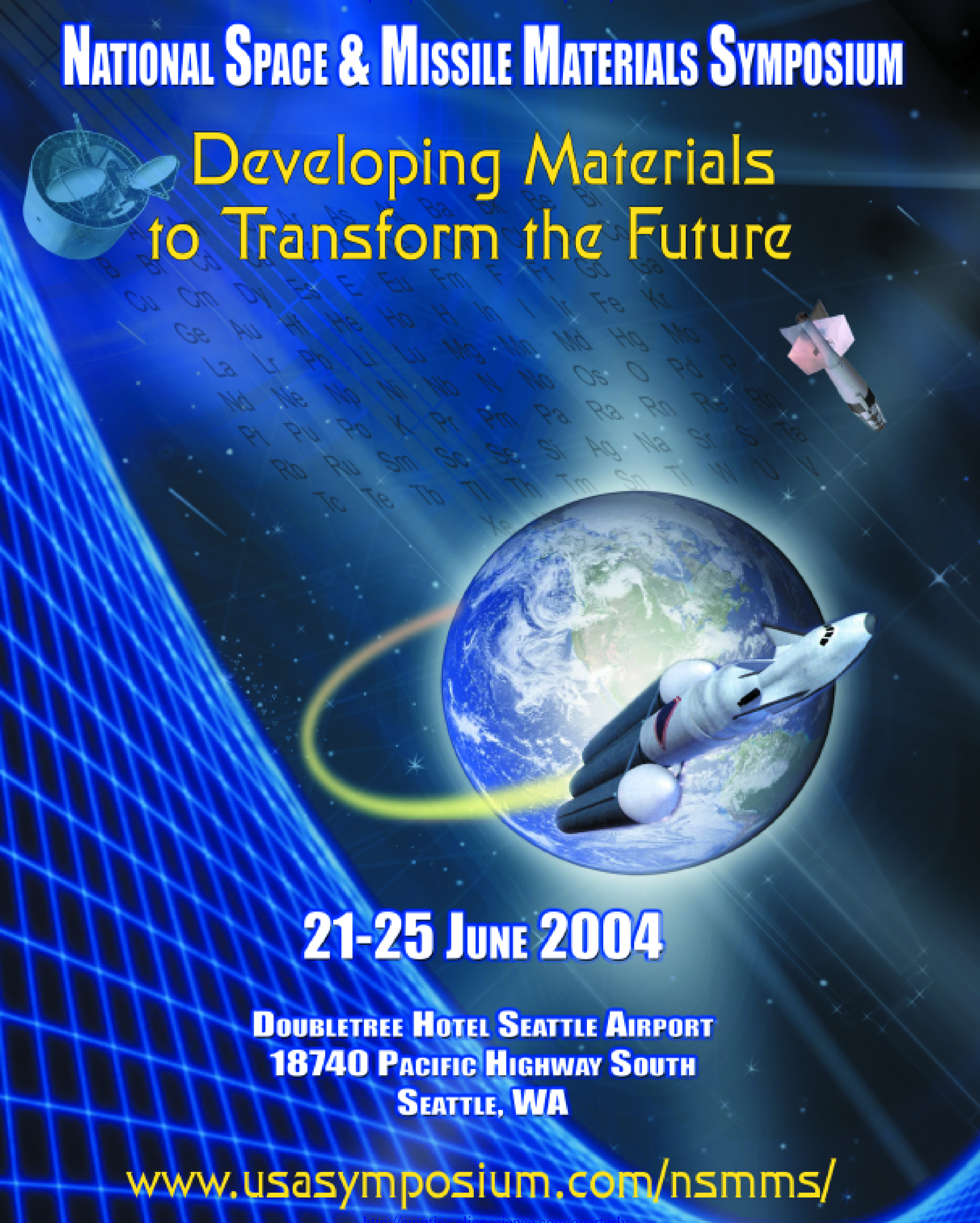
The transition of HgCdTe detectors to space systems presented major producibility challenges, especially with the large production quantities associated with national missile defense. Low yields, lack of uniformity, and high cost caused major system concerns. A sizable MT program was launched with remarkable results. Yields were improved over tenfold, performance and uniformity was enhanced; and a strong manufacturing base was established.

Surface Analysis for Traveling Wave Tubes: 1980's

Premature failures of traveling wave tubes (TWTs) have caused major upsets to Space and Missile Center (SMC) and other programs. More than one failure mode has been identified for TWTs. ML was asked to study those modes related to emitter failures. Working in close association with tube manufactures and the program office (supported by the Aerospace Corporation), ML put together a sophisticated in-house team of surface scientists. Supported with state-of-the-art instrumentation, the team established new analysis techniques, which resulted in a vastly improved understanding of the surface physics involved with emission and emitter contamination. The data and models developed were used to modify tube fabrication and material acceptance criteria.



Mr. Paul M. Propp has over 40 years experience in working with materials for space and missile applications. He was first assigned to the then Air Force Materials Laboratory as a Military officer in 1960, where he served as a chemist. Mr. Propp rejoined the Air Force in 1964 as a civilian and served as the Materials Directorate's representative at the Air Force Space and Missile Systems Center until his retirement in 1993. He has participated in many significant materials advancement throughout the course of his career.


National Space & Missile Materials Symposium
Developing Materials
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An ever-increasing reliance on space and missile assets, over the full spectrum of applications, has strengthened the call for reusable launch systems and advanced spacecraft and payloads that are both more reliable and more affordable. These needs will only be met by commensurate advances in space and missile technology. The fundamental sciences of designing materials and the related areas of material processing and evaluating material performance in space environments represent the cornerstones of these enabling technologies.

The National Space & Missile Materials Symposium (NSMMS) can trace its origins back to the 1996 AFRL Materials Directorate Program Review. In September of that year, over 250 engineers & project managers from the Air Force, NASA, and Industry participated in the Review. Building on the success of that review and an overwhelming request for expansion by Tri-Service and NASA attendees, Dr. Vincent Russo, former Director of AFRL/ML and current Executive Director, Aeronautical Systems Center, founded the National Tri-Service and NASA-sponsored Symposium in 1998. With the Air Force continuing to act as lead, the NSMMS provides a national forum on the technical challenges facing future generations of space and missile systems in materials and processes.

NSMMS presents information on the state-of-the-art issues in materials and process technology development for space and missiles. It provides attendees a global perspective for aiding investment planning and contributes to the exchange of technical information and interaction of managers, project engineers, and scientists. Additionally, users of materials and advanced technologies impacting the future direction of science and technology in space related fields gain insight into the thinking of leaders in space materials and processing technology.

The focus of the 2004 NSMMS is on critical enabling materials, materials processing technologies, and the integral role of advanced materials in space, missile and surveillance applications. Distinguished speakers for the plenary sessions this year include:

- Mr. Sean O'Keefe, Administrator, National Aeronautics and Space Administration
- General Lance Lord, Commander, Air Force Space Command
- Mr. Peter Teets, Director, National Reconnaissance Office
- Dr. Anthony Tether, Director, Defense Advanced Research Projects Agency
- Major General John Urias, Deputy Commander, Research, Development and Acquisition, US Army Space and Missile Defense Command
- Dr. Steven Chu, Nobel Laureate
- Mr. Storey Musgrave, NASA Astronaut (Dinner Speaker)

This year's conference has four major technical thrusts; each of which is the topic of one of the technical session:

Technical Session 1, New Directions in Materials Science, focuses on the frontier of the next materials science revolution. Papers address needs for future space and missile applications, discuss new directions in materials science, and identify new opportunities where new technologies can address those needs. Applicable system applications include spacecraft, reusable launch vehicles, hypersonic systems, missiles, and reentry systems. Breakthroughs and developments in this arena will depend on many disciplines, including materials scientists, chemists, biologists, computational scientists, and engineers

Technical Session 2, Access to Space, addresses critical material and process technologies for enabling access to space, focusing on both airbreathing and rocket propulsion vehicles. NASA's goal is affordable, safe space transportation. The Air Force's goal includes this, as well as "aircraft-like operations" for space operations vehicles.

Technical Session 3, Operating in Space, covers materials used on hardware and systems in various space environments. Emphasis is on critical materials for current and planned satellites, spacecraft, and payloads for both commercial and government missions.

Technical Session 4, Missiles and Missile Defense, addresses material and process technologies for missile defense interceptors, ICBMs, SLBMs, and reentry vehicles (ballistic and maneuvering RVs/CAVs). The focus is on critical enabling materials and materials processing technologies related to detection, tracking, and engagement of enemy ballistic missiles, as well as missile materials issues relative to delivery and lethality of offensive weapons.

For more information see http://usasymposium.com/nsmms/default.htm or contact:

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Materials and the 'Final Frontier'

Benjamin D. Craig
Richard A. Lane
AMPTIAC
Rome, NY

If necessity is the mother of invention, then it is equally true that materials are the enablers of technology. Without the constant drive to develop new and better materials; possessing properties and capabilities above and beyond their predecessors, technological innovation would grind to a halt. No place is this more true than in the highly demanding (and unforgiving) realm of outer space. Over the past several decades, groups of dedicated scientists, engineers, physicists, chemists, astronomers, and many others from all sectors – military, civilian government, industry, and academia – have all labored to make space more accessible.

While most Americans, technical and layperson alike, have a general appreciation of space technology's benefits to humanity and are aware of many of its historical highpoints, the total number of people who actually make the technology work is an elite few. The truth is, there are only a handful of technical professionals outside of the space technology field who have first-hand knowledge of, or are well-read when it comes to what demands are placed on space vehicles. Satellites, probes, and launch vehicles share very few common design and performance issues with vehicles and systems operating on land, sea, or air. The articles in this issue of the AMPTIAC Quarterly *explore many of the technical aspects and challenges of accessing, surviving, and succeeding in space. While preparing this issue, it became evident to us that many of our readers might find it beneficial to do a little 'catch-up' reading before diving into the specific technical issues that make operating in space the challenge it is.*

Two articles in this issue address this point. This first article is a 'Space 101' piece, which will introduce the reader to the basic concepts of space and space technology. The second article, our MaterialEASE *feature (the next article in this issue), discusses how materials and subsystems are tested and evaluated for use in the space environment. So, for the space neophytes among you, we humbly submit that this might be the right place to start. We trust that you'll find it helpful and enlightening. Enjoy! -* Editor

INTRODUCTION

America's legacy of space technology is nearly a half a century old, yet there have been a multitude of achievements in this short time. Even with the many successes, much of the technology is still early in the development phase. The United States continues to lead the development of space technology, but has seen the emergence of competitors, as several other countries are working to close this gap.

By far, NASA is the most visible representative of America's space program. Many Americans incorrectly perceive that our efforts to explore space and develop space technology are exclusively the purview of NASA. The US Military has been a leader in developing space technology since the late 1940's, a full decade before NASA's establishment. In the past several decades, the commercial presence in space has become a critical element of our nation's communication infrastructure. It has grown significantly as well.

The Military, and more specifically the Air Force, has quite an extensive history in developing and utilizing space technology. In fact, a continued presence in space is critical for the Military to remain strong and capable of protecting our country from all enemies. The military's presence in space has recently taken on new importance by providing our fighting forces with information needed to defeat the continually adapting landscape of terrorist organizations. Therefore, sustained development of space technology is critical for the Military to evolve and defend against all threats to our national security. The following article provides an overview of space vehicle basics, and provides readers with some of the factors that go into designing spacecraft.

SPACE MISSIONS

A spacecraft's design depends entirely on the vehicle's intended function. Most spacecraft launched into Earth's orbit fulfill one of four primary space missions:

- Weather
- Navigation
- Communications
- Intelligence/Surveillance/Reconnaissance (ISR)

The Military has interests in each of these four mission categories. For example, weather and navigation satellites (Figure 1) can provide valuable information for military units serving on the ground in foreign territories, and even more so for those serving at sea. Communications are an essential component of coordinating military operations, and thus communication satellites are similarly critical. Finally, the vital importance of ISR satellites for Military purposes requires no substantiation.

While cost is a strongly prohibitive factor which tapers the frequency of spacecraft launches, it is not the sole obstacle. Scheduling, regulations, politics (domestic and international) and environmental considerations also tend to be contributing

Figure 1. **A US Military Navigation Satellite – The Air Force's Navstar Global Positioning System Satellite.[1]**

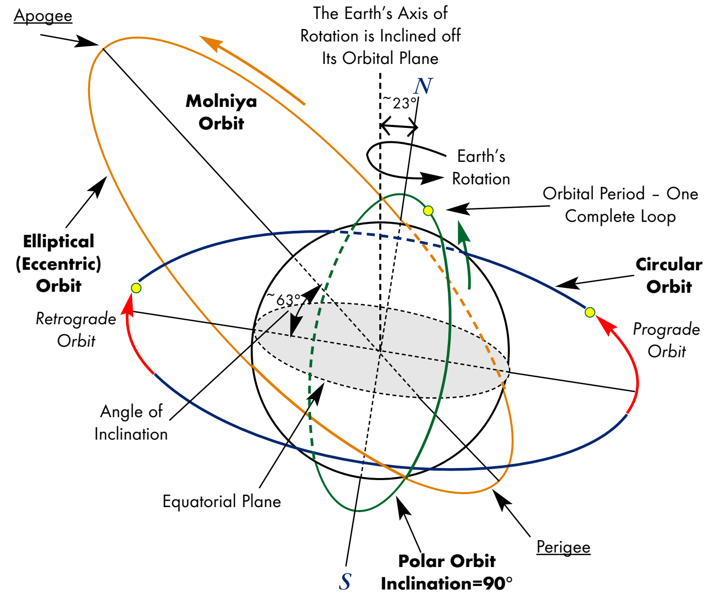

Figure 2. **Illustration of Orbital Concepts and Specific Types of Orbits (not to scale).**

factors. In the late 1960's, the majority of the satellites launched into orbit were used for military purposes (excluding communications), but since then, communications satellite launches are being launched with increasing frequency.

In the past, most launches to send satellites into orbit were dominated by the US Military and NASA. In recent years, the commercial sector has been extremely active in putting satellites into orbit since space has become a critical aspect of the commercial communication, navigation, and weather infrastructure. Most of the commercial space technology is in the form of orbiting communication satellites.

ORBITS

Part of defining a spacecraft's mission is to choose an orbital path suitable for carrying out the mission. In general, the mission type dictates what orbit must be chosen, and the mission and orbit together determine many aspects of the spacecraft design. This is because the type of environment a spacecraft encounters is highly dependent on the orbital path. Moreover, the orbit (altitude) and mission type (weight) together will determine the propulsion requirements.

Humans have been launching objects into Earth orbit since 1957. There is a common misconception that there are an almost infinite number of orbital paths that can be chosen when launching spacecraft. In practice, there are only a handful of *useful* orbits, each offering specific benefits to certain mission types. Many of these different orbit types have several variations, the most common of which are discussed later. Some of the factors that go into selecting an appropriate orbit for a spacecraft are mission requirements, Earth coverage, space environments to be encountered, and whether it will function as a single satellite or as part of a constellation.

Orbits are characterized by several aspects: altitude, eccentricity, inclination, and synchronization. An orbit can be considered as a complete geometric loop around a celestial body (for the purposes of this article we'll just consider the Earth as the center for every orbit), where the farthest point on the loop from the body is the *apogee*, the nearest point is the *perigee*, the elapsed time for one complete circuit is the *orbit period*, and the angle between the orbital plane and the equatorial plane is the *inclination*. The altitude is simply the height above the Earth, or the distance of the satellite from the Earth's surface. The eccentricity is the degree to which the orbital path is elliptical (i.e. can be anywhere from highly elliptical to circular). The direction of the orbit, in most cases, is either direct or retrograde. A direct (or prograde) orbit is any type of orbit that moves in the same direction as the Earth's rotation (East with respect to the Earth). A retrograde orbit is any type of orbit that moves in a direction opposite to that of the Earth's rotation (West with respect to the Earth). Figure 2 is an illustration of these and other concepts.

Types of Orbits

The four primary types of orbits are the Low Earth Orbit (LEO), the Medium Earth Orbit (MEO), Geosynchronous Earth Orbit (GEO), and High Earth Orbit (HEO). While these terms are all commonly used by the international space community, the current definitions of LEO, MEO, and GEO lack specificity, and thus are more rules of thumb. General definitions of these types of orbits are displayed in Table 1.

Low Earth Orbit The low Earth orbit is up to 1500 km above the Earth, and is mostly circular (an eccentricity near zero). Communication satellites in LEO have the advantage of a significantly reduced signal delay, as compared to satellites in

Table 1. **Summary of Useful Orbit Types.[3]**

Orbit Type	Orbital Altitude (km)	Orbital Period	Space Environment Hazards
Sun Synchronous	800	~ 100 min	Trapped Particles, Cosmic Radiation, Solar Events
Semi Synchronous MEO	27,000	12 hrs	Trapped Particles, Cosmic Radiation, Solar Events
Molniya	40,000 (apogee) 800 (perigee)	12 hrs	Trapped Particles, Cosmic Radiation, Solar Events
GEO	35,790 km	24 hrs	Cosmic Radiation, Solar Events

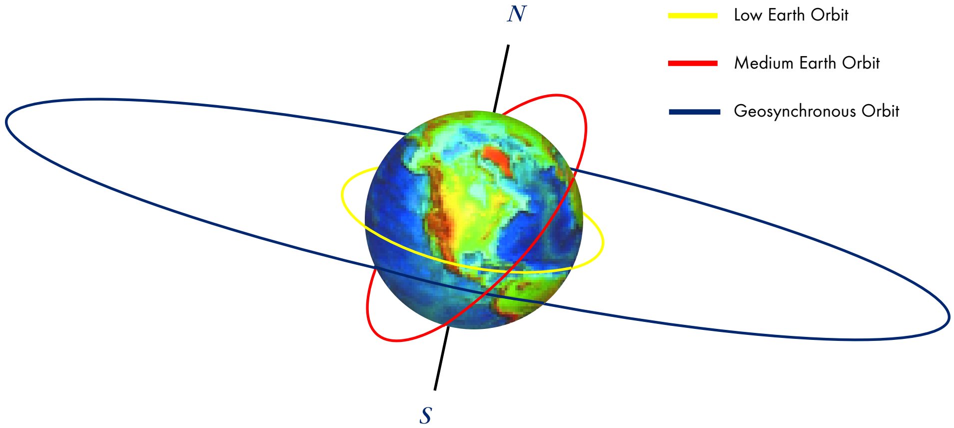

Figure 3. Illustration of the Primary Types of Orbits.

GEO (as they are much closer to the Earth). Moreover, satellites in LEO can cover every area of the Earth's surface, although it may take several orbits. Surveillance satellites in LEO require less power for sensing since the range is closer. However, the coverage area is smaller because of this reduced range. Therefore, more satellites are required in a constellation to achieve global coverage. For this reason, reconnaissance and observational satellites are placed in LEO. Satellites in LEO, however, may experience a harsher radiation environment than those in GEO.

Medium Earth Orbit The medium or mid-Earth orbit is a vaguely defined orbit, but is generally considered to be between the LEO and GEO at approximately 1,500 – 20,000 km. There is a moderate signal delay for ground antennas receiving signals from satellites in MEO, but not as significant as those from GEO. MEO satellites are a balance between power requirements, coverage, and resolution.

Semi-Synchronous Orbit A special MEO orbit, a semi synchronous orbit has a period of 12 hours, such that it covers an identical ground track every 24 hours. This orbit is uniquely suited to some communication and navigation missions. Global Positioning System (GPS) satellites use this special orbit located at approximately 20,200 km.

High Altitude Earth Orbit The high altitude Earth orbit (HEO) is an orbit that provides the largest coverage with the fewest satellites. HEO satellites have higher power requirements than LEO and MEO satellites.

Geosynchronous Orbit Geosynchronous orbits are the most common HEO orbit, where objects in the geosynchronous orbit move through space at the same angular rate as the Earth's rotation. That is, satellites in GEO have an orbital period of approximately 23 hours, 56 minutes and 4 seconds. A more specific type of GEO is the geostationary orbit, which has an inclination very close to zero and is a circular orbit. (Geosynchronous and geostationary are often used interchangeably despite the technical difference.) This results in the orbiting object constantly looking at the same part of the Earth at all times, and can see up to 1/3 of the Earth's surface at a time. The altitude for GEO is approximately 35,790 km (22,240 miles). Most GEO satellites are in a geostationary orbit (which is on the equatorial plane). This orbit is used by communications satellites to transmit signals to antennas that are at a fixed location on the Earth's surface. At this transmission distance, the signal delay is a quarter of a second for a round trip. Satellite TV communications satellites and some weather satellites are typically located in a geosynchronous orbit. Some surveillance satellites are also parked in geosynchronous orbits. When large area coverage of the Earth's surface is needed (except polar regions), geostationary orbits are preferred.

The primary types of orbits are depicted in Figure 3. Some common variations of these orbits include sun synchronous, polar, and Molniya orbits.

Molniya The Molniya orbit is a highly elliptically semi-synchronous HEO. Its inclination is about 63 degrees (depicted in Figure 2). A satellite in this orbit spends 23 out of 24 hours over the northern hemisphere, and it will repeat its ground track every 24 hours. Satellites "hover" near their apogee over the northern hemisphere because of the highly elliptical orbit. This orbit is ideal for large coverage of the northern latitudes. Much like the sun-synchronous orbit, the Molniya orbit uses gravitational disturbances to keep the apogee (40,000 km) and perigee (800 km) from rotating.

Polar Orbit A polar orbit (see Figure 2) has a very high angle of inclination, close to 90 degrees, and is typically at an altitude of 700 – 800 km above the surface of the Earth; thus it is a LEO. This type of orbit is useful for being able to see the entire surface of Earth at a relatively low altitude. When a satellite is launched to attain a polar orbit, it requires more energy (rocket fuel) for it to achieve its destination orbit, as compared to satellites sent to an orbit that rotates with the Earth. This is because the latter uses some inertial velocity provided by the Earth's rotation to achieve its final orbital speed, whereas the former has no assistance from the rotation of the Earth and thus depends completely on rocket fuel to achieve the final orbital speed.

Sun Synchronous Orbit The Earth revolves around the Sun about every 365 days. If the orbital plane of a satellite in a slightly retrograde, 'near-polar' orbit is rotated about 1 degree per day, this satellite will pass over a point on the Earth's surface at the same time every day. Since the Earth is not an exact sphere, satellites get an extra gravitational 'pull' as they cross the equator. This pull is a result of the Earth's equatorial bulge. A sun-synchronous orbit uses this extra pull to shift, or 'twist' the orbital plane the needed fraction of a degree to maintain a fixed

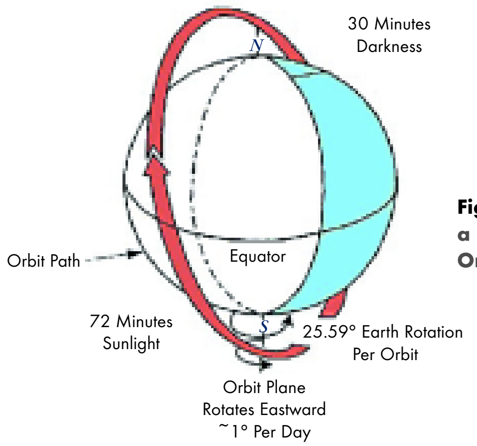

Figure 4. **Depiction of a Sun Synchronous Orbit.[2]**

orientation to the Sun. The amount of pull corresponds to the altitude and inclination. The specific sun-synchronous orbit resulting in the correct rate of planar rotation occurs at an inclination of 98 degrees (8 degrees off-polar in a retrograde orbit) and an altitude range of 800 to 1000 km. This orbit is extremely useful for weather satellites, surface mapping, navigation, and especially surveillance. Surveillance satellites can pass over a particular location on the Earth during the most optimum viewing conditions. Figure 4 shows the concept of a sun-synchronous orbit.

SPACECRAFT DESIGN

The design of spacecraft can be divided into space access (launch, and in some cases, reentry vehicles), and orbital satellites. The following sections describe the various components of the spacecraft along with their functions.

Launch Vehicles

Launch vehicles, excluding intercontinental ballistic missiles (ICBMs), have essentially two purposes: first, to protect the spacecraft from the severe launch and ascent environments, and secondly, to accelerate a spacecraft (or other mission payload) into orbit. There are two fundamental types: Expendable Launch Vehicles (ELVs) and Reusable Launch Vehicles (RLVs). ELVs, as their name suggests, are used only once to get a payload into space, and are thereafter allowed to fall back to Earth, to either splash into the ocean, or burn up upon reentering the atmosphere (this usually happens to some of the smaller components). Very few launch vehicle components are left orbiting the Earth. The number of orbiting discarded components, known as space junk, is growing, which poses a hazard to systems in LEO and MEO. In contrast, after RLVs return to Earth from orbit, their subsystems are either replaced or refurbished to prepare the vehicle for its next launch. An additional consideration for both ELVs and RLVs is whether the flight will be manned. Manned flights are constrained to much smaller launch acceleration loads (about 3g's versus 6+).

ELVs are used far more often than RLVs because they are lighter, require less rocket fuel, and consequently, are less expensive. There are also a number of different ELV designs in use, all having different mission capabilities. This variety allows a launch vehicle to be chosen which best suits the payload and mission. The premise of RLVs and their potential long-term payoff remain very attractive to some for obvious reasons (e.g. the entire vehicle does not have to be replaced after every launch).

RLVs encounter all the same conditions that ELVs do during launch, but additionally they face the arduous task of re-entering the Earth's atmosphere and landing. As a result, they must be designed to withstand these very severe conditions. This added capability requires additional systems, which in turn adds more mass to the vehicle. It has therefore proven to be a difficult challenge to design and build a reusable vehicle that is safe and reliable. To date, the shuttle is the only *partially* reusable vehicle.

RLVs encounter high wind loads during launch and descent, and also experience extreme aerodynamic heating during re-entry, which requires them to employ thermal protection systems. Furthermore, the external surface of the RLVs must have an inherent resistance to erosion and other damage from sand and dust particles, as well as rain, and possibly even hail; all of which may be encountered during re-entry. RLVs also must endure strenuous mechanical loads during landing. Consequently, the landing systems add significant weight to the launch vehicle since they are made of steel (they must be able to support the entire weight of the vehicle upon landing. Other necessary systems, such as the brakes and parachute, also add a significant amount of weight.

There are numerous systems that are typically incorporated into launches. These include wings (on some vehicles), engines, oxidizer tanks, fuel tanks, intertanks, fuel tank structure, fuel tank TPS/insulation, fuel tank propulsion systems, fuel tank electrical systems, and avionics. Some RLVs have wings for stabilization while re-entering the atmosphere, although the wings serve no purpose while in space. This is why RLVs must have additional systems, such as thrusters, that can provide stabilization in space.

The design considerations for launch vehicles differ greatly from those of aircraft due to the vastly different environmental conditions they experience. Launch vehicles must typically

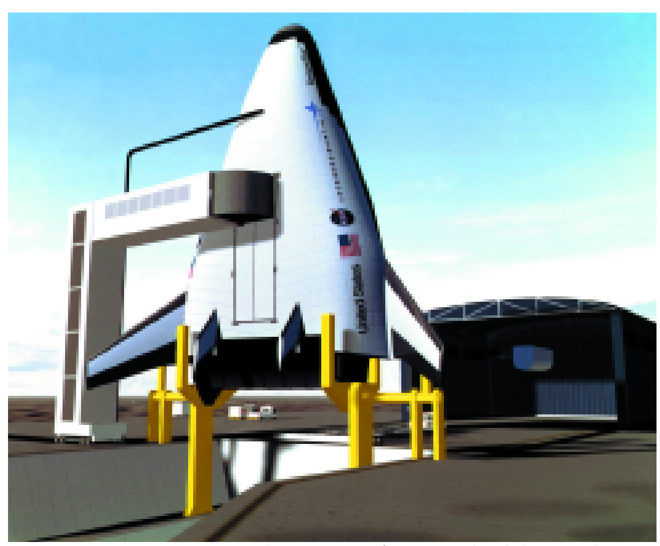

Photo Courtesy of NASA Dryden Flight Research Center

Figure 5. **Artistic Concept of the X-33 on the Launch Pad [7].**

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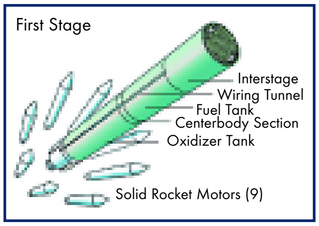
endure extreme mechanical and thermal environments, in addition to the severe environment of space. For instance, they experience mechanical stresses from such conditions as liftoff and ascent acceleration loads, shock loads, vibrational loads, and aerodynamic loads (wind). Other stresses and loads include those imposed by fluid flow and sloshing (fuel), and internal loads (such as from turbomachinery).[4] Thermal environments include aerodynamic heating, heat from the combustion of rocket fuel, and heat from the rocket exhaust plume. Some of the most important considerations when selecting materials for use in such launch vehicle systems are mass efficiency (strength-to-weight), fatigue properties, fracture properties, stiffness, manufacturing processes (eliminating stress concentrations), and environmental compatibility.

Staged Launch Vehicles

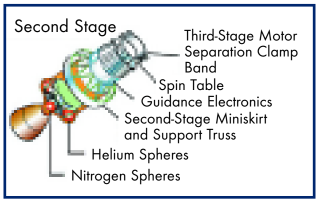
There are other aspects to launch vehicles besides simply being expendable or reusable. That is, they can be single-stage-to-orbit (SSTO), or have multiple stages that boost the payload into its final orbit. In multi-stage systems, the propellant is contained in several smaller tanks, as opposed to keeping it all in one large tank, such as in the SSTO systems. The multi-stage system, therefore, allows for the tanks to be jettisoned when the fuel has been expended, thereby decreasing the mass of the launch vehicle during the next stage of its ascent.

Single-Stage-To-Orbit One of the attractions of using SSTO launch vehicle is its similarity to the relative simplicity and cost-effective operation of an aircraft.[5] The primary disadvantage is that because the entire launch vehicle rides into orbit, a greater percentage of the dry mass is required to be the vehicle rather than the payload. From the SSTO performance equation, the takeoff weight of the vehicle plus its payload (excluding rocket fuel) can only be 10% of the total liftoff weight if the desired vehicle is intended for a low Earth orbit at 30,000 feet per second.[6] Although there have been many attempts at developing an SSTO launch vehicle, none thus far have been entirely successful, including the recent X-33, which is shown in Figure 5.



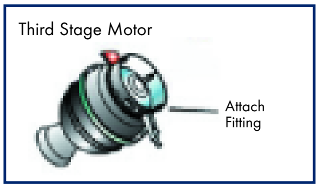
Courtesy NASA Jet Propulsion Laboratory

Figure 6. Components of the First Stage of a Launch Vehicle[8].



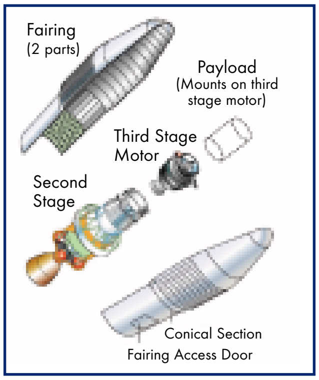
Courtesy NASA Jet Propulsion Laboratory

Figure 7. Components of the Second Stage of a Launch Vehicle[8].



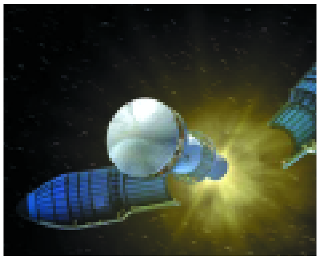
Courtesy NASA Jet Propulsion Laboratory

Figure 8. Components of the Third Stage Motor of a Launch Vehicle[8].



Courtesy NASA Jet Propulsion Laboratory

Figure 9. The Upper Stages, Payload, and Payload Fairing of a Launch Vehicle[8].



Courtesy NASA Jet Propulsion Laboratory

Figure 10. Artistic Depiction of the Release of the Payload Fairing[8].

Multi-Stage-To-Orbit The vast majority of launch vehicles in use today are of the multi-stage design. This is primarily because the mass fraction of the payload can be higher compared to SSTO, since a significant portion of the weight is discarded during the ascent to orbit. Each separate propulsion unit is called a stage. All launch vehicles have at least 2 stages, with possible additional stages depending on the mission.

The first stage contains the rocket engine, fuel, and fuel tanks, as shown in Figure 6. The center body section contains electronics which control the first stage performance. The rocket engine burns the rocket fuel. The strap-on rocket motors provide additional thrust to help lift the launch vehicle from the ground. The turbomachinery inside the rocket motors compress the fuel to increase the combustion efficiency. The first stage rockets also provide stabilization to keep the vehicle following its intended flight path. The main drawback to using multi-stage launch components is that the lower stages are used only once and are disposed of during ascent – never to be used again. Hence, the long-term manufacturing costs are higher since new components must be made for every launch vehicle.

The second stage is used to boost what's remaining of the launch vehicle through the final phases of ascent into an orbit, and also can provide some attitude control. An example of the components that make up a second stage are shown in Figure 7. A third stage can be used to change orbital altitude, or may even be used to push the spacecraft out of Earth's orbit. Both ELVs and RLVs employ orbit transfer stages to move and position satellites into their final orbit. Reusable orbit transfer vehicles are envisioned to perform this same mission. Concepts for these "space tugs" would use electric propulsion. An example of a third stage motor is shown in Figure 8. A payload fairing, as shown in Figure 9, is used to protect the spacecraft and upper stage from severe atmospheric and aerodynamic conditions (during launch and ascent). This protective structure is discarded (see Figure 10) after the launch vehicle has cleared Earth's atmosphere, usually around the time the second stage rocket ignites.

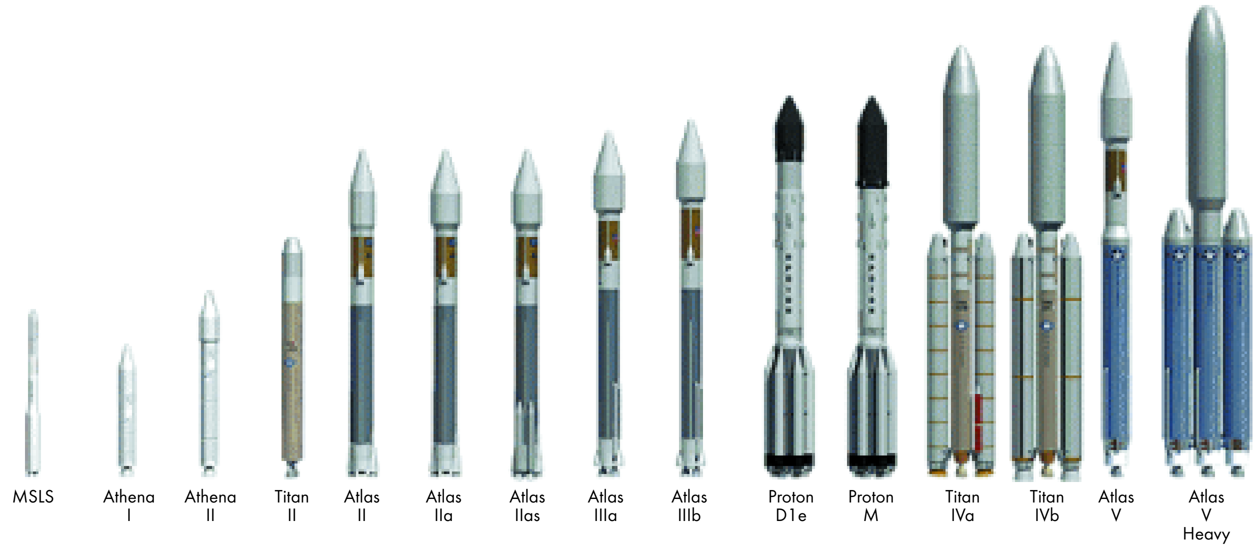


Figure 11. Examples of Expendable Launch Vehicles[3].

Current Launch Vehicles

There are a number of launch vehicles currently in use. Each one offers a variety of different features; including payload capacity, reliability, etc. Most importantly, they support different payload masses. Current launch vehicles include the Pegasus, Atlas, Delta, Space Shuttle, and Titan. Some ELVs are shown in Figure 11.

PROPULSION

Propulsion systems serve three functions in spacecraft: 1) They propel the spacecraft from lift-off into low-Earth orbit; 2) they transfer the spacecraft between orbits, primarily from a low-Earth orbit to a high-Earth orbit; and 3) they provide thrust to maintain the spacecraft in proper orbit and attitude.

Types of Propulsion

Components of propulsion systems includes turbomachinery, lines, ducts, valves, control systems, fuel tanks, pressurant storage tanks, rocket nozzles, and exit cones. Liquid propellant is stored in metallic tanks, usually aluminum, or titanium. Pressurant tanks are often made of aluminum over-wrapped with carbon/epoxy composites. The Space Shuttle Orbiter uses many metallic tanks over-wrapped with aramid fiber/epoxy. Reaction chambers and exit cones require high temperature materials. Current materials include niobium (columbium), other refractory and high temperature metals, and carbon/carbon composites. Of course, the heart of the propulsion system is the type of propellant.[6]

A major consideration when using liquid oxygen and liquid hydrogen for propellants is that they require very strict monitoring and control. Fuel boil-off, especially when the launch vehicle is sitting on the launch pad on a hot day, can be significant. Another major concern is the density of hydrogen can change significantly with small temperature changes. Since there is an enormous volume of hydrogen propellant, a small percent change in density can throw off the design weight of the launch vehicle to a significant extent.

SATELLITE SUBSYSTEMS

Satellites are conceptually divided into two components, the bus and the payload. The bus is common to all mission types and consists of the following subsystems: structures, guidance and navigation, attitude determination and control, electrical power, communications, command and data handling, and thermal control. The payload mainly consists of components to fulfill its mission. The sensors are connected to the command and data handling as well as the communication bus subsystems. The following sections describe the satellite bus subsystems and their interaction with one another. Figure 12 is a depiction of a satellite's subsystems and payload, although the structure and placement of the subsystems will vary for the different missions and even between different satellite manufacturers.

Structures

A satellite's structure includes both the primary structure, which supports the main body, as well as secondary structures which support the various functional components. These structures are dictated by the mission type, and the launch loads. The structural designs must be able to handle the mechanical requirements of both on-orbit and launch events. The highest mechanical loads a satellite will be required to endure are typically seen during structural testing, handling, and launch.[3] Once in orbit, the loads become very small. In most cases, a satellite is placed in an orbital path for its entire existence. In this case, the mechanical requirements are primarily for providing stiffness for dimensional stability, as pointing accuracy of sensors and communication equipment is crucial. The only maneuvers are associated with small orbital adjustments and deploying components, such as the solar arrays. Aluminum alloys and composites are widely used in the primary structure due to their combination of low density and mechanical properties. Secondary structures are typically made from aluminum, steel, or titanium. Once in orbit, the ideal weight of structures is zero. Common structural designs include flat sandwich panels and trusses.

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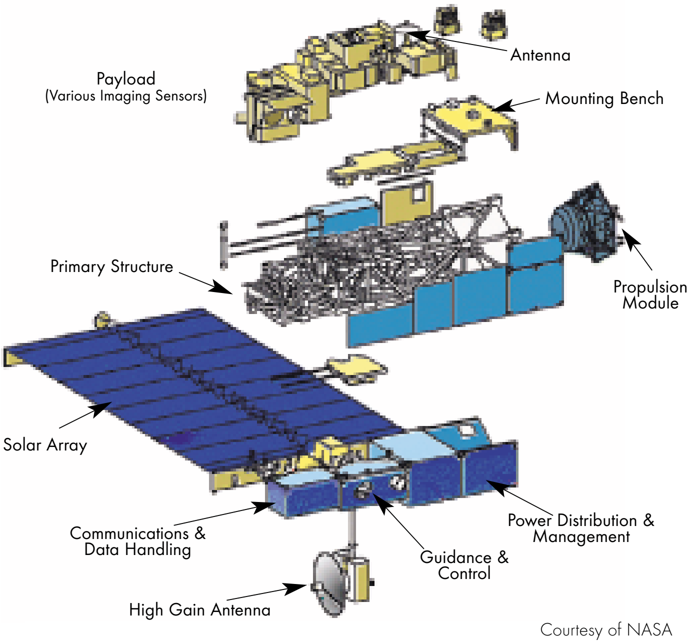

Figure 12. **Typical Satellite Subsystems[9].**

Guidance and Navigation

The guidance and navigation subsystem is responsible for maintaining a satellite in orbit. The orbital path is determined via communications with ground operations and/or other satellites. The data is processed by either ground operations or on-board computers which then command the propulsion systems for maneuvering as required for orbital adjustments. Guidance and navigation has traditionally been controlled by ground operations. However, with the current GPS satellites and on-board computers, autonomous orbit control is now an option.

Attitude Determination and Control

The attitude determination and control subsystem maintains the satellite's orientation with respect to its center of gravity. Sun sensors, horizon sensors and star trackers help determine a satellite's position. There are two concepts used for attitude stabilization. The three-axes method may use gyroscopes, propulsion systems, magnetic torquers, momentum wheels, and/or reaction wheels to maintain its orientation. Spin stabilized satellites, or spinners, use rotation about the direction of flight to maintain proper orientation. In most spin stabilized systems, a component referred to as a 'de-spun' rotates with equal angular velocity in the opposite direction, so as to be fixed with respect to some reference point such as the Earth or other satellite.

With a trend towards higher power satellites, 3-axis stabilized satellites are preferred since they offer more usable "acreage" for solar cells. Other stationkeeping and propulsion is done through propellant systems. Cold gas systems are not typically used except when hot gases must be avoided or when safety issues with the solid and liquid systems arise. Solid propellant systems are used quite extensively, but only for space access. Liquid bipropellant systems (fuel and oxidizer are separate components) are attractive since they have the ability to serve all three propulsion functions. However, they are also more complex than the traditional solid plus liquid monopropellant combined systems (fuel and oxidizer are combined). Dual and hybrid systems make use of both a monopropellant and bipropellant. Typically, hydrazine (N_2H_4) is used as a monopropellant and can be combined, using onboard systems, with nitrogen tetroxide N_2O_4 to produce a bipropellant fuel.

Electrical Power

The electrical power subsystem converts energy, stores, and distributes electrical power to the various subsystems of the satellite. The power system is typically designed to supply 2-3 times the average power required in order to cover peak demands. It must also be designed to account for degradation of the power systems over the life of the satellite. The photovoltaic solar cells lose efficiency over time and can suffer damage from the space environment. Batteries will lose power storage capacity with use. Therefore the electrical power subsystem is determined by the average electrical power required at the end of life. The most common power sources for Earth orbiting satellites are the solar arrays (silicon or gallium arsenide photovoltaic cells), and batteries (typically nickel-cadmium). The solar arrays provide power and recharge the batteries during the sunlit period, while the batteries provide power when the satellite is in the Earth's shadow.

Communications

The communications subsystem, also known as the telemetry, tracking, and command subsystem, provides the link between the satellite and outside systems. Transmitters and receivers, and/or transponders are used for sending and receiving radio frequency communications.

Command and Data Handling

The command and data handling subsystem receives and processes information which is sent to ground operations or on-board computers. It is also used to control the various satellite subsystems. The size and complexity of the command and data handling system is directly related to the size of the subsystems and complexity of the mission.

Thermal Control

The thermal control subsystem maintains the temperatures of a satellite's subsystems within their acceptable operating ranges. This challenging task is accomplished by balancing heat generated within the spacecraft and exchanged with the environment. Spacecraft thermal control is complicated by the absence of convection, which is a key method of heat transfer in terrestrial systems.[4] In space, thermal control has to rely on conduction and radiation. Key components of the thermal control subsystem are thermal control coatings, insulation, heaters and radiators. Thermal control coatings include paints and second-surface mirrors. The latter are polymers or glasses with reflective coating, such as silver, on the side facing the spacecraft. Multilayer blankets consisting of polymer films with reflective metallic coatings, separated by fibrous mats typically provide the necessary insulation. Heaters with thermostats maintain the minimum operating temperatures of the various subsystems. And radiators are used to expel excess heat into space.

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SUMMARY

The US Air Force is a key player in the US space program, and the Air Force Research Laboratory continues to advance space technology with fundamental research and development that applies to the various systems, subsystems and components discussed in this article. Many of the articles in this special issue of the *AMPTIAC Quarterly* focus on specific components and technologies used to build the various spacecraft subsystems. These include rocket nozzles, thin-film membrane reflectors, high precision mirrors, thermal control coatings, and thermal protection systems.

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TESTING IN THE SPACE ENVIRONMENT

The previous article asked (and hopefully answered) the question, "What are the technical challenges of operating military systems in the space environment, and how do materials enable many of these missions to succeed?" Subsequently, this article poses the next logical question, "How do we know that our material, component, assembly, or system will work in space?" Like applications in any other service environment (e.g. land, sea, or air), the only way to validate material and design choices prior to fielding is to test them. For space systems, this is easier said than done. The vacuum, microgravity, thermal, and radiation effects of space are extremely difficult to reproduce on the surface of the earth; thus only a handful of facilities exist which can reproduce some of these conditions.

This article explores some of the conditions of space environments that systems are designed to operate in; and how their materials and components are tested, both at earthbound facilities, and in space. We are sure you will find this an informative companion piece to the previous article. - Editor

THE SPACE ENVIRONMENT

Space is an unforgiving environment – one of harshest known to mankind. Yet, space is far less understood than other service environments in which DOD systems operate. It has been known to limit the useful life of satellites, with 20 to 25% of all mission failures being attributed to the effects of the space environment.[1] Since access to space is so costly, materials and components must function throughout the life of a mission without repair or replacement. Yet, overdesign is not an option, as the cost of launch (driven by payload weight and volume) severely limits the redundancy and size of components. Adding to these challenges, future spacecraft will be designed to last longer, their functionality will become ever more complex, and their power requirements will continue to increase.

The natural space environment (often referred to as space weather) depends heavily on the satellite orbit, the time of year, and the solar activity. The environment is largely determined by the type of orbit. Low-Earth-Orbits (LEO) provide maximum sensor resolution for weather and reconnaissance missions. Satellites and spacecraft in LEO are subjected to atomic oxygen and can experience greater thermal cycling than in other orbits. Moving farther away from Earth, satellites in geosynchronous orbits (GEO) around the equator have the same angular velocity as the earth, thus GEO satellites remain over a fixed point on the Earth. Many communication and weather satellites are parked in GEO. Mid-Earth Orbits (MEO) are between LEO and GEO. Systems in MEO are subjected to the trapped radiation in the Van Allen Belts. A polar orbit is a special LEO to MEO orbit where the satellite travels over the poles. Since the Earth turns underneath the satellite, it can cover the entire globe in a short time period. Polar orbiting satellites typically experience higher radiation environments. A sun-synchronous orbit is a special polar orbit where the satellite passes over the same part of the Earth at roughly the same local time each day (for more information, please refer to the '*Orbits*' section of the article, '*Materials and the Final Frontier*' in this issue). This can make communication and various forms of data collection convenient.

Space weather causes a range of problems to materials on spacecraft. Thermal/vacuum effects, atomic oxygen, micrometeorites, ultraviolet radiation, and electron and proton radiation can all adversely impact space materials. The following sections describe these environmental factors and the materials problems they create.

THERMAL/VACUUM EFFECTS

The atmospheric density at an altitude of 300 km (Space Shuttle orbit) is ten orders of magnitude less than at sea level. Most organic materials will outgas under these vacuum conditions. The majority of metallic and ceramic materials do not outgas unless they have a high vapor pressure, like cadmium or zinc. Organic outgassing products include moisture and volatile organic compounds. Moisture sources include both desorption of moisture trapped inside the organic material and loss of water vapor adsorbed on the surface. For structural components, outgassing can lead to changes in the dimensional stability for stiffness-critical components such as optical benches. The more serious issue is that the outgassing products can condense and contaminate critical surfaces such as radiometers, solar cells, and sensors. Cold systems (<100°K), like infrared detectors, are especially prone to condensing contamination.[2] Microgravity can compound the effects of contamination products by keeping the contaminants near the satellite.

In addition, the vacuum environment eliminates convective cooling as a form of heat transfer. Structures can only be cooled if the heat is con-

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ducted to a point where it can be radiated to space. At lower earth orbits, moving in and out of the earth's shadow occurs frequently. For a 550 km circular orbit, the satellite would experience 15 eclipses each day. Under such circumstances, a number of special materials would be required to provide thermal management for the satellite. Thermal management typically accounts for roughly 5% of the mass of a satellite.[1] See our article on *Thermal Control Coatings* and *Space Environmental Testing* for more details on thermal management.

Atomic Oxygen

Atomic oxygen is produced in the upper atmosphere when ultraviolet radiation (UV) from the sun is absorbed by oxygen molecules (O_2) and causes them to dissociate into negatively charged ions. Atomic oxygen is prevalent in orbits between 100 and 650 kilometers. The atmospheric density at these altitudes depends highly on both orbit and solar activity. While the density is small, the ionic flux encountered is high given the spacecraft's velocity of orbit. At Space Shuttle orbits of 250 km to 300 km, a density of 10^9 atoms/cm^3 yields a flux of 8 x 10^{14} atoms/cm^{2}s. The high velocity of orbit also gives atomic oxygen roughly 5 electron volts (eV) impact energy per ion.[2] The carbon bonds of many organic materials are susceptible to impact energies of this magnitude. As an example, the polyimide film Kapton (a material used extensively for thermal blankets on spacecraft) shows erosion rates of 150 mils (milli-inches) per year in a 200 km orbit. Additionally, a few metallic materials (such as silver) exhibit degradation/erosion in atomic oxygen. Some metals that form protective oxide films are susceptible to degradation, since low gas pressures can inhibit the formation of adherent oxide films. Atomic oxygen can also excite some materials to emit radiation. The glow around the Space Shuttle is attributed to this phenomenon.

Particle Impact

Spacecraft must also contend with impact of particles either from space debris or dust. Most of the space debris is found in low earth orbits from 350 km to 2000 km. The debris largely consists of materials ejected from spacecraft during launch and deorbit, including alumina from solid rocket motor propellants, aluminum, and oxides from thermal control coatings (zinc and titanium oxides). All told, it is estimated that there is over 3,000,000 kg of space debris. The United States Strategic Command currently tracks over 8,000 objects in space that are over a centimeter in size - but there are an estimated 1,000 kg of particles under this limit.[3] Relative impact velocities depend upon the satellite orbit but are on the order of 10 km/s. Particles as small as 0.1 mm cause erosion on most materials and particles greater than 1 mm cause significant damage.[1]

Micrometeoroids and interplanetary dust also can damage spacecraft. Most micrometeoroids are a result of comet ejection. These particles typically have velocities relative to the earth from between 10 to 70 km/s. They are at least 0.2 microns in diameter since smaller particles are swept away by the solar wind.[4]

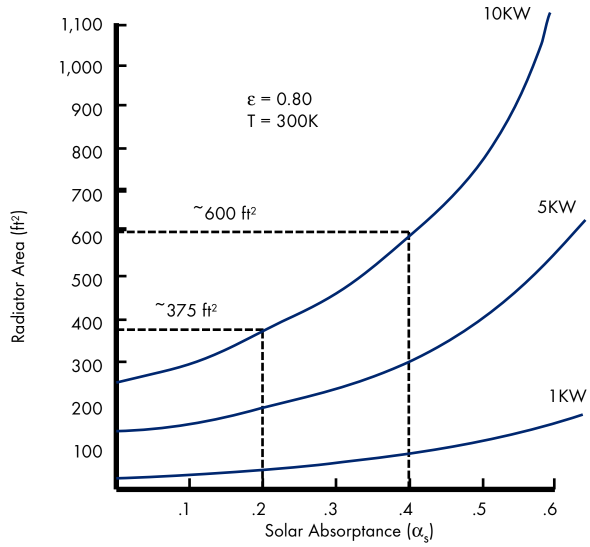

Figure 1. **Radiator Size vs. End-of-Life Solar Absorptance.**

Space Radiation

Radiation can wreak havoc on materials, causing either permanent or transient changes in their physical and electrical properties. Radiation comes in electromagnetic and particle forms. Nearly 99% of the solar electromagnetic radiation at one astronomical unit (distance from the earth to the sun) has a wavelength between 0.3 and 11 µm. In fact, visible light accounts for 41% of the total electromagnetic energy emitted from the sun. Together, both the ultraviolet and infrared spectrums account for most of the remaining energy. X-Rays, extreme ultraviolet, and radio wavelengths account for less than 0.1% of the solar energy. Solar electromagnetic radiation changes with solar activity and season (the distance between the earth and the sun changes, as the earth's orbital path is slightly elliptical).[5] Reflected radiation (albedo) from both the earth and the moon contribute to the total irradiance. The albedo is important to low earth orbits and varies with clouds and terrain.

Ultraviolet Radiation: Ultraviolet radiation (UV) is particularly damaging to some materials. Most UV radiation is absorbed by the Earth's ozone layer. However, in space, high intensity UV radiation can sever organic chemical bonds. In addition, UV can lead to discolorations in polymeric materials and ceramics (e.g. glasses), which change the solar absorptivity of materials. Changes to a material's performance, such as the absorptance of white thermal control coatings must be accounted for in the design process, since the rate of heat transfer will change proportionately. As Figure 1 shows, changing the solar absorptance from 0.2 to 0.4 over the life of a satellite dramatically increases the needed radiator area from 375 ft^2 to 600 ft^2 for a 10 KW satellite. Note, the emissivity (ε) of the white coating does not change much during the satellite life and it is shown as a constant 0.80. Designers must account for end-of-life properties by overdesigning components such as radiators. However, increased area translates to extra weight. It is important to note that as the trend to higher power satellites continues, accounting for the degradation of thermal control paints will become increasingly critical during their design phase.

Charged Particle Radiation: The sun also emits a continuous stream of energetic charged particles. These electrons and protons (and some heavier ions) are called the "solar wind". On average these particles travel at over 400 km/s with a density of 5 particles per cubic centimeter. During solar flares the charged particles are accelerated. In addition, particles emitted by other stars pass through our solar system. Charged particles from a solar flare are referred to as solar cosmic radiation while particles from other stars are known as galactic cosmic radiation. Electrons and protons found in cosmic radiation typically have much higher energy levels than those found in the solar wind.

The earth's magnetic field traps charged particles in radiation belts known as the *Van Allen Belts*. The Van Allen Belts consists of two concentric donut-shaped belts that surround the Earth. Because of the effect of the solar wind on the magnetic field, both belts are asymmetrically shaped. On the Earth's sun-facing side, its magnetic field is compressed from the solar wind, while the field is expanded on the other side. The magnetic fields have funnel shaped cusps over the poles that allow penetrating radiation to reach much lower altitudes. In the inner Van Allen belt, the maximum proton density is found at about 5,000 km above the Earth's surface. This belt contains mostly high energy protons produced by cosmic ray collisions with the Earth's upper atmosphere. The particles in this belt are highly energetic, and with prolonged exposure they can damage materials. The outer belt's maximum proton density occurs at 16,000 to 20,000 km. This belt contains low to medium energy electrons and protons mostly generated from the influx of particles during geomagnetic storms, which occur after solar flares. These particles are deflected by the Earth's magnetic field, but are captured on the night side of the planet. Particle densities can increase by a factor of 10 to 1000 in less than an hour.[6]

Effect of Energetic Particles: Charged particles can damage an impacted material by a combination of ionization and atomic displacements. These effects can lead in turn to chemical reactions and changes in the local morphology. Electrons slow by generating a continuous ionized path in materials. Protons are heavily ionizing and produce higher ionization near the end of the particle path. The size of damage depends upon total flux, intensity of radiation, and the angle of impingement. The interaction of these particles with organic materials can lead to outgassing, shrinkage, cracking, pitting, embrittlement and discoloration. Energetic particle radiation also influences the absorptivity of materials. As seen with UV radiation, the solar absorptance of thermal control coatings show an increase over time. For example, when simulating the Galileo mission, the solar absorptance of Zinc OrthoTitanate (ZOT), a thermal control coating, increased from 0.13 to 0.42.[7] Charged particle radiation also can lead to "darkening" of optical materials.

Satellite electrical charging (the buildup of static electricity on the satellite surface) is one of the most common anomalies caused by radiation. Charging occurs when a satellite moves through charged particles (called "wake charging"). Charging can also occur through direct particle bombardment or through a photoelectric effect, with some materials subjected to electromagnetic solar radiation. When the breakdown voltage of a material is exceeded, an electrostatic charge will ultimately result in a discharge or arc; which can severely damage materials, cause spurious circuit switching, or result in false sensor readings. Materials especially prone to damage include electronic materials, thermal coatings, and solar cell materials.[5]

The high-energy protons from either cosmic radiation or the inner Van Allen Belt can completely penetrate a satellite. As they pass through, they can ionize particles deep inside the system. A single proton can deposit enough charge to cause a circuit switch, spurious command, or memory change. These incidents are labeled "single event upsets". With a push towards lower voltage commercial-off-the-shelf microelectronics, it is actually easier to cause electrical upsets than with older satellites. Additionally, the lessening of the perceived nuclear threat has reduced the level of nuclear hardening of satellites. While intended to protect systems from the radiation of a nuclear explosion, this type of hardening also helped to protect satellites from the radiation naturally present in the space environment.[5]

Many satellites use electro-optical sensors to maintain their orientation in space. These sensors reference the direction of certain stars to achieve precise pointing accuracy. When a high energy proton impacts a sensor material, a flash of light is produced and misinterpreted as a star. The computer will then try to find the star in its star catalogue. At this point the satellite could become disoriented, creating the possibility that communications antennas, sensors, solar panels all could fail to orient themselves properly, thus impacting the mission. In extreme cases, the satellite could even be lost if the batteries were to drain from a lack of solar power. For this reason, nearly all satellites have a sun sensor. While not providing the navigational accuracy of a star sensor; a sun sensor can help the satellite recover its orientation following an upset.[5]

SPACE COMBINED EFFECTS PRIMARY TEST RESEARCH EQUIPMENT (SCEPTRE)

The extreme conditions present in the space environment and the high cost associated with placing space systems in orbit require that spacecraft be thoroughly tested prior to deployment. Every spacecraft program must address the effect of the space environment on their hardware. Additionally, all new materials must be space flight qualified prior to use. Ground-based testing offers the flexibility to study multiple materials in the appropriate environmental conditions, without the extreme cost and limited availability of space flight testing. New materials can be subjected to an initial screening, with a rapid turnaround of test results. Additionally, ground-based testing allows for multiple sample exposures of a material to gain statistical confidence in its life cycle performance. Even small modifications in current state-of-the-art materials, such as changing a raw material supplier or imposing a material processing change, requires satellite manufacturers to initiate a re-qualification program to assure that the new version of the same material performs at least as well as the previous one. Ground-based testing is appropriate for these re-qualifications.

The space environment is difficult to simulate and no facilities exist that can test all of its aspects. On January 31 1958, Explorer I (the first US satellite) discovered charged particle radiation in space using a Geiger counter package designed by Dr. James Van Allen. This discovery led to the acknowledgment that environmental conditions in space were much harsher than originally thought. Later in 1958, the predecessor to the Air Force Research Laboratory's Materials and Manufacturing Directorate (AFRL/ML) opened a facility to examine some of the environmental conditions found in space, including the combined effects of vacuum and UV. Over the years, its capabilities have increased to include the effects of electron bombardment. Today, it is known as the Space Combined Effects Primary Test and Research Equipment (SCEPTRE) facility. SCEPTRE is the only Air Force-owned facility designed specifically for testing and qualification of spacecraft materials by exposing them to a simulated space radiation environment (Figure 2).

SCEPTRE is designed primarily to simulate the conditions of MEO to GEO with variable temperature, accelerated UV, near visible UV, and electron exposures; all simultaneously in a vacuum environment. SCEPTRE does not simulate the proton environment, nor the extremely high energy particles associated with cosmic radiation or the inner Van Allen Belt. With an eight-inch target area, SCEPTRE can expose 19 one-inch diameter samples and four reference samples per test. During exposure, SCEPTRE measures specimen spectral reflectance, solar absorptance, temperature, electron flux, gross outgassing, and the spectral irradiance of the UV source. After exposure, SCEPTRE can measure the thermal emittance. Additional pre- and post-test measurements can be made in a state-of-the-art optical measurements facility. These optical facilities measure reflectance, absorptance (emittance), transmittance, and scattering as functions of wavelength (0.25 to 15 mm), incidence angle (0 to 89°), polarization, and temperature (-65°F to +450°F).

Flight test data confirms that SCEPTRE simulates a variety of orbital environments and accurately reproduces the rate and extent to which a material will degrade in the actual space environment. The Air Force thermal control coating development program is predicated on performing in-house space environmental testing and validation. To date, SCEPTRE is responsible for greatly advancing the development of thermal control materials and coatings. In addition, SCEPTRE has recently expanded its testing to a wide variety of materials including polymeric films, optical thin films, and threat protection materials. The facility is also used in charging studies, thin film space stability studies, and degradation mechanics studies.

The University of Dayton Research Institute (UDRI) is currently responsible for the operation of the SCEPTRE facility. Under a 1999 Cooperative Research and Development Agreement, UDRI performs material degradation testing on a fee-for-service basis for both government and non-government sponsors.

SPACE FLIGHT TESTING

Despite advancements in ground-based testing, flight experiments are necessary to verify ground-based simulation and analytical modeling efforts. Additionally, flight testing helps validate new materials technology and demonstrates their performance in components. The Materials and Manufacturing Directorate has a rich history of space flight testing despite the often limited availability of such tests. Some of the past experiments include: Spacecraft Charging at High Altitude (SCATHA), Skylab, Long Duration Exposure Facility (LDEF), and the Materials on the International Space Station Experiment (MISSE).

Figure 2. The SCEPTRE Chamber.

Several examples of lessons learned from prominent flight experiments that AFRL/ML has participated in follow. The objective of these experiments was to gain understanding of the changes in the properties before and after exposure to the space environment. This knowledge helped improve predictions based on laboratory experiments and subsequently influenced the design of future flight experiments.

Skylab

Skylab was America's first space station. It was launched on 14 May 1973 by a Saturn V rocket and placed in a low earth orbit (415 km). Three separate astronaut crews occupied the facility for a total of 171 days, 13 hours. The last manned flight returned on 8 February 1974. During this time, Skylab completed 3900 orbits during a period of low solar activity. On July 11, 1979, Skylab returned to Earth and scattered its debris from the Southeastern Indian Ocean across a sparsely populated section of Western Australia.

The Skylab Thermal Control Coatings and Polymeric Films Experiment[8, 9] consisted of three duplicate sets of 36 thermal control coating samples and eight different polymeric film specimens. The thermal control trays were mounted perpendicular to the incident light from the sun for maximum solar exposure. The polymeric films were located 39 degrees off axis to the solar vector. The first set of specimens was retrieved after 35 days/550 hours of solar exposure and the second set after 74 days/1150 hours of solar exposure. A third set of samples was retrieved after 131 days/2040 hours of exposure. All samples were badly contaminated during launch. Post flight analysis of the thermal control coatings indicated that measured changes in specimen thermo-optical properties were due to a combination of excessive contamination and solar degradation. The results from this experiment were used in the design of the Long Duration Exposure Facility M0003-5 Thermal Control Materials Experiment and offered a direct comparison for many on the materials between the two flight experiments.

Long Duration Exposure Facility (LDEF)

The Long Duration Exposure Facility was launched into LEO (410 km orbit) from the Space Shuttle Orbiter Challenger in April 1984 and

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retrieved by the Columbia in January 1990. LDEF contained 57 experiments from the Air Force, Navy, NASA, European Space Agency, academia, and industry. LDEF contained over 10,000 materials specimens subjected to 32,422 Earth orbits. The 5.8-year flight greatly enhanced the potential value of most LDEF materials, compared to that of the original 1-year flight plan. Most of the exposed surface of LDEF consisted of chromic anodized aluminum and silver Teflon thermal blankets.

Upon retrieval, particulate debris was observed trailing LDEF. This debris mostly consisted of vapor-deposited aluminum backing from failed thermal-control blankets on the leading edge of the spacecraft. In general, organic materials such as Mylar, Kapton, paint binders, and bare composites were severely eroded. The degradation of these materials was expected since they received prolonged exposure to atomic oxygen. Coated composite materials survived and generally maintained their mechanical properties.

AFRL/ML and the Aerospace Corporation conducted the M0003 experiment on LDEF which consisted of coatings, thermal paints, polymers, glasses, composites, semiconductors, and detectors that provided data on environmental parameters. Most of the materials selected were from various development programs in the 1978 to 1982 time frame. Materials from previous space flight experiments, including Skylab, were included to provide data correlation. The materials were exposed in four separate locations on the vehicle. The first set was exposed on the leading edge of the satellite. The second set was exposed on the trailing edge of the vehicle. The third and fourth sets were exposed in environmental exposure control canisters located 30 degrees off normal to the leading and trailing edges.

The leading edge tray showed atomic oxygen damaged some materials, especially to two silver front surface mirrors, which were destroyed. There was extensive damage to the polymeric film strips. Composite material samples remained intact, but they were bleached or discolored. Silver Teflon covers remained intact; however, they had changed from silver to milky white, where components were located beneath them; and to a gold color where there were no components. The trailing edge showed that contamination discolored many of the specimens. Again, the polymeric film strips were damaged. The thermal control materials were discolored from both contamination and radiation.

Materials on International Space Station Experiment (MISSE)

The first of four Materials International Space Station Experiments (MISSE-1) was attached to the International Space Station (ISS, 350 km orbit) on 10 August 2001. MISSE is a cooperative experiment involving Boeing Phantom Works, AFRL/ML, NASA's Langley Research Center, NASA's Marshall Space Flight Center, and NASA's Glenn Research Center. AFRL/ML coordinated the project between the participating agencies and aerospace companies. In addition, AFRL/ML funded the integration of the passive experimental carrier "suitcases" that carry and hold the materials test samples. The AFRL/ML-led "Space Systems Support and Affordability Effort" (S3AE) consortium, comprised of major spacecraft manufacturers, shared in the experiment. Over 450 candidate spacecraft materials on MISSE-1 (1,700 samples) are currently being exposed to the space environment during solar maximum conditions (Figure 3). Some of the materials classes represented include: bulk polymers, composites, thermal control coatings, gossamer films, inflatable materials, optical materials including mirror materials, and thermal protection materials.

In addition to helping coordinate activities under MISSE, Mr. Edward Stutz from AFRL/ML's Sensor Materials Branch (AFRL/MLPS) designed an experiment to evaluate various emerging semiconductor materials on the space station. The experimental matrix focused on one emerging class of high performance semiconductors, which may have inherent radiation tolerance. Known as "Wide Bandgap Semiconductors" due to their inherent electronic properties, these materials have already led to the demonstration of exceptionally high power density devices, as well as exceptional low noise amplifiers (LNAs) which are critical for space electronics.

The MISSE Semiconductor Materials Evaluation Experiment incorporated a broad spectrum of wide bandgap materials, including gallium nitride (GaN), silicon carbide (SiC) and zinc oxide (ZnO). Mr. Stutz coordinated this activity with a complimentary program sponsored by AFRL's Sensors Directorate (AFRL/SN). AFRL/SN delivered GaN High Electron Mobility Transistors (HEMTs), as well as basic epitaxial materials structures that were included in the MISSE experiment. The devices used are the result of a joint collaboration between Cree, Inc (Durham, NC) and AFRL/SN under a Dual Use Science and Technology program. The program focused on the development of wide bandgap semiconductors for microwave technology applications which are capable of operating under extreme conditions, such as a crowded or hostile electromagnetic spectrum; as well as under limited environmental controls due to constraints of mass, volume, or prime power.

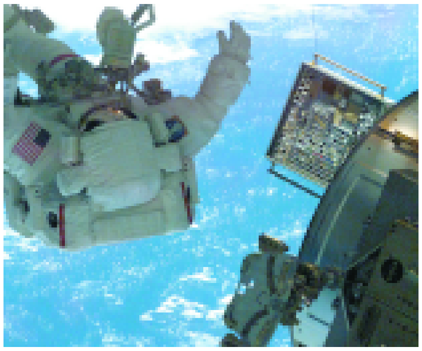

Figure 3. MISSE Integrated on the International Space Station.

All materials and devices flying on the MISSE payload were extensively characterized by structural, optical, and electronic measurement techniques prior to inclusion on the mission. Upon return, the materials and devices will undergo further testing. The test results will be analyzed to provide an assessment of the impact of the actual space environment on performance. Results of this work will be instrumental in guiding the future development of semiconductor materials and devices for space applications.

SUMMARY

Exploiting space requires a thorough understanding of the space environment's effects on materials. The criticality of new materials to Air Force space missions dictate that all materials be qualified before use. The Air Force Research Laboratory's Materials and Manufacturing Directorate has an extensive 45-plus year history of studying the fundamental interactions of the space environment's effect on materials, and to qualify new materials for use in space. Using its unique ground-based facility, SCEPTRE, AFRL/ML can approximate the MEO and GEO environments, and thus measure changes in optical properties resulting from exposure to these conditions. In addition, AFRL/ML continues to aggressively pursue space flight testing opportunities to strengthen the understanding of this complex environment.

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Mr. Jeffrey D. Guthrie has been a senior materials engineer for AMPTIAC since 1998. Prior to joining AMPTIAC, he served as a liaison between the Air Force Philips Laboratory (now AFRL/VS and AFRL/DE) and the Materials Directorate. Mr. Guthrie also spent six years working on Carbon-Carbon Composites for space applications for the Structural Materials Branch (AFRL/MLBC). Mr. Guthrie holds BS and MS degrees in Metallurgical Engineering from Montana College of Mineral Science and Technology.

Mr. Clifford Cerbus is a research physicist with the University of Dayton Research Institute (UDRI). For the past 16-years, he has managed and operated the United States Air Force Research Laboratory's space simulation chamber known as the SCEPTRE Facility. He has also participated in spaceflight experiments including the Long Duration Exposure Facility (LDEF) and the Materials on the International Space Station Experiment (MISSE). Mr. Cerbus received his BS in Physics and Mathematics from Xavier University and his MS in Mathematics from the University of Dayton.

Dr. Elizabeth S. Berman is a senior materials research engineer and the space materials direction leader in the Nonstructural Materials Branch within the Materials and Manufacturing Directorate (AFRL/MLBT) at Wright-Patterson AFB, OH. She is in charge of developing both thermal control coatings and tribological materials for space. She is the government lead for the only Air Force owned facility capable of simulating the space environment for testing of space materials. She also is the AFRL/ML Program Manager for the AFRL MISSE (Materials on the International Space Station Experiment). Dr. Berman holds a BS in Chemical Engineering from the University of Minnesota, an MS in Chemical Engineering from Purdue University, and a PhD in Polymer Science from Pennsylvania State University.

Ms. Laura Rea has served as a program manager for compound semiconductor materials development for the Air Force Research Laboratory for over fifteen years. Her responsibilities as Technology Advisor for the AFRL Sensor Materials Branch include oversight of an electronic and optical materials portfolio with an annual budget of over $20M per year. In 1998, she was selected to serve a one-year assignment as a member of the staff at the Office of the Secretary of Defense, supporting the Director of Defense Research and Engineering, at the Pentagon.

Laser Hardened Materials Evaluation Laboratory Simulates Space Environment for Advanced Materials, Space Systems Testing

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Material and Process Technologies are some of the critical enablers that permit spacecraft and launch vehicles to operate in the harsh environs of outer space. While developing and identifying these materials are vital, validating their performance in a prospective service environment is equally important. Short of taking material samples into space, evaluation of their properties must be performed in earth-bound test facilities. Laboratories capable of reliably testing materials in simulated space environments are few. The Air Force Research Laboratory (AFRL) is home to one such state of the art facility that serves as a resource to both the military and civilian aerospace community. - Editor

In an age when shuttles routinely pierce the atmosphere, astronauts visit the International Space Station, and hundreds of satellites quietly sail thousands of miles overhead; access to space means more than just exploring the unknown. It means access to satellite television, Global Positioning and domination of the battlefield from the highest possible ground.

Unfortunately, access to space also comes with a high price tag. In fact, the current cost of putting payloads into space is estimated to be $10,000 per-pound. Given the inherent risks of launch and deployment, combined with the substantial financial investment in these systems, government agencies and corporations make every effort to ensure that their spacecraft and satellites are built with materials and manufacturing technologies that will ensure the integrity and functionality needed to accomplish their varied missions. Not surprisingly, as public and private ventures into space become even more frequent occurrences, the impetus to knock one or two zeroes off the price of launching and parking these systems in orbit becomes more paramount.

American airpower visionary, Gen. H.H. "Hap" Arnold once said, "The first essential of air power is pre-eminence in research." In keeping with this vision, scientists and engineers at the Air Force Research Laboratory's Materials and Manufacturing Directorate's Laser Hardened Materials Evaluation Laboratory (LHMEL), are conducting the cutting edge research General Arnold called for – research that will allow the Air Force to dominate space both now and in the future. Established as a world-class material characterization facility, LHMEL provides results the government and industry need to lower costs and improve spacecraft and satellite capabilities.

ABOUT LHMEL

The LHMEL is a "one-stop" infrared testing resource; providing the Air Force with basic laser-material interaction data, optical material characterization, laser hardening concept validation, and thermal simulation capabilities using a unique collection of laser wavelengths, power levels and operating modes to deliver high quality material response data. LHMEL supports the Materials and Manufacturing Directorate's (ML) mission to provide laser protection materials and hardening expertise for Department of Defense (DOD) personnel and systems.

LHMEL provides data on laser-materials interaction for current and new materials using a wide range of infrared laser sources. This comprehensive testing resource provides reliable, economical laser testing in a calibrated National Institute for Standards and Technology (NIST)-traceable environment.

HIGH-ENERGY TESTING

The LHMEL uses a collection of high-energy gas and solid state lasers along with environmental simulation equipment (such as vacuum chambers, wind tunnels, and structural loading machines), diagnostics, and data acquisition systems to support testing needs for the DOD, the National Aeronautics and Space Administration (NASA), and commercial industry. Tests typically involve experiments to investigate material response, demonstrate system performance, or validate a hardening concept. As a result of efforts to diversify the type and increase the quantity of facility users, recent efforts also investigated the use of lasers both as thermal simulation sources and as tools to assist in materials processing.

The high-energy testing area is currently equipped with three

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Figure 1. Nd:Glass Laser Laboratory.

unique lasers: LHMEL I, LHMEL II, and the neodymium (Nd):Glass laser (Figure 1). LHMEL I, the workhorse of the facility, is a 15 kW continuous wave (CW), carbon dioxide (CO_2) laser capable of supporting as many as 50 tests per day. The turnkey design makes it ideal for low-cost, high-throughput material response testing and laser processing research. Its primary assets include excellent beam quality, predictable output, and NIST-traceable diagnostics.

With 150 kW of continuous wave output power, LHMEL II is the nation's largest CO_2 laser (Figure 2). In addition to providing a dynamic range of laser powers and spot sizes for general material testing, this laser serves as a mid-scale bridge between laboratory level "science" and costly full-scale phenomenology and effects testing. A virtual twin to LHMEL I as far as reliable performance and testing throughput, LHMEL II is a one-of-a-kind, high-energy test resource for the DOD. LHMEL II is routinely used to economically validate material response models prior to conducting high-cost, full-scale validation tests at other facilities.

Donated to the Air Force in 1993, the Nd:Glass laser provides LHMEL with a near infrared, pulsed source with up to 10 MJ of repetitively pulsed energy in either q-switched or long pulse mode. Its flexible configuration permits the simulation of a variety of laser types and pulse trains. When coupled with in-house optical elements, this device provides one-of-a-kind, high energy pulses in the near infrared, visible, and ultraviolet wavelength regions. This device can produce 5 kJ macropulses in the 0.5 or 5 msec pulse length regime or 100 J pulse streams in the 20 to 100 nsec pulselength regime.

LHMEL EXPANDS ITS SIMULATION CAPABILITIES

A recent cooperative effort between the Materials and Manufacturing Directorate and the Air Force Space Battlelab resulted in an upgrade of the Laser Hardened Materials Evaluation Laboratory. Because of these efforts, the facility has been expanded beyond laser effects testing to include large-scale thermal testing and space environment simulation. The Space Battlelab, located at Schriever AFB, CO, operates under the direction of the Air Force Space Command and directly supports combat operations through space systems.

The collaboration between ML and the Space Battlelab enabled LHMEL to activate a highly-capable, 27-foot tall, 20-foot diameter, cryogenically-shrouded vacuum chamber (Figure 3). In addition to activating the chamber, LHMEL added a one-sun solar simulator and a cryogenic and high vacuum-compatible turntable, which can be used to mount and rotate samples 360° in the chamber. These new capabilities, which allow researchers to simulate the effects of the space environment on materials and systems, are valued at over $25 million dollars.

Originally built by the Propulsion Laboratory in the early 1960s (now the Air Force Research Laboratory Propulsion Directorate), the vacuum chamber was originally used for space materials and systems qualification work. The Materials and Manufacturing Directorate Hardened Materials Branch, which oversees LHMEL operations, and the Space Battlelab shared the cost of modifications required to make the chamber operational after years of sitting idle.

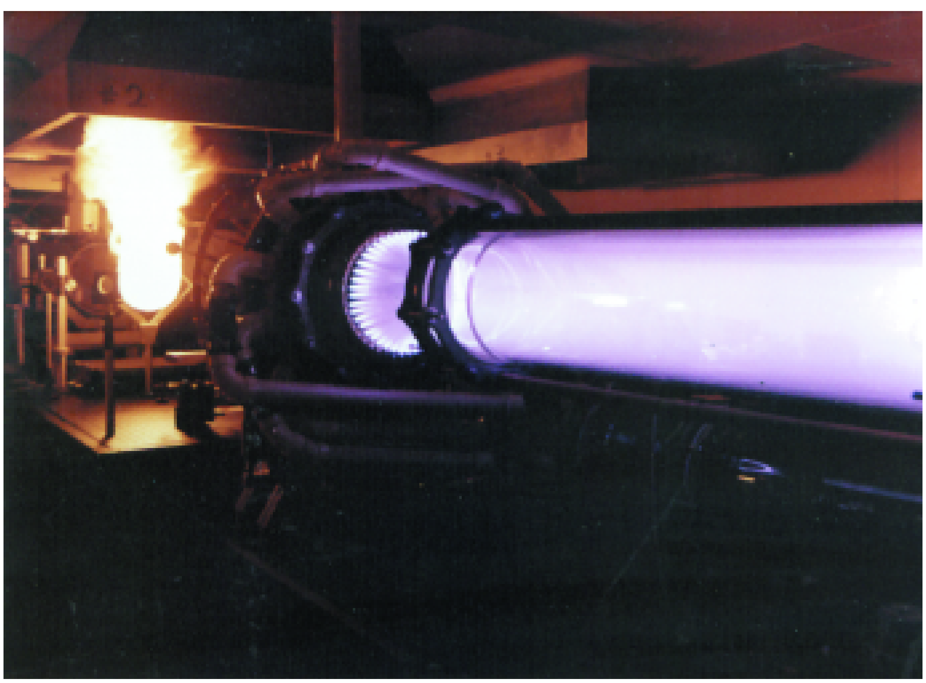

Figure 2. The LHMEL II High-Energy CO_2 CW Laser.

In April 2002, after the chamber became operational, scientists and engineers at LHMEL began seven weeks of thermal and environmental testing of a space-qualified, fully functioning, operational micro-satellite (Figure 4). Tests simulated conditions that the satellite would encounter during its lifetime, including regular solar cycles representing excursions into day and night. A simulated ground station collected telemetry data and received signals produced by the satellite during testing.

The largest of three vacuum chambers currently available at LHMEL, the new space simulation chamber, "pumps-down" using a series of vacuum pumps and its cryoshroud, an internal chamber liner that is filled with liquid nitrogen, from ambient pressure (760 torr) to 10^{-6} torr in an

Figure 3. **An Outside View of LHMEL's Cryogenically-Shrouded Vacuum Chamber.**

hour and a half. In addition to aiding the vacuum "pump-down" process by attracting and trapping stray molecules for the diffusion pumps to carry out; the cryoshroud simulates the cold temperature of space, reaching a temperature as low as 77° Kelvin.

The chamber is also equipped with vacuum "feed-throughs" so that scientists can monitor samples or systems with diagnostics equipment such as thermocouples, strain gauges, and infrared (IR) detectors. During testing of the microsatellite, 32 thermocouples were connected via these "feed-throughs" to data collection equipment outside of the chamber.

The LHMEL space simulation chamber is situated to enable laser interaction testing in a large area, high-vacuum, simulated space environment. Connected to LHMEL II, scientists working at the facility can use the 150 kW laser to focus a low energy level beam on the target, simulating sun-equivalent numbers on a six-foot diameter area.

The Laser Hardened Materials Evaluation Laboratory has two additional vacuum chambers; one measuring seven feet in diameter by nine feet in length, and the other measuring 30 inches in diameter by 30 inches in length. The seven-foot by nine-foot chamber was built during the LHMEL facility upgrades in the late 80s. It can achieve vacuum levels of 10^{-6} torr and can also be operated in conjunction with the LHMEL II laser. This chamber has been used for a variety of simulated space environment testing scenarios, including thermal simulation testing for solar cells and arrays for the Propulsion Directorate's Survivable Power Systems for Satellites (SUPER) program. In addition, the chamber has been involved in NASA-sponsored programs that examined space debris removal. The concept behind the program was to introduce heat and energy to one side of a piece of space junk, changing its momentum and knocking it out of its stable orbit, and allowing it to enter the atmosphere and burn up. LHMEL scientists have also used this chamber for theoretical testing of laser-based propulsion concepts, evaluating the idea that objects can be propelled through space using lasers.

The remaining 30-inch x 30-inch chamber, which is portable, is used for materials phenomenology experiments at the basic material level. Most often, this chamber is used in conjunction with the 15 kW LHMEL I laser to test basic material responses of two-, four- and six-inch test coupons.

SHUTTLE REUSABLE SOLID ROCKET MOTOR PROGRAM

The LHMEL facility has also supported space-related testing outside of the vacuum chamber. During the last five years, scientists at LHMEL have used the LHMEL I and LHMEL II lasers to simulate the thermal environment inside solid rocket nozzles (upwards of 4,000° Kelvin) in support of the Reusable Solid Rocket Motor (RSRM) program.

Engineers have taken advantage of LHMEL's unique capabilities to reduce the cost of testing composite nozzle materials (used on solid rocket motors) by over 90 percent. Using the 150 kW laser, LHMEL provided a reproducible, controllable, and affordable testing environment, capable of simulating the thermal conditions inside a solid rocket motor nozzle during firing.

Solid-fuel rockets use nozzles made of carbon-phenolic composite to focus and direct hot exhaust gases. Some charring and lifting of plies in the composite material is expected and acceptable during firing, but too much leads directly to nozzle failure. Nozzle thickness is critical – excess thickness adds

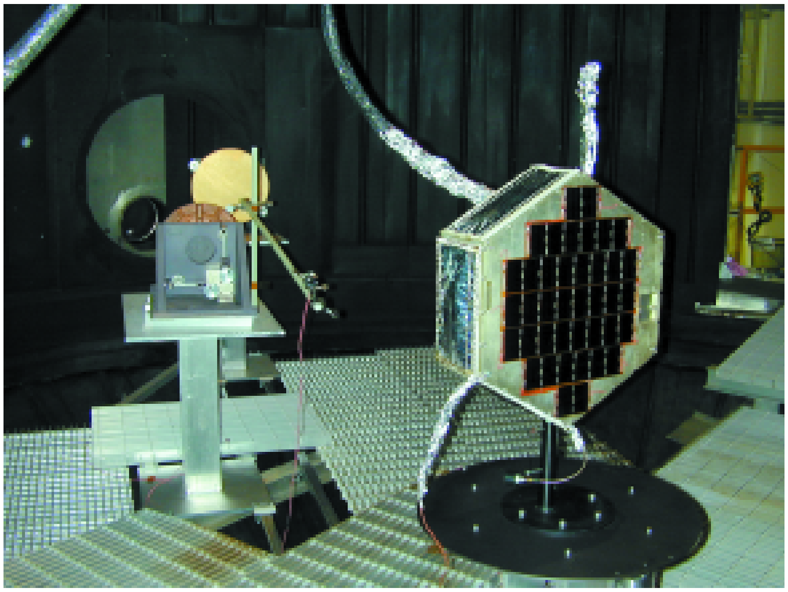

Figure 4. **Thermal and Environmental Testing of a Space-Qualified Micro-Satellite.**

costly weight and reduces payload; not enough thickness destroys the nozzle and its usefulness. Traditional nozzle testing was complicated and expensive, involving the ground firing of a solid rocket motor equipped with data-gathering instrumentation. The cost of each firing was $2 million, and all too often nozzles and instrumentation were consumed, making it difficult to quantify test results.

The 150 kW CW carbon dioxide laser uses electric discharge technology to provide a large, uniform flat-top beam profile at a wavelength of 10.6 µm. As material is irradiated during testing, its surface temperature can be precision-controlled within a range of 20° Celsius. For the solid rocket motor nozzle composite, 22 tests were conducted on eight material configurations to determine the relationship of test sample ply lifting and charring to that seen in actual solid rocket motor nozzles. The carefully controlled laser exposures, as well as the combination of the range of specimens and the visualization techniques, allowed thorough investigation of the modes of material response.

In simulating the performance of a solid rocket motor, the LHMEL 150 kW laser proved its value and versatility as a tool for simulating the thermal conditions inside a solid rocket motor nozzle during firing. The total cost of a two-day LHMEL test was $18,000, a 99.1 percent reduction in cost over the traditional nozzle testing method.

SUMMARY

A national asset, LHMEL offers unique material testing and laser processing opportunities. From its inception, LHMEL has provided reliable yet economical testing in an environment that allows the user to focus on testing needs rather than on facility-related performance issues. While other laser test facilities exist in the DOD, none provides the scope of capabilities, the throughput-per-unit-dollar, or the ease of use that are available at the LHMEL facility. LHMEL is truly a "one-stop" shop for government agencies and industry who, like early astronomers, are fascinated by space, but who are also savvy enough to understand the importance of "getting bang for their buck."

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Doubling our Reach to Space

The IHPRPT Materials Working Group Focuses On Next-Generation of Rockets

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INTRODUCTION

Material and process technologies are extremely critical to all future space systems. These types of technologies are also among a system's most limiting factors because space-launch applications require lightweight, affordable, durable, reliable, high temperature materials. Additionally, these materials must be easy to inspect to facilitate quick vehicle maintenance and turnaround.

Because the current state-of-the-art in materials and process technology limits the ability of the Air Force and the National Aeronautics and Space Administration (NASA) to have cheap and routine access to space, revolutionary material technologies are needed to ensure that the US has a lasting presence in the final frontier. It is understood by most people involved in space technology that revolutionary material technologies take a generation or more to achieve. In response to this prospect, the space and defense communities and industry are involving materials experts in forming and implementing a national plan to ensure that material technology advancement is kept at the forefront of national research and development efforts.

The primary objective of IHPRPT is to double rocket propulsion capability by 2010.

INTEGRATED HIGH PAYOFF ROCKET PROPULSION TECHNOLOGY PROGRAM

The Integrated High-Payoff Rocket Propulsion Technology (IHPRPT) program, which began in 1995, is a collaborative effort initiated by the Department of Defense (DOD), NASA, and industry. The primary objective of IHPRPT is to double rocket propulsion capability by 2010. IHPRPT's Steering Committee, is co-chaired by Mr. Andrew Culbertson from DOD, and Dr. John Rogacki from NASA.

The IHPRPT approach is to develop and satisfy a set of firm, challenging, but attainable propulsion technology goals that are time-phased and measurable. The program is focused on looking at the overall propulsion needs and developing common advanced component technologies that can be tailored to meet specific operational requirements. In the past, technology requirements for a system were typically determined up-front during the program planning stage so that schedule risk could be minimized. The problem with this approach is that the costs associated with the technology development are often borne by a single program or a single organization. Another problem with this process is that the potential exists for duplication of technical effort.

Propulsion systems, whether for manned space flight, satellites, or tactical weapon delivery systems, have a large degree of commonality between them. The components required to construct these military, civil, or commercial rockets are similar, providing an opportunity for joint research and development of technologies that will meet the technical requirements of multiple applications. Coordination of technology developments between government agencies and outside organizations, as occurs in the IHPRPT program, is a valuable tool for technology transition and transfer to meet a broad range of needs in the government and commercial arenas.

The IHPRPT program is supported by a series of subplans from industry designed to cooperatively ensure that the consolidated research and development goals are met. The IHPRPT team is responsible for using this plan to establish the required program budgets and schedules. All resulting technology advancements will be available for use in new or existing military, civil, and commercial propulsion systems. IHPRPT planning has identified the technologies that have the highest potential benefit to systems and focuses government and industry resources on developing them. From this plan, multi-year development programs can proceed without interruption. To maximize technology transition opportunities, time-phased technology demonstrations are conducted in configurations that verify the maturity of the technology and show that it is ready to be applied to a specific system.

While IHPRPT members have a vested interest in meeting IHPRPT goals, each organization derives different benefits from the program. So, a major part of the IHPRPT planning process involves analysis of component level needs as they relate to specific goals and mission needs of the organizations and industries involved. These specific needs are incorporated into IHPRPT goals where appropriate. For example, while NASA's major thrust may be affordable, reusable space transportation, the Air Force's thrusts may revolve around aircraft-like operations such as quicker alerts, increased sorties, easier maintenance, and all-weather capability. Finding commonality of requirements in differing operational philosophies is the crux of the IHPRPT program. Current baseline materials being used for propulsion components will not allow the IHPRPT program to achieve their anticipated goals in liquid propulsion, boost and orbit transfer, and tactical and spacecraft propulsion. IHPRPT-developed materials will be required to operate in liquid oxygen and liquid hydrogen, high-temperature and high-pressure environments.

Finding commonality of requirements in differing operational philosophies is the crux of the IHPRPT program.

Perhaps the most significant challenge facing IHPRPT participants involves weight, mass, and volume improvements in boost and orbit transfer, spacecraft, and tactical propulsion systems. Satisfying this critical challenge will require development of affordable materials and processes, and subsequently supporting them with an adequate industrial base.

Moreover, the liquid-rocket engine, solid fuel motor, and spacecraft systems research and development arenas all come with their own unique set of challenges. Improved liquid-rocket engine systems will require higher temperature, higher strength-to-weight materials, improved and more robust turbopump materials, oxidation resistant materials and coatings, lightweight, high temperature materials for chambers and nozzles, and reduced part count for processing and manufacturing. Solid fuel motor system developments will rely on adapting polymeric materials for reduced weight components, lighter, and lower cost insulation materials, and high-strength case materials that will decrease component mass and volume. Durable energy conversion devices for electric propulsion and monopropellant-compatible materials are just a few of the challenges awaiting development teams in the spacecraft arena.

IHPRPT MATERIALS WORKING GROUP

Because materials are at the core of space systems like the Reusable Launch Vehicle (RLV), the IHPRPT Materials Working Group (IMWG) was chartered by the IHPRPT Steering Committee in February 1997. The IMWG enables focused and unified materials development and collaboration between NASA, DOD, and industry. Together, they have developed joint requirements that are intended to satisfy multiple program needs. The IMWG partners share information and resources, proceeding from a joint roadmap. In short, IMWG is one example of government-funded technology development designed to achieve breakthroughs despite budgetary constraints and other seemingly insurmountable limitations.

Like the national IHPRPT steering committee, IMWG is comprised of representatives from various NASA, DOD, and industry organizations (such as Aerojet, Boeing Rocketdyne, ARC, TRW, Pratt and Whitney and ATK/Thiokol). However, while IHPRPT is focused on broad system challenges, IMWG's membership specializes in specific material and component concerns. Currently co-chaired by Mr. Eric Becker from the Air Force Research Laboratory Materials and Manufacturing Directorate, and Dr. Raymond (Corky) Clinton of NASA's Marshall Space Flight Center, their primary activities include developing material plans to meet IHPRPT's liquid, solid, and spacecraft propulsion goals.

MATERIALS AND MANUFACTURING DIRECTORATE'S CRITICAL ROLE

Representatives from the Air Force Research Laboratory's Materials and Manufacturing Directorate, who first received funding for their participation in IHPRPT in 2001, are currently conducting research and development efforts designed to address the requirements of several of the team's plans. These include materials and process development for advanced solid rocket motors, rockets used for boost and orbit transfer, and spacecraft propulsion and liquid boost and orbit transfer requirements.

For example, to meet goals in the boost and orbit transfer arena, IMWG collaborators are developing management devices* for liquid propellant, combustion and energy conversion devices, nozzles, throats, cases and insulation for solid propulsion components. When successful, IHPRPT expects reduced hardware costs, reduced support costs, improved thrust to weight ratio, increased mean time between removals, improved mission life and reusability, and reduced stage failure rates.

Similarly, in the spacecraft materials and processes arena are projects to develop Hydroxyl Ammonium Nitrate (HAN) catalyst materials, laminated ceramic hall thruster chambers, and carbon-carbon ion grid screens; as well as improve the processing of high temperature reaction materials. Several benefits are expected to result from these efforts, including reduced handling costs and safety risks related to hydrazine propellants, larger spacecraft propulsion margins for extended mission profiles, and extended operational lifetimes for thrusters and grids.

From these plans, a consolidated list of materials needs was developed, which has dictated the resulting materials development programs that the directorate has undertaken. The directorate currently manages 23 programs, which stretch across four Core Technology Areas (CTAs), as well as a handful of delivery order contracts. Many of the directorate's projects consist of applied research efforts; such as assessing the applicability of emerging materials (like metal matrix composites or nanomaterials) for aerospace systems. Working closely with each individual program, experts from the directorate have established cost and performance requirements for potential materials. One such organization is the Air Force Research

Laboratory's Propulsion Directorate at Edwards AFB, CA, which manages IHPRPT's technology demonstrators. They are closely surveying challenges related to the representative geometries and shapes of system components, and the processing requirements of these materials.

The directorate is addressing a number of IHPRPT goals. Among these goals are developing advanced materials for lightweight ducts, turbopumps, chambers, and nozzles, and developing key applications for solid fuel motors; including nozzle throats, insulation, tools and cases, thruster chambers and grids, and reaction chambers. These materials and applications will enhance the overall performance of rockets by increased usage temperatures, reducing the number of processing steps, lowering erosion rates, and developing lighter weight components.

TRANSPIRATION COOLING RESEARCH

For example, scientists and engineers at the Materials and Manufacturing Directorate are developing and demonstrating transpiration-cooling concepts and materials that could lead to lightweight, high-efficiency combustion chambers for rocket engines. Researchers expect the new technology to reduce the weight of current, actively-cooled thrust chambers by 50%, along with significantly reducing system complexity, part count, cost, and coolant volume.

In a liquid-fueled rocket engine, such as the Space Shuttle Main Engine, a fuel (in this case liquid hydrogen) and an oxidizer (liquid oxygen) are injected into a thrust chamber where they mix and react. The fuel/oxidizer reaction products are high temperature gases, which expand through a nozzle producing thrust (see Figure 4 in our article, *Ceramic Materials for Reusable Liquid Fueled Rocket Engine Combustion Devices*). Combustion takes place at temperatures in excess of 6000°F, which is higher than the melting point of conventional engine materials. Therefore, the chamber materials must be cooled by the continuous flow of a fluid that carries heat away from the chamber walls. In this case the hydrogen fuel also serves as the coolant fluid.

The directorate has partnered with Ultramet, a small business in Pacoima, CA, to demonstrate the transpiration-cooling concept. To date, numerous small cylinders, representing thrust chambers, have been fabricated. At this stage in development there are two main concepts being explored: a metallic-based concept and a ceramic-based one.

With IHPRPT funding and input from the directorate's Ceramics Branch, partners from Boeing-Rocketdyne began conducting a series of tests on the small cylindrical thrust chamber specimens. Coolant was pumped into the cylindrical plenum where it then transpired through the porous inner liner. The tests demonstrated that the amount of coolant that flowed through the specimens would be adequate to cool an actual thrust chamber. During the next year, researchers will prepare a sub-scale combustion chamber for hot-fire testing at the National Aeronautics and Space Administration (NASA) Glenn Research Center's Cell-22 rocket test facility. One chamber of each design, using the metal and ceramic concepts, was scheduled to be delivered to NASA for testing in February 2004. More information on this subject is available in our article, *Ceramic Materials for Reusable Liquid Fueled Rocket Engine Combustion Devices*, also published in this issue of the *AMPTIAC Quarterly*.

ROCKET MOTOR CASE RESEARCH

Yet another example of an area where the directorate is enjoying tremendous success is in reducing the steps needed to produce a rocket motor case. Currently, a significant number of cost-inefficient and labor-intensive process steps are involved in the manufacturing of a contemporary motor case. Some examples of these labor and cost intensive process steps include metal component machining, hand-spraying or automated spraying of layers with single functionality, such as primers, adhesives, barrier coatings and linings, and the process of choosing and incorporating appropriate insulation materials.

Under the management of the Nonmetallic Materials Division's Polymer Branch, five external contractual programs focus on developing technologies to decrease labor and costs and improve performance of rocket motor technology in consonance with the goals set forth by the IHPRPT Program Steering Committee. The contractors, ATK/Thiokol, Aerojet Corporation (formerly Atlantic Research Corporation), and Pratt &Whitney Space Propulsion-CSD, are expected to drive future design programs for larger scale development of tactical and boost propulsion.

One example of an approach to improve the rocket motor case structure is to design a case in which materials perform several functions. Besides serving as a structural component, materials may enhance the energy of a propellant grain, provide ablative properties, and insulate the rocket motor. Engineers from the Polymer Branch recognize that multifunctional composites may provide those attractive physical properties, weight savings, and reduction in production process steps need to significantly improve rocket motor case structures. Because composite materials are traditionally composed of a resin and fiber reinforcement, the combination of a material with insulation properties, such as inherently insulative fiber reinforcement, and a high performance resin yields a multifunctional composite with both structural and insulating properties. Thus, a combination of the materials choices and the processing of the composite influence the ultimate performance and use of the multifunctional material in the motor case.

Research and design collaborators from industry are currently developing small-scale prototype motors and will be studying the degradation of materials following exposure to the rocket motor environment during test firings at their facilities. Engineers from the Polymer Branch expect to have selected a stable case structure design by 2006 and anticipate beginning live fire testing of the advance technology demonstrator structure at China Lake in the out-years of IHPRPT.

ADDITIONAL MATERIALS AND MANUFACTURING DIRECTORATE EFFORTS

The directorate has achieved a wide variety of successes in other areas as well. For liquid rockets, engineers have completed permeability testing of chemical vapor-deposited (CVD) foam chambers. Contributing to solid rocket propulsion, the directorate's experts have successfully tested Plasma-Sprayed Tungsten and Electroplated Tungsten (1 percent Rhenium) 1" diameter nozzles during seven-second firings, demonstrating minimal erosion. In addition, researchers have developed insulator materials surpassing a 400°F target for the self-insulating case program. HAN propellant catalyst materials also passed a 1650°C tube test and met sintering targets.

The examples above represent just a small sample of the activities undertaken by the IMWG, and by the Materials and Manufacturing Directorate. Considering the complexity of rocket engines and the multitude of components such as fuel lines, ducts, valves, thrust chambers, throats, and nozzles that comprise them, it becomes easy to recognize the critical importance of materials and process technology research and development efforts to the IHPRPT program.

IMWG MEETINGS AND PEER REVIEW

IMWG meetings are conducted once or twice each year so that members of the team can stay abreast of developments and results on all fronts. During 2002, a peer review was conducted on efforts at the Materials and Manufacturing Directorate. Experts from NASA, the Navy, and the Air Force reviewed each of the directorate's IHPRPT-related projects and offered their feedback and technical expertise/advice. Though feedback was extremely positive, the directorate's scientists and engineers capitalized on the information windfall provided by experts from each visiting organization, using it to modify a few of the parameters of their current projects and testing plans.

The collaborative environment represents a significant benefit to the taxpayer in terms of cost savings and technical output.

The collaborative environment created by the IMWG's approach represents a significant benefit to the taxpayers, realized in terms of cost-savings and technical output. Simply put, a single, unified effort drawing from all contributors yields greater technical dividends than multiple parallel projects. For example, the Materials and Manufacturing Directorate is conducting a project related to thermal barrier coatings, which are, in this case, used as linings for chambers where the combustion of liquid hydrogen and oxygen takes place. The directorate's goal is to develop coatings that will keep the inside wall of the chamber cool enough that melting, or other problems associated with transferring heat from the combustion chamber, will not affect the operability of a system. During the 1980s and 1990s, NASA conducted research and gathered data on several potential thermal barrier coatings, which they were able to provide to scientists and engineers at the directorate. This atmosphere of shared goals and collaboration allowed the Air Force to avoid duplication of previous research efforts, and the additional costs associated with undertaking the efforts. In this way, they are able to direct their time, energy and budget towards potential solutions that push the technology envelope in new directions.

CONCLUSION

The key to IHPRPT's success will be the ambitious shared vision of its participants and advocates. By working together, participants have already begun to see the benefits of sharing information, sharing funding, joint planning, and joint research and development. The program is already yielding significant improvements to the nation's capability to move into full-scale development of rocket propulsion systems with improved performance, affordability, operability, reliability, and maintainability. Work accomplished during IHPRPT is also expected to set the baseline for future, cutting-edge projects such as the Orbital Space Plane.

NOTES AND REFERENCES

* *Propellant management devices* ensure proper fuel flow from the propellant tanks to the engines in many satellites. The microgravity environment of space causes liquid fuels to randomly slosh around inside propellant tanks (which hampers fuel flow) when not controlled with these devices.

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Ceramic Materials for Reusable Liquid Fueled Rocket Engine Combustion Devices

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The Air Force Research Laboratory's Materials and Manufacturing Directorate (AFRL/ML) and their industry partners are developing ceramic materials and manufacturing processes for use in reusable liquid fueled booster rocket engine combustion devices (thrust chambers and nozzles) for next-generation, reusable launch vehicles. Part of the Integrated High Payoff Rocket Propulsion Technology (IHPRPT) program, the efforts of the directorate include:

1. Developing continuous fiber reinforced ceramic matrix composites (CMCs) for actively cooled thrust chambers and nozzles
2. Demonstrating the feasibility of a transpiration-cooled thrust chamber
3. Evaluating ceramic matrix composites for radiation cooled nozzles.

The goal is to develop and demonstrate these new technologies so that they may be incorporated into future rocket engines. Using lightweight ceramics has the potential to reduce the weight of the combustion devices by up to 50%.

COMBUSTION DEVICE MATERIALS- HISTORICAL PERSPECTIVE

In a liquid-fueled rocket engine, a fuel (such as hydrogen or kerosene) and an oxidizer (such as liquid oxygen) are injected into a thrust chamber where they mix and react. The fuel/oxidizer reaction products are high temperature gases, which expand through a bell-shaped nozzle to produce thrust. Gas temperatures in the chamber may exceed 6000°F, while gas temperatures in the nozzle may range from 3000°F - 5000°F. These temperatures are too extreme for any conventional aerospace material; therefore engines must employ some type of cooling scheme. Often the walls of combustion devices are constructed of tubes or channels. During operation, coolant is pumped through the tubes or channels to keep materials within their temperature limitations.

To illustrate, take the state-of-the-art in reusable rocket engines, the Space Shuttle Main Engine (SSME). The SSME thrust chamber consists of an inner copper liner with 390 milled cooling channels that run axially the length of the liner. The cooling channels are closed out with a layer of electrodeposited nickel and then an outer structural jacket made of a nickel-based superalloy is welded in place. During operation, hydrogen coolant flows through the slotted channels in the high conductivity copper liner to keep the component cool. The SSME nozzle consists of 1080 tapered stainless steel tubes that are brazed together and then brazed to an outer structural jacket made of a nickel-based superalloy. During operation, hydrogen coolant flows through the tubes to keep the nozzle materials from exceeding their melting points.

Table 1 lists the materials and type of construction of numerous combustion devices, both historical and current. As the table shows, the materials of choice (for all the engine manufacturers) for combustion devices in large liquid fueled rocket engines have historically been stainless steels, nickel-based superalloys, and copper alloys. These materials are selected for their high strength and high thermal conductivity in order to cope with the stresses and extreme thermal environments of rocket engines. Since these alloys also have high densities (8-9 g/cm^3), widespread reliance on them has traditionally resulted in heavy engines.

Designers would like to reduce the weight of rocket engines. A key performance criterion for engines is thrust-to-weight ratio. Lighter engines and launch vehicles would allow heavier payloads to be placed into orbit at a lower cost. One path to lighter weight engines is replacement of conventional high-density engine alloys with lightweight, high specific strength ceramic composites. Two attractive candidates for this application are carbon fiber reinforced silicon carbide (C/SiC) and silicon carbide fiber reinforced silicon carbide (SiC/SiC). These materials have low densities (2.0-2.4 g/cm^3) and high strengths that they maintain to relatively high temperatures (2400-3000°F).

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Table 1. Materials and Construction Details for Past and Current Rocket Engines.

Engine	Year	Launch Vehicle	Device	Construction	Material
V-2 German Army	1942	V-2	Chamber	Double wall	Low alloy steel Cr-Mn-V
LR91 Aerojet	1960	Titan Stage II	Chamber	Tube wall	Stainless steel later Hastelloy X
RL-10 Pratt & Whitney	1963	Centaur	Chamber	Tube wall	AISI 347 stainless steel
F-1 Rocketdyne	1967	Saturn V	Chamber	Tube wall	Inconel X
SSME Rocketdyne	1981	Space Shuttle	Chamber	Channel wall	CuAgZr liner Inconel 718 jacket
SSME Rocketdyne	1981	Space Shuttle	Nozzle	Tube wall	A248 stainless steel tubes Inconel 718 jacket
Vulcain 2 Astrium	2003	Ariane 5	Chamber	Channel wall	CuAgZr liner Nickel jacket
Vulcain 2 Volvo	2003	Ariane 5	Nozzle	Square tube wall	Inco 600

ACTIVELY COOLED CERAMIC STRUCTURES – PREVIOUS DEVELOPMENT

Preliminary work on actively cooled ceramic composite structures occurred under earlier government funded programs such as the Actively Cooled Airframe Program for the National Aerospace Plane (NASP) and the Linear Aerospike Engine Nozzle Ramp for the X-33 reusable launch vehicle. The goal of these programs was to demonstrate the feasibility of using actively cooled lightweight ceramic composites for hot structures such as scramjet nozzles or the aerospike engine nozzle ramps. These programs included proof-of-concept demonstrations of small actively cooled C/SiC panels. Numerous different concepts were fabricated and tested. Several of the concepts consisted of a C/SiC composite panel structure with metallic tubes embedded within, through which the coolant flowed. C/SiC is an inherently porous material as fabricated, so the metallic tubes were used to provide impermeable coolant containment.

Figure 1. C/SiC Panel with Integrally Woven Tubes.

An alternative concept to the hybrid metallic-ceramic panels described above was also demonstrated in the aerospike engine nozzle ramp program. This was an all-C/SiC panel. The all-composite approach has even greater potential for weight savings than the hybrid approach. However, further development is needed to make the C/SiC less permeable so that it can contain coolant without leaking. Figure 1 shows one of the all-C/SiC panels. The panel was fabricated by Rockwell Scientific Company of Thousand Oaks, CA.

One of the unique attributes of this technology is the weaving process that allows the carbon fiber preform for an entire tube-wall panel to be integrally woven as a single piece, as opposed to single tubes being constructed separately and then joined together as is the case for a metallic tube-wall nozzle. This simplifies nozzle construction and results in a strong component with fewer joints. The feasibility of using structures like the one shown in Figure 1 for nozzles was demonstrated in tests. Technicians pumped water through the tubes while subjecting the panels to rocket exhaust gases. The panels were exposed to rocket nozzle-like conditions for a total duration of several minutes.

CURRENT DEVELOPMENT OF ACTIVELY COOLED CMCS

Given these promising past results, the AFRL/ML Ceramics Branch wanted to investigate whether the integrally woven C/SiC technology could be adapted to the bell-shaped rocket nozzle component geometry. AFRL/ML and partners from Rockwell Scientific Company and Boeing-Rocketdyne have begun to investigate whether the structures made previously for the aerospike engine application are adaptable to the bell-shaped nozzle application. Specific challenges include: weaving tapered tubes rather than constant diameter tubes, forming the curved panels needed to form the bell-nozzle, joining the separate panels together to form a complete nozzle, and developing coatings or surface treatments to reduce the composite's permeability. An additional challenge for a reusable nozzle is to make the ceramic composite durable enough to withstand hours of exposure to high temperature exhaust gases without degrading.

Results achieved to date show that the integrally woven C/SiC composite technology is adaptable to the bell-shaped nozzle geometry. Figure 2 shows a carbon fiber preform that has been woven and formed into the shape of a bell nozzle segment. The preform is a single piece with the tube structure integrally woven into the panel. Figure 3 shows a similar preform after it has been infiltrated with the silicon carbide matrix. Sixteen segments like the one shown will be fabricated and then joined together to form a complete subscale bell nozzle. Techniques for joining the segments together are currently under development.

An additional goal of the current research is to extend the integrally woven tube panel technology to SiC/SiC composites. SiC/SiC composite panels will be slightly heavier than C/SiC, but they will be more oxidation resistant and may therefore be more durable in a nozzle application. SiC/SiC composites may also be less permeable than C/SiC and therefore provide better coolant containment. Research thus far has shown that the integrally woven tube panel technology is amenable to SiC/SiC composites. The higher modulus of SiC fibers means that they

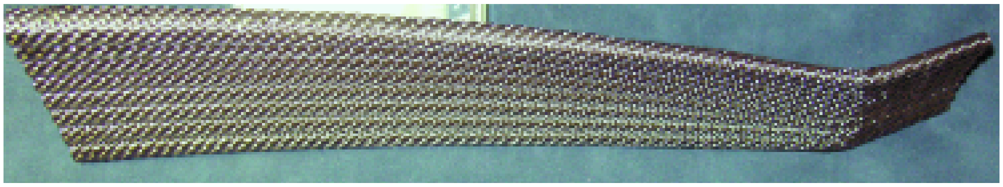

Figure 2. **Carbon Fiber Preform for Bell Nozzle Segment.**

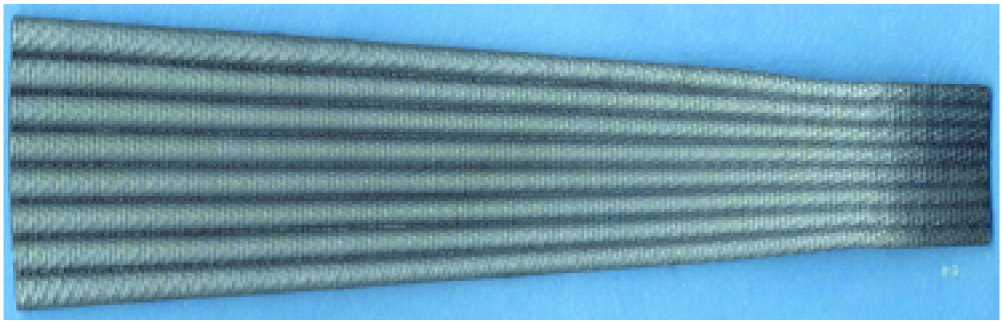

Figure 3. **C/SiC Bell Nozzle Segment.**

are more difficult to weave into intricate preforms. However, in this program SiC fibers have been woven into straight tube panel preforms like the configuration shown in Figure 1. The tapered tube panel geometry remains to be demonstrated with SiC fibers. Early tests of pressurized SiC/SiC tubes also verified that they are indeed less permeable than the C/SiC.

In the on-going work, researchers will continue to develop both the C/SiC and the SiC/SiC panels and nozzle segments. Woven panels will be fabricated and subjected to high-heat flux testing and thermal and mechanical fatigue testing. Sub-scale actively cooled nozzles will be fabricated from C/SiC and/or SiC/SiC and tested in an actual rocket environment at NASA Glenn Research Center's Cell 22 rocket test facility.

TRANSPIRATION-COOLED THRUST CHAMBER

A second area of research is focused on an alternate and potentially more efficient form of active cooling, transpiration cooling. To investigate the feasibility of a transpiration-cooled thrust chamber, AFRL/ML has partnered with Ultramet, a small business in Pacoima, CA, and Boeing-Rocketdyne. This innovative thrust chamber concept would do away with the traditional cooling tubes and channels that have become standard in liquid rocket engines. A concept for a transpiration-cooled thrust chamber is shown in Figure 4.

The transpiration-cooled thrust chamber concept is comprised of three major components; a porous inner liner, an intermediate foam core and an outer jacket for structural support and cooling containment. During operation, coolant would be pumped into the foam layer. The coolant would flow through the open cell foam and be dispersed throughout the foam layer. From the foam layer the coolant would then seep through the millions of naturally occurring micropores of the inner liner. The micropores distribute the coolant evenly and efficiently over the combustion facing surface to keep it cool and enable it to withstand exposure to the high temperature combustion gases.

Research thus far has focused on the inner liner, particularly achieving the right amount of permeability in the liner to allow adequate coolant flow. To date, Ultramet has fabricated numerous small cylinders, representing thrust chambers. The optimum materials for the application have not yet been determined; however the ceramic demonstration articles consist of a lightweight silicon carbide foam core with a mixed molybdenum disilicide-silicon carbide inner liner. The microporous inner liner is integrally bonded to the macroporous foam support structure. The cylinders were fabricated with different inner liner thicknesses to determine the effect of liner thickness on coolant flow. The use of high temperature ceramics is appealing because they will minimize the amount of coolant that must be provided to the liner surface. The temperature limits of the materials are about 3000°F, so the optimum amount of coolant would keep the inner surface of the liner to just below this temperature.

Boeing-Rocketdyne tested the small cylindrical thrust chamber specimens in the fixture shown in Figure 5. Gases were pumped into the cylindrical foam plenum where they then transpired through the porous inner liner. The coolant flow was visualized by applying a soap film to the inner liner and observing the bubble pattern as shown in Figure 6. The amount of coolant that flowed through each cylinder was measured and compared to computer models which were used to predict the amount of coolant flow needed for a transpiration-cooled thrust chamber. The tests demonstrated that the microporous inner liner would allow an adequate amount of coolant flow to cool the thrust chamber under predicted operating conditions. The thickness of the liner can be varied to provide different coolant flow rates. The cylindrical test specimens were also subjected to high pressures to verify the integrity of the foam-liner

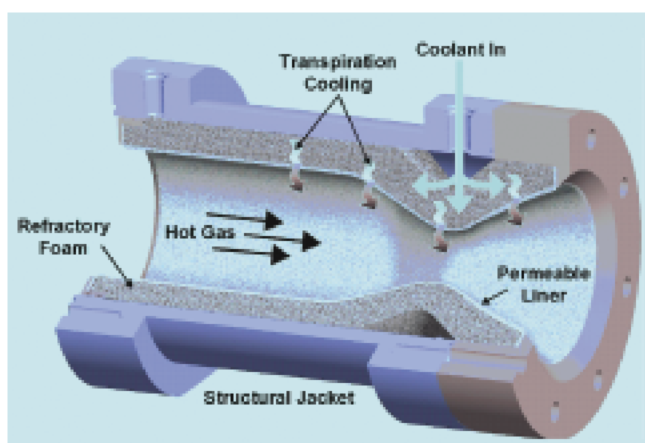

Figure 4. **Transpiration-Cooled Thrust Chamber Concept.**

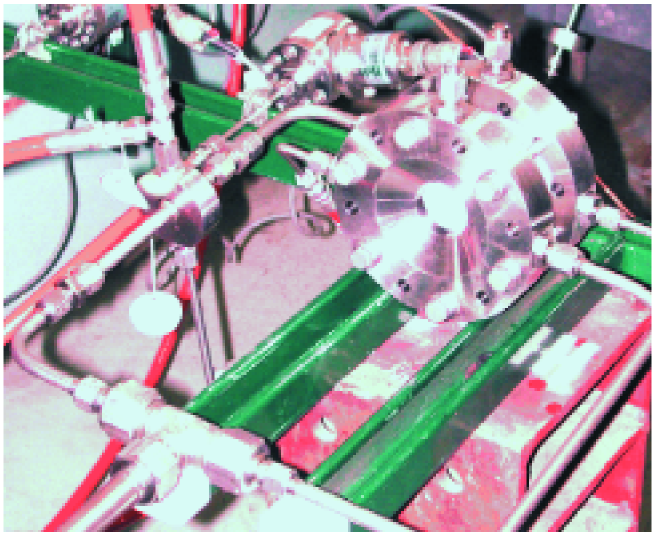

Figure 5. Permeability Testing of Cylindrical Specimens.

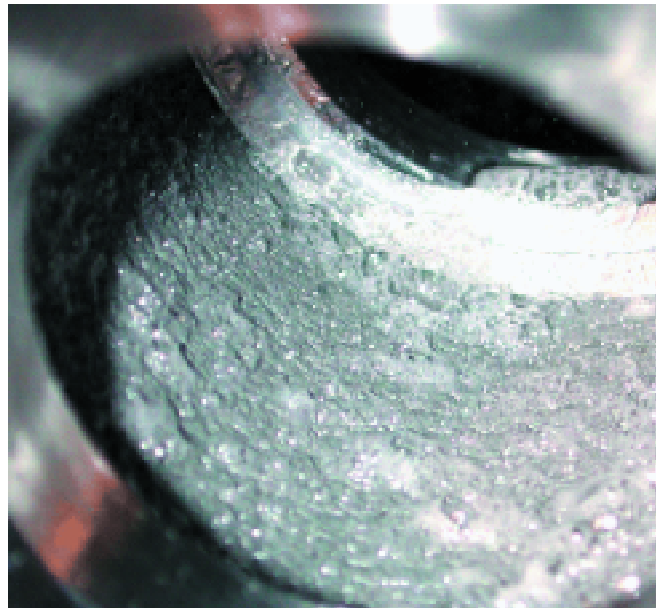

Figure 6. Soap Bubbles Show Gas Flow Pattern.

bond. These "burst" tests verified that the foam-liner bond was strong enough to withstand the pressures found in a rocket engine.

On-going research includes further optimization of the inner liner to provide the optimal amount of coolant flow for peak engine efficiency. In the tests of the cylindrical specimens it was noted that occasional large pores in the inner liner would cause an excessive amount of cooling flow. In an actual engine this would mean wasted fuel and reduced engine efficiency. Additionally, the geometric complexity of the fabricated chambers will be increased from the current cylindrical shape to the "hour-glass" shape of an actual thrust chamber. A silicon carbide foam core for a thruster is shown in Figure 7. The subscale combustion chamber will be hot-fire tested in an actual rocket environment at the NASA Glenn Research Center's Cell-22 rocket test facility. The hot-fire test will determine if the chamber can withstand the thermal stresses associated with the rocket environment.

CERAMIC MATRIX COMPOSITES FOR RADIATION-COOLED NOZZLES

An alternative approach to using actively cooled ceramics as described above is to construct a component from a high temperature ceramic matrix composite that does not require any active cooling. The component is cooled only by the radiation of heat from its surface, thus eliminating the need for cooling tubes or channels. Rocket engine construction would be simplified by the reduced cooling requirements and the elimination of tubes and manifolds. This approach is not feasible in the hottest regions of combustion devices where temperatures exceed the capability of prospective materials. However, one could envision a rocket engine that consists of an actively cooled thrust chamber and forward nozzle section that transition to an uncooled aft nozzle section at a downstream location where gas temperatures are less extreme.

It should be noted that uncooled nozzles have been used frequently in the past in the form of ablative nozzles. Ablative nozzles have been used since the 1950s and are still a viable option today. For example, Boeing-Rocketdyne selected an ablative nozzle, for its simplicity and technology readiness, for the new RS-68 engine. Ablative nozzles are constructed of phenolic plastics with various reinforcements that have included asbestos, silica and carbon fibers. However, ablative nozzles must be constructed with thick walls to account for the charring and vaporization of the phenolics during use. They are therefore very

Figure 7. Silicon Carbide Foam Thrust Chamber Core Shown on Right; A Molybdenum Foam Core is Shown on Left.

heavy. Furthermore, due to the loss of material during operation, ablative nozzles are not suitable for reusable applications.

To identify and evaluate potentially suitable high temperature composites for the uncooled nozzle application, AFRL/ML has partnered with Boeing-Rocketdyne and Rockwell Scientific Company. For this application materials must be able to withstand temperatures of 3000°F-4000°F. They must also resist degradation when exposed to a rocket engine's combustion environment; including temperature, environment, and stress; all for durations on the order of 10 hours (For a booster engine 8.5 minutes per launch with a desired life of 40-100 launches).

In this research effort a variety of high temperature materials are being evaluated. Candidates materials include C/SiC, SiC/SiC, C/C (carbon fiber reinforced carbon matrix) and C/ZrC (carbon fiber reinforced zirconium carbide matrix). Left unprotected, these materials would react with oxygen and/or steam present in rocket exhaust gases and would quickly degrade. Therefore the materials must incorporate a protective coating, oxidation inhibitors in the matrix, or some other form of protection. The materials screened in this effort were selected for their innovative oxidation protection schemes.

Candidate materials were fabricated by seven different material suppliers and are currently being subjected to a battery of screening tests. Key among these are stress tests, both static and cyclic, on small specimens in an air atmosphere in a high temperature furnace. So far, the best performing material can support a load of about 20 ksi for 8 hours at 3000°F. Material degradation mechanisms have been analyzed using microscopy of post-test specimens. Ways to improve the materials have been identified and will guide the next round of material selection and synthesis. The goal is to develop an improved oxidation resistant material and then demonstrate it in an actual rocket nozzle environment.

The application of ceramics and ceramic matrix composites to rocket engines is still in its infancy. This article has described three on-going research efforts to apply ceramics to combustion devices of liquid fueled rocket engines. Replacing metallic materials that have been in use for over 50 years in rocket engines will not happen overnight. This research is laying the groundwork for future application of these materials to help create the next generation of lightweight rocket engines.

Captain Steven Steel received a BS in Mechanical Engineering from the Ohio State University and an MS in Material Science from the Air Force Institute of Technology. He recently retired from the Air Force after 20 years of service. The last four years of his Air Force career were spent working in the Ceramics Branch of the Air Force Research Laboratory's Materials and Manufacturing Directorate at Wright-Patterson Air Force Base.

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Textile Preforms for Composite Material Technology

Newly released, this publication is the first and only one of its kind – A panoramic and thorough examination of fiber/textile preform technology and its critical role in the development and manufacture of high-performance composite materials. This product was prepared in collaboration with Drexel University and authored by Dr. Frank Ko, the Director of Drexel's Fibrous Materials Research Center. Dr. Ko is one the world's foremost authorities on fibrous preforms and textile technology.

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Applications of Structural Materials for Protection from Explosions

This State-of-the-Art Review provides an examination of existing technologies for protecting structures from explosions. The report does not discuss materials and properties on an absolute scale; rather, it addresses the functionality of structural materials in the protection against blast. Each chapter incorporates information according to its relevance to blast mitigation. For example, the section on military structures describes concrete in arches, and concrete in roof beams for hardened shelters. The discussion on concrete is not limited to materials only; rather, it addresses the issue of structural components that incorporate concrete, and describes the materials that work in concert with the concrete to produce a blast-resistant structure. The report also illustrates various materials used for concrete reinforcement.

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Material Selection and Manufacturing for Spacecraft and Launch Vehicles

A first of its kind publication, this State-of-the-Art Review provides a comprehensive overview of the unique requirements, problems, and opportunities faced by engineers designing and manufacturing spacecraft and launch vehicles. The book is authored by Dr. Carl Zweben, a major leader in the materials and space communities over the past several decades. While all material aspects of spacecraft and launch vehicles are addressed in this work, a special emphasis is placed on the unique qualities of materials used in space and highlights differences between them and their counterparts used in air/land/sea applications.

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Computational Materials Science (CMS) – A Critical Review and Technology Assessment

AMPTIAC surveyed DOD, government, and academic efforts currently studying materials science by computational methods and from this research compiled this report. It provides an in-depth examination of CMS and describes many of the programs, techniques, and methodologies being used and developed. The report was sponsored by Dr. Lewis Sloter, Staff Specialist, Materials and Structures, in the Office of the Deputy Undersecretary of Defense for Science and Technology. BONUS MATERIAL: Dr. Sloter also hosted a workshop (organized by AMPTIAC) in April 2001 for the nation's leaders in CMS to discuss their current programs and predict the future of CMS. The workshop proceedings comprise all original submitted materials for the workshop – presentations, papers, minutes, and roundtable discussion highlights and are included with purchase of the above report.

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Blast and Penetration Resistant Materials

This State-of-the-Art Review compiles the recent and legacy DOD unclassified data on blast and penetration resistant materials (BPRM) and how they are used in structures and armor. Special attention was paid to novel combinations of materials and new, unique uses for traditional materials. This report was sponsored by Dr. Lewis Sloter, Staff Specialist, Materials and Structures, in the Office of the Deputy Undersecretary of Defense for Science & Technology. BONUS MATERIAL: Dr. Sloter also hosted a workshop in April, 2001 (organized by AMPTIAC) for selected experts in the field of BPRM and its application. The workshop focused on novel approaches to structural protection from both blast effects and penetration phenomena. Some areas covered are: building protection from bomb blast and fragments, vehicle protection, storage of munitions and containment of accidental detonations, and executive protection. The proceedings of this workshop are included with purchase of the above.

Order Code: AMPT-26 Price: $115 US, $150 Non-US

$YBa_2Cu_3O_x$ Superconductors – A Critical Review and Technology Assessment

An up-to-date report highlighting recent research on the processing of $YBa_2Cu_3O_{(7-\delta)}$ (YBCO) superconducting materials to produce high critical current densities. The processing of powders through the fabrication of bulk materials and the deposition of films is covered, along with advantages and disadvantages of the various manufacturing methods. Problems in finding suitable substrate materials along with the associated property characterizations are presented. Some applications for YBCO superconductors under research, and ones that have been realized, complete the report.

Order Code: AMPT-27 Price: $50 US, $75 Non-US

Cooperative Planning is Accelerating the Development of Advanced TPS

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BACKGROUND

Thermal protection systems (TPS) are materials that are used to protect launch vehicles, reentry vehicles, and spacecraft from exposure to high temperatures experienced during operation. The tiles on the Space Shuttle are an example of TPS but there are numerous other kinds as well. Some of these materials ablate (degrade away) during operation while other classes are either insulative or actively cooled by some sort of fluid flowing through interior passageways. A final type of TPS, known as "hot structure" is made from materials that can withstand the direct exposure to high temperatures without experiencing any degradation. These materials possess the strength and temperature resistance to function in high-temperature applications but they do nothing to insulate and protect underlying components.

TPS materials enable high temperature operation of launch, reentry, and spacecraft systems. They are either single-use or reusable materials that require significant maintenance following use. The current state-of-the-art in TPS technologies does not provide the characteristics and properties required to enable advanced space systems. Planners for both the Air Force and NASA envision future reusable launch vehicles (RLVs) that are far easier to maintain than the Space Shuttle. Advanced TPS is not needed just for RLVs. Expendable launch vehicles and hypersonic weapon systems also require TPS to protect critical systems during use.

One of the critical factors limiting the availability of advanced TPS today is the difficulty in maturing new technologies. For example, the fundamental science of designing a material, and the related sciences of processing the material to an application and understanding its reaction to an environment provides a major challenge to TPS system development. Breakthroughs cannot be scheduled, and they may take a generation to achieve; however, new technologies must be available, or at least their availability must be assured, during the early stages of engineering planning and design for new systems or capabilities. Development times can take very long and there are many fundamental limitations imposed by the basic laws of physics. The only way to effectively mitigate these factors and to accelerate development is to begin work on advanced TPS during the earliest stages of the development cycle when future systems are being planned.

A TEAM APPROACH TO TECHNOLOGY DEVELOPMENT

The Air Force and NASA recognize both the limitations of current TPS technologies and the difficulties associated with developing replacement materials. To strategically address future needs, a joint DOD/NASA/industry team has been working for nearly five years to develop requirements, technology forecasts, and program roadmaps to facilitate development planning for the technologies needed for our future systems. Modeled after the Integrated High Payoff Rocket Propulsion Technology (IHPRPT) materials working group [IMWG, reported in Volume 4, Number 2 (2000) of the *AMPTIAC Quarterly*] the TPS team has structured an approach whereby the DOD, NASA, and industry will cooperatively develop a plan addressing and prioritizing TPS technology approaches necessary for future space systems and military weaponry.

In 1999 the first TPS materials workshop was held in Dayton, OH. This was a government-only meeting intended to develop a better understanding of the TPS materials research efforts sponsored by the Air Force and NASA. An additional goal was to use the information gained at this meeting to help develop the Air Force Research Laboratory's Materials and Manufacturing Directorate's investment strategy for future TPS materials development. Attendees agreed that a partnership between various government agencies and industry could provide the focus to develop the needed technologies.

A number of recommendations were made at the first meeting. One of the most important was to hold a continuing series of workshops to help ensure coordination between DOD and NASA research efforts. Also recommended was the development of a national TPS plan to help ensure coordination and advocacy for research efforts, thus maximizing cooperation and minimizing the potential for duplicative programs. The final recommendation was to use the planning process developed under the IHPRPT program.

A government and industry supported TPS working group has been formed to provide the guidance needed to carefully plan future research and development efforts. Led by a small steering committee of Air Force and NASA representatives, this group contains a good cross-section of the users and developers of TPS technologies. Table 1 displays the organizations supporting this group.

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Table 1. Primary Organizations Supporting the TPS Working Group.

Government	Industry
AFRL/Materials and Manufacturing Directorate*	Boeing
AFRL/Space Vehicles Directorate	Lockheed Martin
NASA/Ames Research Center*	Goodrich
NASA/Goddard Space Flight Center	Northrop Grumman
NASA/Johnson Space Center	Orbital Sciences Inc.
NASA/Langley Research Center*	Oceaneering
NASA/Kennedy Space Center	Triton Systems
NASA/Marshall Space Flight Center	Hitco
NASA/Dryden Flight Research Center	Ultramet
Carderock Division, Naval Surface Warfare Center	Fiber Materials Inc. (FMI)
Department of Energy/Oak Ridge National Laboratory	Composite Optics Inc.
Army/Redstone	Alliant Technologies (ATK)

*co-chairs

Following the initial meeting, a series of workshops have been used to develop and refine a National TPS plan and strategy. Figure 1 illustrates the purpose and outcomes from each of these workshops. The single most important outcome has been the development of an integrated plan and strategy that the Air Force and NASA are now using to prioritize their TPS research investments. Because of the coordination resulting from the working groups, the Air Force and NASA can now maximize their use of resources, provide opportunities for cooperative programs, and maintain world-class leadership in TPS technology.

The challenge in developing an integrated plan that both the Air Force and NASA could live with was in determining common requirements. The DOD is interested in "operationally responsive" space lift and hypersonic weapons. To be an effective tool for promoting and defending national political objectives, the Air Force requires space systems that perform similar to aircraft in that they can operate in all weather conditions and also be rapidly brought back to flight-ready status after returning from space. While reduction of TPS maintenance is a goal for NASA, the agency doesn't have the goal to develop aircraft-like operations. NASA's primary emphasis concerns low-cost and crew safety for manned spaceflight. Likewise, since commercial spacecraft typically rely upon expendable rockets, they don't have the requirement for reusability. DOD also requires expendable systems so there is a commonality of need here. The seemingly small differences between DOD and NASA RLV requirements do have an impact on the technologies that must be developed for future systems. The TPS materials working group has been successful in finding enough commonality of requirements to assign priorities to future RLV and expendable launch system technology development efforts.

The National TPS materials plan addresses the strategy needed to maintain the momentum to advance the state-of-the-art in TPS technologies. One of the most important attributes

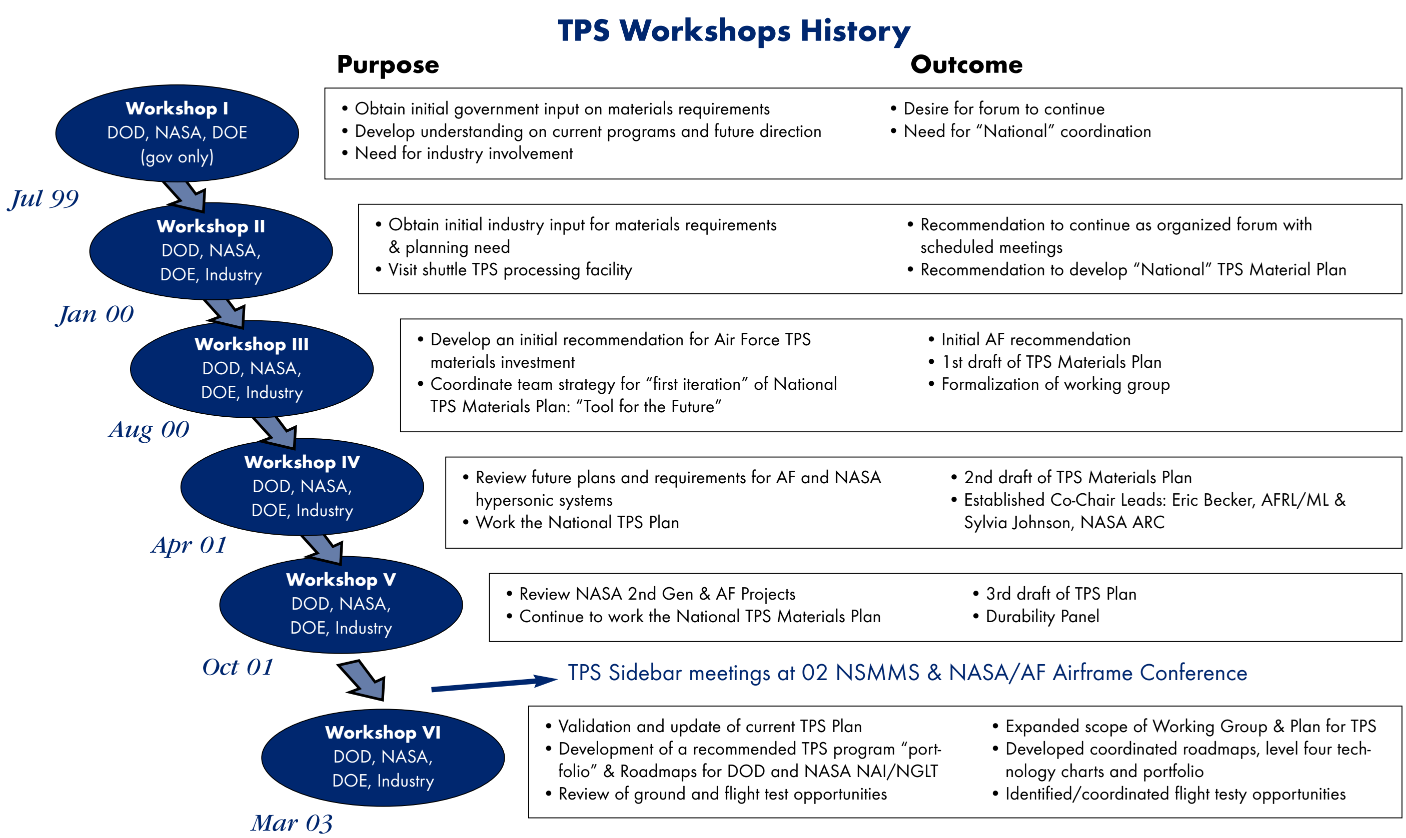

Figure 1. History of TPS Workshops.

of the plan is that it addresses the critical path (highest priority) required to develop the needed technologies. It is instrumental in helping to determine technology areas that need investment and it is certainly helping to avoid duplication of efforts. It also is providing an opportunity for each participating organization to leverage the efforts of the other participants, thus accelerating the development of new technologies.

Initially, the working group was primarily focused on materials technologies, but over the past several years the scope has broadened. Following numerous discussions and meetings with TPS developers and with the joint DOD/NASA National Aerospace Initiative (NAI) team and NASA's Next Generation Launch Technology (NGLT) team, the TPS Materials Working Group's steering committee recommended the expansion of the scope of the working group and current materials plan to incorporate structures, integration, and testing, thus becoming a more complete "TPS Working Group." There is also a recommendation to include TPS "operations" at a point in the near future.

APPROACH FOR DEVELOPING PLAN

The first thing that had to be done was to look at current and projected programs and from this analysis determine individual performance requirements by system. During the timeframe that the plan was being developed, the Air Force had a number of proposed systems requiring advanced TPS; including the Space Operations Vehicle (SOV), Space Maneuvering Vehicle (SMV), Common Aero Vehicle (CAV), hypersonic vehicles, and engines. Similarly NASA projected a number of systems requiring advanced TPS; including Shuttle upgrades, RLVs, Orbital Space Plane (OSP), hypersonic vehicles, and engines. Performance requirements for these systems were analyzed and compared so that common TPS solutions could be identified.

Table 2. **Plan Elements.**

Identify vehicle components requiring TPS
Identify performance requirements associated with component objectives
Identify candidate material options for the TPS component
Identify candidate materials' current properties
Identify issues/risks associated with candidate materials
Identify current materials programs associated with component
Identify recommended materials initiatives associated with component

In normal circumstances when materials engineers are developing new materials or evolving existing ones, there is no need to consider the full spectrum of how the materials will be applied and maintained. In most cases the new materials are similar enough to existing materials that expanding the research to incorporate the additional requirements is not needed. Anyone who has followed NASA's experience with the Space Shuttle knows that the TPS currently being used, while effective in operation, is fragile and requires costly maintenance between flights.

A building block approach to developing new TPS is being used. Included is a time-phased strategy for incrementally advancing TPS performance to meet the needs of near-term, mid-term, and far-term projected systems. For each phase of

Figure 2. **National Aerospace Initiative Goals.**

the plan a number of elements must be considered. Table 2 outlines those issues that must be addressed in order to ensure that the new system can operate with an acceptable level of risk.

Specific performance goals at the materials level are dictated by system level performance requirements. The National Aerospace Initiative (NAI) is a joint DOD/NASA effort to improve access to space. NAI has three objectives:

- Space Access: Develop and demonstrate technologies that enable responsive, safe, reliable, and affordable access to and from space.
- High Speed/Hypersonics: Develop and demonstrate technologies that enable air-breathing hypersonic flight.
- Space Technology: Develop and demonstrate technologies that enable transformational and responsive in-space capabilities.

NAI has established goals and a phased timeline for new technology development. Figure 2 outlines these goals.

TPS MATERIALS TECHNOLOGY REQUIREMENTS

If we are to achieve more responsive, reliable, and affordable space transportation vehicles then major advances in TPS materials technology is required for each of the critical path components. Included in these components are leading edges, control surfaces, acreage TPS, and seals. Figure 3 illustrates these critical components. Each of the critical path items will be discussed more fully later but the one thing to note is that

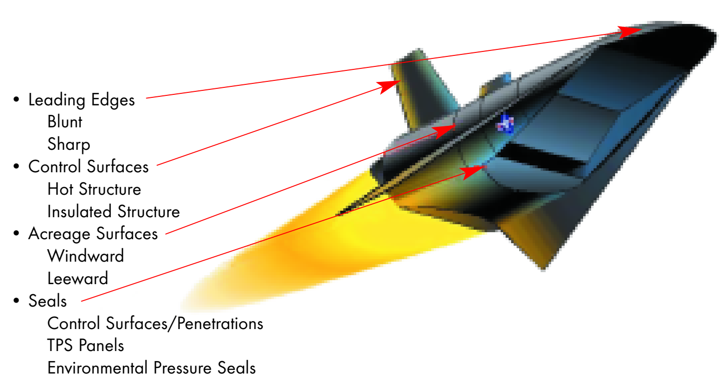

Figure 3. **TPS Components.**

Table 3. Technology Issues to Consider during TPS Development.

Fabrication and Processing
- Cost

Durability
- All weather
- Strength at temperature
- Thermal shock
- Cycling resistance
- Cycles to failure/repair/replacement
- Handling
- No shape change
- Low to no water absorption
- Abrasion/erosion

Impact Resistance
- Low speed
- Hypervelocity

Health Monitoring

Operability
- Repair, rework, inspection
- Field or depot repair
- Accessibility: Installation/removal
- Minimal processing for turnaround
- Cross range max L/D
- Abort capable
- Cost

Performance
- Temperature (single and multi-use)
- Pressure
- Time duration
- Structural loads
- Heat flux
- Vibro-acoustic
- Material design allowables
- Density
- Life
- Refurbishment

Thermal Properties
- Conductivity
- Emissivity

Less Variability on Material Properties

since each of the critical path components experience different maximum sustained temperatures and heat flux, then a variety of TPS materials is required.

Leading Edges: Concepts for advanced leading edge materials included passive and active systems. Passive systems are designed to withstand the rigors of operation with no need for removing the excess heat. Cooled leading edges have either heat pipes buried within them or involve some other mechanism that allows for the heat flux to be absorbed and carried away.

There are three approaches being considered for passive leading edge materials: refractory composites, functionally graded/hybrid materials, and ultra-high temperature-capable materials. Refractory composites including coated carbon-carbon (C/C) and carbon fiber reinforced silicon carbide (C/SiC) show promise for multi-cycle use in lightly loaded structures exposed to maximum temperatures in the range of 3000-3200°F. Functionally graded and hybrid concepts utilizing novel applications of existing materials such as carbon and/or ceramic foams, tiles, and other high temperature materials are also being considered. The "holy grail" is ultra-high temperature materials that can withstand the same conditions as refractory composites with the exception that the maximum temperature capability would be in excess of 3600°F. Materials being considered include monolithic ceramics and fiber reinforced composites. Actively cooled leading edges comprised of composite, ceramic, or metallic materials are also being considered.

Control Surfaces: Materials used for constructing control surfaces will experience different conditions than leading edges so a different approach is needed. Control surfaces are load-bearing and this major difference alone requires additional considerations during design. Also, control surfaces cannot be cooled, so the materials used to construct them must be capable of handling the heat flux experienced during flight.

There are two types of control surfaces: hot structures and insulated structures. Both of these approaches must be able to withstand multi-cycle use in an oxidizing environment. The materials used to construct hot structures are designed to withstand the heat flux during operation as well as the mechanical loads. For hot structures, three types of materials; metals, C/SiC and C/C, are being considered. The major differences between these are the maximum temperatures that they can withstand during operation. Metallic materials can be used up to approximately 1500°F. C/SiC can experience a maximum temperature in the range of 2800°F while C/C is expected to be good through approximately 3200°F. Conversely, insulated structures consist of an insulative material over the top of the load bearing structure. Different insulation materials could be selectively used to address the thermal/mechanical requirements at various control surface locations.

Acreage: Acreage TPS refers to the materials used to cover the large portions of the external structure of the vehicle. The most recognizable example of this type of material is the tiles used on the Space Shuttle. In an RLV like the Space Shuttle, or in the advanced concepts being considered, there are different environmental conditions imposed on the aeroshell depending upon the orientation of the vehicle during reentry. For example, since the bottom of the craft (the "windward" side) is more directly exposed to airflow during reentry, it experiences increased heating as compared to the "leeward" surfaces found on the top of the craft. Again using the Shuttle as an example, the tiles on the windward side are black while the leeward side tiles are white. The differences in these two different tiles relates to their ability to withstand the heat flux during reentry.

High temperature metal and intermetallic acreage TPS are being considered as a means to facilitate multi-use, low maintenance, and rapid turn around times for future applications. Specific types of materials being considered include oxide dispersion-stabilized (ODS) alloys, superalloys and aluminides. These materials have an expected temperature range of 1000-2500°F (depending upon the exact material used). Ceramic matrix composites than can withstand temperatures on the order of 2000-2600°F are also being considered. Likewise, C/SiC shows promise for demonstrating long-life multi-use capability in the 2600-3000°F range.

Seals: Seal materials are used to protect the area where two different types of structures are joined. An example of a seal location is where the flight control surfaces are joined to the wing. This is a very important location because there is movement between adjacent structures. Seals must be resistant to a variety of different temperatures depending upon the usage and location on the craft. Pressure seals have much lower requirements and must only withstand temperatures around 800°F. Light-weight, all-weather, multi-cycle life materials are required for advanced control surface and TPS seals. Control surface seals that abut hot control surfaces must withstand a temperature in the range of 2000-2500°F. Interpanel seals for highly reusable TPS are expected to experience even greater temperatures in the range of 2500°F or higher.

MUCH WORK REMAINS TO BE DONE

A tremendous amount of work has to be done to bring a new material to a technology readiness level sufficient for safe operation. This is especially true for thermal protection systems since they have to operate in such harsh environmental conditions. Issues such as joining requirements and anti-oxidative coatings by themselves can be showstoppers. There are numerous other technical issues that must be addressed before a new TPS technology can be considered mature. Table 3 outlines some of the issues that must be addressed during a technology development program.

CONCLUSIONS

Successfully developing advanced spacecraft and hypersonic systems can only be achieved if new thermal protection systems are developed. Existing TPS have fundamental limitations that preclude them from being effectively used in many of the proposed applications. (It is for this reason that these materials are viewed as enabling technologies.)

The Air Force and NASA has built upon the successful collaboration that started with the IHPRPT program's materials working group and assembled a parallel group consisting of government agencies and industry to focus upon TPS. This group has worked with development teams planning for future systems within the two agencies, and from the knowledge gained, have assembled a consolidated list that prioritizes needed technologies. This list has subsequently been used to develop programmatic roadmaps to help plan for the needed TPS research efforts.

The existing TPS plan has been through a number of iterations, starting with the first draft in August of 2000. Planners involved with the National Aerospace Initiative have used the plan extensively. With the focus now provided, these planners can have some confidence that the development of the required TPS technologies will be accelerated and new materials will be available at the time they are needed for future systems.

Advanced TPS are an essential group of technologies that must be available if the Air Force and NASA are to develop the systems envisioned. Over the years there have been numerous instances where materials technology was developed concurrently with a new system. However, when considering that TPS must survive high temperature and often ionizing environments, developing new materials to survive even more extreme conditions will be very difficult. Only if the technology development is separated from the system development and the proper resources, focus, and planning are applied can the development of advanced thermal protection system technologies be accelerated and available when needed for future systems. The TPS working group has made excellent progress in this area. By the consolidated efforts of the Air Force and NASA, we can now develop the enabling technologies that will allow us to reduce the cost and increase the rate at which our country can gain access to space for military and commercial purposes.

Mr. David H. Rose has been with AMPTIAC since its beginning in 1996, and has been its Director since June of 1998. Prior to AMPTIAC, he was an officer in the US Air Force, retiring in 1996. During his Air Force career he worked in a variety of technical and acquisition roles including five years at the Materials and Manufacturing Directorate where his research interests included micromechanical analyses of composite materials. He has a BS in Mechanical Engineering from the University of Washington, an MS in Mechanical Engineering and has completed his PhD coursework in Materials Engineering from the University of Dayton.

Mr. Daniel A. Cleyrat had a 24-year distinguished military career as an Air Force officer, where he served in Missile and Space operations and other capacities. He is currently with Anteon Corporation in Dayton, OH and is assigned as the principal engineer to the Space Office of AFRL/ML. Mr. Cleyrat also serves as the Technical Chair for the National Space and Missile Materials Symposium.

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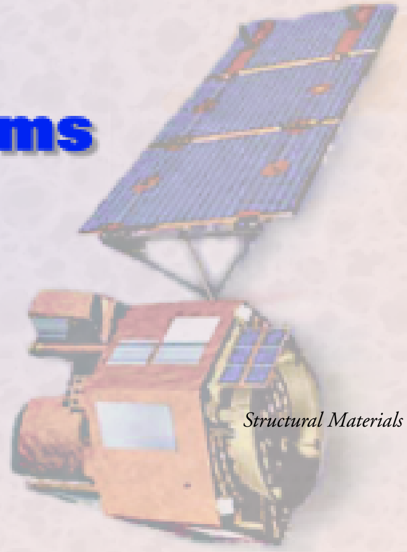
Composites for Orbiting Platforms



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OVERVIEW

The cost of placing objects into low earth orbit has been estimated to be roughly $10,000 per pound. Because of this fact weight is closely managed during system design. Given that a launch vehicle's lift capability is fixed, designers have historically paid close attention to the weight of satellite subsystems. Reducing the weight of support subsystems allows for additional payload mass that translates into more transponders on communication satellites or perhaps larger aperture optics and sensors for surveillance satellites.

The backbone of the satellite, referred to as its primary structure, accounts for 10% to 20% of the total dry mass. This estimate does not account for station keeping propellant or secondary structures such as antennas, solar array supports, or component boxes. Thermal management components account for an additional 2% to 5% of dry mass.[1] As mentioned above, reducing the weight of these systems provides opportunities for increasing satellite performance. For over 40 years the Nonmetallic Materials Division's Structural Materials Branch (AFRL/MLBC) has led the way by developing composite materials to reduce the weight of satellite structures and subsystems.

WHY COMPOSITES

Composite materials are one of eleven technologies that the Materials and Manufacturing Directorate currently identifies as a core technology area. However, emphasis on composites by the Air Force is not a recent development. In 1963 the USAF initiated *Project Forecast* with the purpose of identifying the most promising breakthrough technologies to enable future air and space systems. The Air Force Materials Laboratory (now AFRL'S Materials and Manufacturing Directorate) alerted the Project Forecast team to the weight savings that could result from using low density polymer matrix composites made from high modulus, high strength fibers. The laboratory staff pointed out that boron fiber-reinforced polymer composites had the strength of steel and a stiffness greater than aluminum, while at the same time possessing a density less than beryllium. As a result, Project Forecast identified the development of advanced composites as one of the technologies that showed tremendous potential for enabling increased systems performance.

After composites were identified as a critical technology, the Materials Laboratory (ML) began work on a long-range plan for developing this new class of materials. The result was a white paper that laid out a $360 million program to bring the promising technology from coupon-level specimens to full aircraft production. In 1965, this white paper was submitted to Air Force officials for consideration of funding. ML was soon thereafter provided with $6 million and a mandate to demonstrate success before further funding would be provided. The Advanced Filaments and Composites Division of the Materials Laboratory was established to begin this work and research into composites has been ongoing ever since.

Since that time, composites have been at the forefront of aircraft and spacecraft research and development. The attributes of composites are well known and include high specific strength (strength per unit weight) and stiffness, corrosion and fatigue resistance, tailorable conductivities, controlled thermal expansion, and the ability to be processed into complex shapes. As structural materials, composites offer numerous system level benefits over their predecessors. They are lightweight, which is critical for any space platform since less structural weight allows for more fuel or payload. The physical, mechanical, electrical, and thermal properties of composites are highly tailorable, which can also afford them multifunctionality (materials that perform more than one critical function simultaneously, such as bear loads, serve as an antenna, and be a thermal radiator). Moreover, composites may be designed with directional properties, enabling the creation of novel structures not possible with conventional materials.

Over the past 40 years, there has been a natural progression of composite technology development and applications, and today composites are viewed as an accepted structural material. Composites have become the first widely used *engineered*

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material and are paving the way for other designed materials, including those based upon nanotechnology and computational materials science. Most in the field agree that for many aerospace applications there's a lot of unexplored design space and undiscovered benefits that composites may yet realize. In fact, the National Research Council's 2003 study, *Materials Research to meet 21st Century Defense Needs*, concluded, "Composites offer the greatest opportunities for significant advances in material design and function".[2]

DESIGN ISSUES WITH COMPOSITES FOR SPACE APPLICATIONS

Launch Environment

One of the functions of a satellite's primary structure is to first help the spacecraft survive the launch environment. Engine thrust during launch and ascent imposes a steady state acceleration to the spacecraft. This acceleration persists until a stage or booster burns out. When the next stage ignites, the acceleration resumes. Together, both the steady state and the transient acceleration events impose inertial loads on the spacecraft. These loads are expressed in multiples of the weight at sea level or Gs. For the Shuttle, this is limited to a relatively light 3.5G load, while the major expendable launch vehicles (Titan, Atlas, Delta) experience a max 4G to 6G load. Acoustic vibration from the launch vehicle's engines coupled with aerodynamically induced vibration provides an additional critical source of loading on satellite structures. During ascent into orbit, several explosive events occur to separate the stages, boosters, and payloads. These explosive events generate shock loading into structures. While shock loads attenuate quickly, their peak value can be extremely high. The combined effect of all of the loading mechanisms discussed above must be considered during the design process.

The satellite must also be rigid enough during launch to avoid interacting with the payload fairing on the launch vehicle (The payload fairing protects the satellite from wind loading and contamination). Structures that use materials with a high modulus of elasticity have a high natural frequency, and thus small deflections. Thus the gap between the payload fairing and the satellite can be made smaller when "stiffer" structures are used.[1]

Orbital Environment

The major function of a satellite's structure in the orbital environment is to keep the sensors and payload components in the same relative position to each other and to protect internal components from the space environment. Consequently, structures must be very stiff to resist dimensional changes. Higher conductivity materials also reduce thermal distortion by isothermalizing the structure from both shadows the vehicle casts upon itself and from cycling in and out of the Earth's shadow. A low (near zero) coefficient of thermal expansion (CTE) can help reduce thermal distortion as well.

A material's strength is not as important once the satellite is in orbit since the loads are minimal. The most common loads are generated by thermal cycling as the spacecraft moves in and out of the Earth's shadow. Turning the satellite (slewing) and moving it to change its orbit can also generate small loads. However, stiffness is again more critical for these events. A slewing or moving maneuver causes the satellite to vibrate. The size of the displacement and the natural frequency of vibration are proportional to the structural material's modulus of elasticity. Thus, after a slewing or moving event, pointing accuracy can be established more quickly with high modulus materials than with lower modulus materials.

The design of composite satellite structures must account for the effect of the space environment. Many polymers outgas when subjected to the vacuum of space. Outgassing can result from desorption of water bound to the external surface of a polymer or contained within its interior. It is also caused when other volatile materials contained within the polymer escape or when the polymer decomposes due to its interaction with the space environment. A portion of the outgassed species will deposit on the satellite and form a film that darkens its surface. This can seriously degrade the performance of optical, sensor, solar cell, and thermal control materials. Materials that have a total mass loss of less than 1% and a collected volatile condensable material of less than 0.1% are typically required. Some satellite systems may have even more stringent requirements.[3] Desorption of water from some polymers can also reduce their dimensional stability. In these cases distortions due to desorption can be forty times greater than the thermal distortions of a high modulus composite. Analogous to CTE, polymer composites have a characteristic coefficient of moisture expansion (CME) that is used as a design parameter for satellite structures.

Composites are also susceptible to dimensional changes from thermal cycling, which can result in matrix microcracking to relieve internal stresses. This phenomenon can occur when the CTE of the matrix and the fiber are substantially different. The problem can be compounded by particle radiation that can embrittle the matrix in some composites. Further compounding this issue is that higher modulus fibers desired for their dimensional stability have higher CTE mismatches with the polymer matrix. Since outgassing is a diffusion-controlled process, microcracks can increase the rate of moisture desorption – further affecting dimensional stability.

For low Earth orbits, such as experienced by the Shuttle or the International Space Station, atomic oxygen (AO) can also degrade the performance of composite materials over time. The carbon bonds of many organic polymer materials are susceptible to the impact energies of AO. Interaction of the polymer with AO can in some cases severely erode the material.

The Structural Materials Branch strives to exploit the benefits of composite materials while addressing the issues of operating in the space environment. The focus of this work has been to provide designers with materials that enable dimensionally stable structures, and other multifunctional applications including structures that also help manage heat generated by mission electronics.

RECENT EFFORTS

During the late 1970's, the Advanced Composite Satellite Equipment Support Module Study sponsored by the Air Force demonstrated that composites could provide a 15-20% weight reduction over satellite construction practices used at the time. Since then AFRL/MLBC has made tremendous strides in advancing the development of composites for both structural and thermal applications. Some of the recent advances in polymer matrix and carbon-carbon composites are highlighted in the following sections.

Dimensionally Stable Structures

Polymer Matrix Composites (PMCs): During the early 1990s AFRL/MLBC teamed with Oak Ridge National Laboratory to explore the potential of thermoplastic composites for Strategic Defense Initiative (SDI) applications. Thermoplastics were investigated because they exhibit low moisture pick-up (low CME), low outgassing, and ease of formability as compared to state-of-the-art graphite/epoxy composites. Composites made from very high modulus fibers and both Polyetheretherketone (PEEK) and Polysulfone polymers were analyzed to determine how they would perform in the space environment. The laminates tested were designed and fabricated so that they had near zero CTEs. Even though thermoplastic composites possessed the performance characteristics desired by satellite designers, the higher processing temperature requirements and increased fabrication costs limited their acceptance.

Despite the fact that thermoplastic matrix materials weren't embraced by the design community, the use of high modulus fibers for dimensionally stable structures was well received. This posed a problem since Dupont had discontinued production of their E series pitch fibers, leaving offshore sources such as the Japanese as the only producers of these materials. A Defense Production Act Title III program was initiated to develop a new domestic source of pitch-based carbon fibers that possessed the high modulus and high thermal conductivity needed for satellite applications. P100 and P120 fibers were the first fibers to be developed under this program. Later efforts improved upon fiber processing methods to yield a higher strength pitch fiber (P100X HTS) that had better handleability without sacrificing the higher modulus. Large quantities of pitch fiber were purchased and made widely available to DOD users with the condition that any data generated through its usage would be reported back to the Air Force.

In 1993 a workshop was held at the Institute for Defense Analysis (IDA) to examine the development needs for a new class of composites based upon cyanate ester resins. AFRL/MLBC along with other government organizations and industry participated in this workshop. Cyanate ester-based composites are processed like epoxies, which makes them affordable, yet they possess the attractive performance characteristics of thermoplastics, including low moisture outgassing and low microcracking. The critical factor identified at this workshop was the need for a statistical properties database. In response, the Structural Materials Branch generated a design-oriented database containing fully characterized mechanical properties pertaining to ultra thin cyanate ester composite laminates made from P100X HTS fibers. The database helped accelerate the acceptance of this new class of materials, which are now the material of choice for many space applications.

Carbon-Carbon Composites: Many of the space systems being developed for SDI during the early 1990's were very large and required extreme pointing accuracies. Coupled with this requirement was the need to withstand directed energy and nuclear threats. AFRL/MLBC initiated five programs to develop carbon-carbon (C-C) composites for survivable and dimensionally stable structures. AFRL/MLBC provided the technologies needed by the Propulsion Directorate (AFRL/PR) for a system that was being developed. In the course of these efforts, thin wall high modulus 2-D C-C structures were demonstrated. Thermal control coatings for space structures were also demonstrated at this time.

C-C composites are desirable for spacecraft usage since their dimensional stabilities are better than other structural materials such as graphite/epoxy composites. This is because the carbon matrix will not absorb moisture, hence the composite doesn't possess a CME. Initially C-C structures were not economically feasible because of their high cost of fabrication. However, the aforementioned programs developed several approaches that dramatically reduced processing costs. C-C also possesses tremendous survivability attributes that were demonstrated in both underground nuclear and directed energy tests. Even when the threat of directed energy or nuclear attack on space structures declined, C-C development continued based upon interest in its extreme dimensional stability.

Using the success of the early SDI programs, AFRL/MLBC initiated a long-range initiative, known as the Lightweight Dimensionally Stable Structures (LDSS) Program, to develop the support technologies needed to transition C-C technology into structural applications. This program employed a building block approach and examined the joining technologies needed to integrate C-C materials into prototype subassemblies. To facilitate design, an extensive material property database was developed for C-C composites. This database addressed C-C containing many of the same leading fiber systems used for space structures made from polymer matrix composites. Applications for several dimensionally stable components were investigated including a metering truss structure and an optical bench.

Thermal Management

Many space structures perform both structural and thermal management roles. For instance, a spacecraft's bus structure usually supports its electronic boxes. These boxes generate heat that must eventually make its way through the structure to a radiator surface. Additionally, with the trend towards higher performance payloads, denser packaging of electronics, and longer mission lives, lightweight materials are needed to dissipate heat energy more effectively than materials used in the past. The development of both high modulus/high thermal conductivity PMCs and C-Cs led to realization that these materials offered substantial weight savings over aluminum thermal management materials. Working with industry as a team, AFRL/MLBC ensured many successful transitions of PMCs and C-Cs for thermal management applications.

Polymer Matrix Composites: In response to major advances in high thermal conductivity fiber and matrix systems seen in the mid 1990's, AFRL/MLBC initiated a pair of programs that examined whether thermal and structural functions of components could be combined to dramatically reduce weight. These

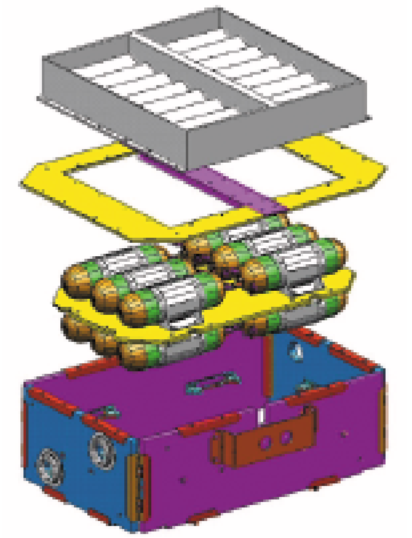

Figure 1. Schematic of Thermal/Structural Battery Panel.

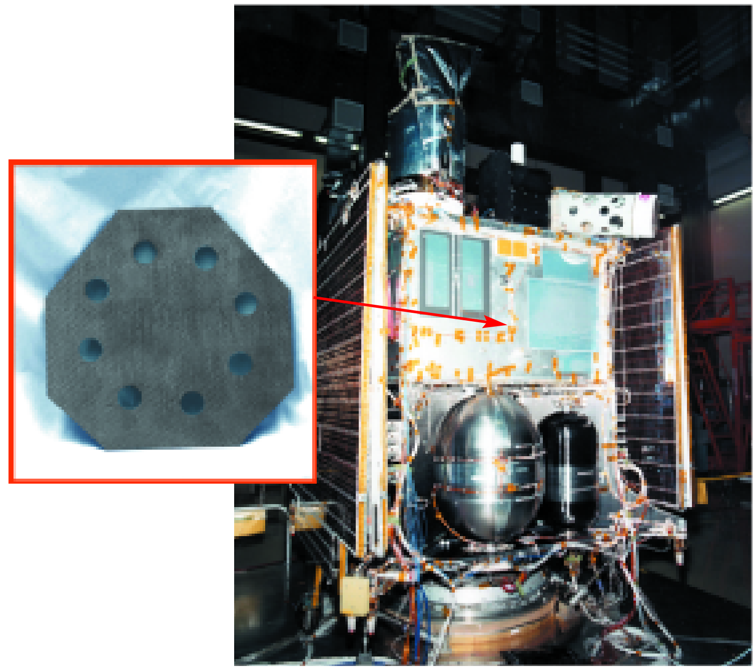

Figure 2. Carbon-Carbon Thermal Doubler on Mar Global Surveyor.

efforts used high thermal conductivity fibers (K13C and K1100) in a cyanate ester matrix to develop and demonstrate affordable, thermally efficient lightweight polymeric composite materials. A prototype radiator panel that provided the required thermal management functions while withstanding launch loads was developed under the first program. This multifunctional panel directly supported nine electronic boxes and weighed one third less than a comparable aluminum design. The second program also utilized thermostructural composites to fabricate a number of flight components for three different spacecraft built at Lockheed-Martin's Astronautics Operation. The components demonstrated include K1100/954-3 radiator fins, a composite battery panel (see Figure 1), and a thermally isolated radiator. Each of the components successfully survived the launch environments, and their in-space performance was consistent with predicted performance.[4, 5]

Carbon-Carbon Composites: Like the PMC efforts described above, C-C composites are excellent materials for thermal applications. PMC and C-C composites can possess equivalent thermal conductivity in the two dimensional plane of the laminate since this property is driven by the thermal conductivity of graphite fibers used. An advantage of C-C is they typically have through-the-thickness thermal conductivities that are a couple of orders of magnitude larger than most PMCs. This is because through-the-thickness conductivity is a property that is highly dependent on the matrix material and carbon conducts heat much better than polymers. A disadvantage of C-C is they are more costly and have mechanical properties that are inferior to PMCs. Thus, C-C technology is traditionally applied in areas where higher conductance is required.

The previously discussed LDSS program examined joining technologies needed to transition C-C into thermal management applications. Thermal components examined under LDSS include thermally conductive battery cases and high temperature radiator fins. As a result of this effort, the materials developed under this program transitioned to components on various flight vehicles. A low modulus, high thermal conductivity C-C thermal doubler flew on the Mars Global Surveyor along with a C-C engine shield (see Figure 2). High modulus, high thermal conductivity C-C composites were used as heat sinks on a Titan instrument subsystem. In addition, the Deep Space 1 spacecraft used a P120/carbon thermal doubler on an optical bench and under multichip modules. The remarkable thing to consider is that high modulus, high conductivity C-C materials were successfully transitioned to flight in just over 10 years from the start of development.[6]

The Carbon-Carbon Spacecraft Radiator Program (CSRP) was a collaborative program between the Air Force, Navy, NASA, and industry that successfully demonstrated a revolutionary radiator panel launched on Earth Orbiter 1 (EO1). This radiator was built to demonstrate that C-C could significantly reduce thermal control costs associated with satellites

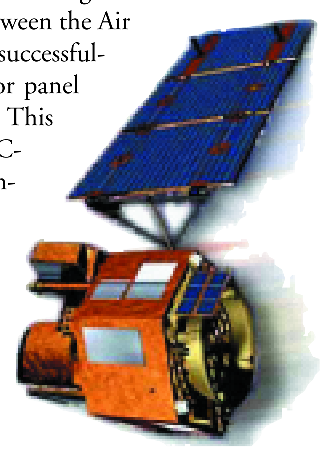

Figure 3. C-C Radiator on EO1.

and possibly extend their operational lives (see Figure 3). For additional information on CSRP, please refer to The *AMPTIAC Quarterly* Volume 2, Number 3.[7]

AFRL/MLBC also developed and demonstrated C-C for heat sinks used in electronic packaging applications and as materials for battery case applications. The effort to develop electronic heat sinks demonstrated an 18% improvement in thermal performance with a 12% decrease in weight over traditional aluminum components. The battery development initiative demonstrated a carbon-carbon multifunctional structure for sodium sulfur (NaS) batteries. Sodium sulfur batteries offer the promise of much higher energy densities than conventional batteries; however, they operate at higher temperatures (roughly 400°C). To further improve the energy density of the batteries being developed, high thermal conductivity 2-D C-C materials for battery cases were developed. These materials are desirable because they are lightweight and chemically inert to the electrolytes. C-C composites not only substantially reduced the weight of the battery case, but their high thermal conductivity eliminated the need for a thermal sleeve that helped isothermalize the battery.

CURRENT PROGRAMS

Dimensionally Stable Structures

Graphitic Foams: Most previous efforts at developing dimensionally stable space structures focused upon tailoring the properties of 2-D laminated composites. One of the earliest attempts at developing a novel material to replace composites for these applications occurred during the early 1990's when an SDI program produced carbon fiber-reinforced carbon foam. While this material exhibited interesting properties it could not be reproduced in usable quantities. Even though the program wasn't entirely successful, it did demonstrate the potential advantages of using a controlled 3-D open cellular graphitic structure with tailored properties in the cell ligaments. Carbon foam is attractive as a structural material because it provides the potential for near net shape parts with near isotropic properties. The initial efforts described above ultimately led to a new class of engineered microcellular materials for structural and thermal applications. Several manufacturers now produce graphitic foam products.

If the mechanical properties can be improved, ultra-lightweight, ultra-stiff carbon foam may be the perfect material for large space mirror structures requiring extreme dimensional stability. The Structural Materials Branch is developing refined foam processing methods with the goal of modifying the microstructure and thus enabling improved compressive, tensile, and shear strengths for mirror and other applications. Additionally, an effort is ongoing to develop the ideal mirror surface. For more information please see the article addressing mirror technologies contained in this issue of the *AMPTIAC Quarterly*.

Thermal Management

Thermal management in the space environment is more critical than in all other environments for two reasons: material density is much more important in space (due to launch costs) and convective cooling is not available. High conductivity materials and active cooling mechanisms employing radiators are used to 'wick' heat away from where it's produced, say for example an electronic box, and allow it to be expelled into space. The Structural Materials Branch is continuing to develop new technologies such as composite heat pipes and highly crystalline graphite that will provide improved thermal management capabilities as compared to current state-of-the-art approaches.

Composite Heat Pipes: Previous AFRL/MLBC efforts have been highly successful at developing composite materials and joining techniques for thermal management applications. However, one of the highest payoff applications for composite materials, radiators, remains unresolved. As satellite power increases, the size of radiators required to emit heat into space through radiative cooling must also increase. To operate at maximum efficiency, heat must be uniformly distributed across a radiator surface. Heat pipes are attached to a radiator panel's surface using a compliant room temperature vulcanizing (RTV) silicone adhesive. The physical contact between the panel and the pipes provides the mechanism for heat to be dispersed into the panel. A critical factor to consider is that the radiator's thermal conductivity must be designed so that the heat will flow away from the heat pipes, thus ensuring a uniform temperature distribution across the radiator.

There are several design factors that must be considered when developing satellite cooling systems. The advantage of using higher conductivity materials is that fewer heat pipes are needed to distribute the heat, which dramatically reduces system weight and complexity. Radiators are normally fabricated by attaching heat pipes to one of its surfaces, which imposes the need for a good thermal joint. However, since two different materials, a composite panel and metallic pipes are used, any change in temperature can cause a distortion of the joint due to differences in the CTE of the two materials. If the distortion causes the heat pipe to pull away from the radiator panel, then heat transfer in that region of the radiator becomes impaired. An additional factor to consider is that a cooling fluid, normally ammonia, is used to transfer heat from where it is generated to the radiator. This requires the pipe to be impermeable and resistant to attack by ammonia.

To further reduce the weight and improve the efficiency of satellite thermal control systems, the Structural Materials Branch has three programs underway that are developing the technologies that will enable advanced heat pipes. Two of these programs are examining a variety of composite heat pipe solutions, including metal/composite hybrids. The third program is investigating heat pipes that are embedded within the radiator panel as well as low CTE metallic pipes.

Some of the composite heat pipe technologies that are being examined include braided carbon/cyanate ester heat pipes, small diameter impermeable glassy carbon in novel radiator designs, pultruded and carbonized carbon/phenolic tubes, both copper and aluminum plated C-C tubes, and a hybrid C-C infiltrated with molten aluminum. Some of these approaches employ grooves machined into the tube wall, known as wick structures, that help return condensed ammonia to an evaporator. Figures 4 and 5 display some of the technologies being

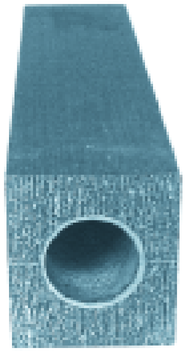

Figure 4. Hybrid C-C Heat Pipe.

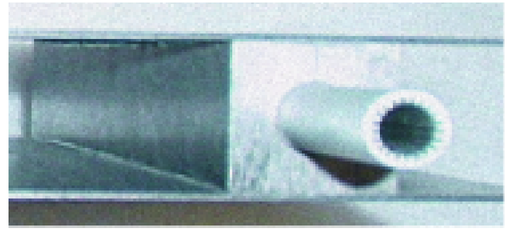

Figure 5. Al Plated C-C with Wick.

considered. As mentioned previously, permeation of the ammonia through the tube is a serious consideration. Nanocarbon particles in the matrix are being investigated as a mechanism that may help decrease permeability.

A partnership between ML and the major spacecraft prime contractors has been established to help resolve key shop floor issues that are common across the industry. This partnership is also examining the issue of the heat pipe/radiator thermal joint. In this program, heat pipes directly embedded into the radiator panel itself are being examined. Other alternatives to resolving the thermal distortion problem, including the use of a low CTE alloy, Invar, for heat pipes are being considered.

Highly Crystalline Graphite: The thermal conductivities of graphitic carbon fibers as measured along the axis of the fiber can exceed that of copper by over three fold. In a composite laminate the amount of high conductivity fiber in any one direction is limited by the composite's construction details and also its fiber volume. As a result, the in-plane thermal conductivity will not approach the axial thermal conductivity of the fiber itself. Planar sheets of graphite offer the extremely high thermal conductivities in two directions that graphitic fibers offer in one direction. However, most of the mechanical properties of graphite are poor in comparison to composites.

The Air Force is striving to exploit the thermal conductivity of planar graphite by using hybrid approaches to improve mechanical robustness. The two approaches currently being considered both involve encapsulating graphite in either C-C, polymer matrix composites, or aluminum. The Space Vehicles Directorate (AFRL/VS) is examining encapsulated annealed pyrolytic graphite (APG), which is manufactured using a chemical vapor deposition (CVD) process. Similarly the Structural Materials Branch is examining encapsulated ThermalGraph®. This product is made using a unique process where raw pitch fibers (before graphitization) are compacted and then graphitized. The process creates a homogeneous graphitic material that depending upon construction details can be highly conductive in one dimension (if the precursor fibers are unidirectionally oriented before compaction) or has good in-plane thermal conductivity (if chopped precursor fibers are randomly oriented). Both AFRL/VS and AFRL/MLBC are examining application of these materials in lightly loaded applications such a thermal doublers or thermal planes (heat sinks for electronics). Figure 6 shows a heat sink made from ThermalGraph® encapsulated by aluminum.

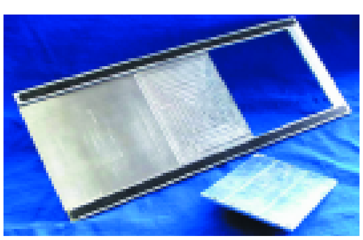

Figure 6. ThermalGraph Heat sink.

Graphitic Foams: Graphitic foams promise tremendous weight savings over conventional materials used in thermal management applications. These materials exhibit thermal conductivities similar to many aluminum alloys at 1/5th the density. Current research efforts are investigating the use of graphitic foam for various thermal management components such as high performance heat sinks used in electronics and as a core material to replace aluminum honeycomb in sandwich panels for structural radiators. The thermal and weight advantages of graphitic foams are so immense that the Air Force is also investigating the use of graphitic foams in heat exchangers for aircraft applications. Figure 7 shows the cellular microstructure of high-density foams.

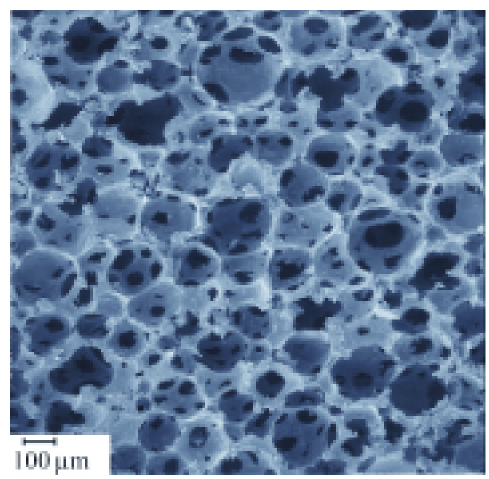

Figure 7: High Density Graphitic Foam.

Nanotailored Composites

Advanced capabilities needed to enable the next generation of satellites will come from multifunctional composites. Nanotechnology offers the potential to combine functions without sacrificing structural performance that designers expect. For satellite applications, AFRL/MLBC is developing nanotailored materials with both thermal and electrical conductivity, which can be processed using traditional composite fabrication tech-

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niques. The following sections describe current efforts.

Nanolayered Silicates: Nanotechnology may provide the ultimate means of tailoring a material's microstructure and properties to yield dimensionally stable structures. Conventional polymer matrix composites have many strong attributes but there are some issues that limit their use for dimensionally stable structures. Matrix microcracking and CTE mismatch between the fiber and matrix are two factors that can reduce a material's dimensional stability when subjected to temperature cycling while in orbit. Incorporating nanoscale reinforcements into the matrix resins used to fabricate PMCs may improve these tendencies and subsequently enable wider use of PMCs for critical applications.

AFRL/MLBC is investigating the potential for nanotailoring of a composite matrix to preclude or reduce microcracking and CTE mismatch issues. This is not a trivial endeavor and as such, some basic research must be undertaken to investigate critical issues. Current efforts are examining the effect of the nanoconstituents on polymer resin viscosity. Nanoscale reinforcement and interface properties are also being characterized. In a related effort, AFRL/MLBC is developing modeling techniques to address the enhancement of composite properties resulting from nanoscale reinforcements. The ultimate goal is to apply this basic knowledge obtained under these programs to both dimensionally stable structures and possibly also to thermal management materials.

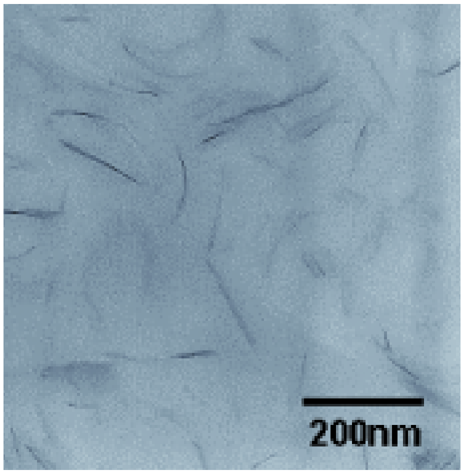

Figure 8. Nanolayered Silicates in Epoxy.

The nanoscale reinforcements currently being considered are hydrated aluminosilicate platelets roughly one nanometer thick. AFRL has been investigating nanocomposites based upon these materials for quite some time[8, 9, 10]. This new initiative builds upon the earlier work and is concentrating upon using smaller quantities of nanoscale particles as a complement to a composite's traditional fiber reinforcement. The challenge of this research is to uniformly disperse the particles and prevent them from agglomerating. While other organizations have overcome these problems in thermoplastic resins, it appears that AFRL/MLBC will be the first to achieve a uniform distribution in thermoset materials key to aerospace applications. Figure 8 shows a photomicrograph of nanolayered silicates (dark phase) distributed in epoxy.

Nanofibers: The Structural Materials Branch is currently investigating the use of vapor grown carbon nanofibers as a means of improving the thermal and electrical conductivity of polymers. These efforts revolve around the use of Pyrograph-III®, a carbon nanofiber produced by Applied Sciences Corporation, which has an axial thermal conductivity roughly five times greater than copper. Pyrograph-III®is a multi-walled nanotube (or nanofiber) that are produced with random diameters that range from 40 to 200 nanometers. The aspect ratios of these fibers are quite large (see Figure 9).

Pyrograph-III® nanofibers are commercially available in large quantities. When dispersed in a polymer matrix, the small diameters and large aspect ratios of these fibers enable them to contact each other and create a network at a relatively small volume fractions of fibers (<5%). This network greatly increases the thermal and electrical conductivity of the base polymer. Current research has focused upon making the nanocomposites discussed above. However, similar to efforts involving the hydrated aluminosilicate platelets discussed earlier, Pyrograph-III® dispersed in small quantities within matrix resins may enable an order of magnitude increase in the through-the-thickness thermal conductivity of polymer matrix composites.[11] Similarly, small additions of these nanofibers to adhesives may greatly increase thermal conductivity.

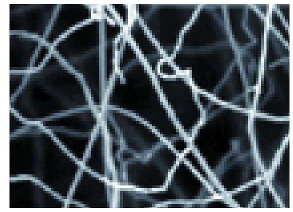

Figure 9. Multi-walled Carbon Nanotubes.

SUMMARY

The AFRL Materials Directorate's Structural Materials Branch has a long history of developing thermal and structural materials for use in satellites. Following this legacy the current diverse and robust research program is helping develop technologies that will enable the next generation of satellite structures. Although not discussed in this article, AFRL/MLBC is similarly focused on developing technologies for space launch applications. Materials being developed include composites for cryogenic tanks and C-C thermal protection materials. An example of this work is the ongoing examination of nanolayered silicates to reduce permeability of cryogenic fuel tanks.

Building upon the successes mentioned above, AFRL/MLBC plans to continue development of hybrid materials, multifunctional structures, and nanocomposites. A new program starting Fall 2004 will examine advanced multifunctional structures. To-date most multifunctional materials have combined thermal and structural functions. This new program will examine whether other functionalities such as electro-static discharge (ESD) protection or electromagnetic interference (EMI) shielding can be built into the structure. Adding additional functionalities creates opportunities for further reducing the weight of space structures, thus enabling increased mission capabilities through the use of additional sensors, transponders, and other systems.

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Mr. David H. Rose has been with AMPTIAC since its beginning in 1996, and has been its Director since June of 1998. Prior to AMPTIAC, he was an officer in the US Air Force, retiring in 1996. During his Air Force career he worked in a variety of technical and acquisition roles including five years at the Materials and Manufacturing Directorate where his research interests included micromechanical analyses of composite materials. He has a BS in Mechanical Engineering from the University of Washington, an MS in Mechanical Engineering and has completed his PhD coursework in Materials Engineering from the University of Dayton.

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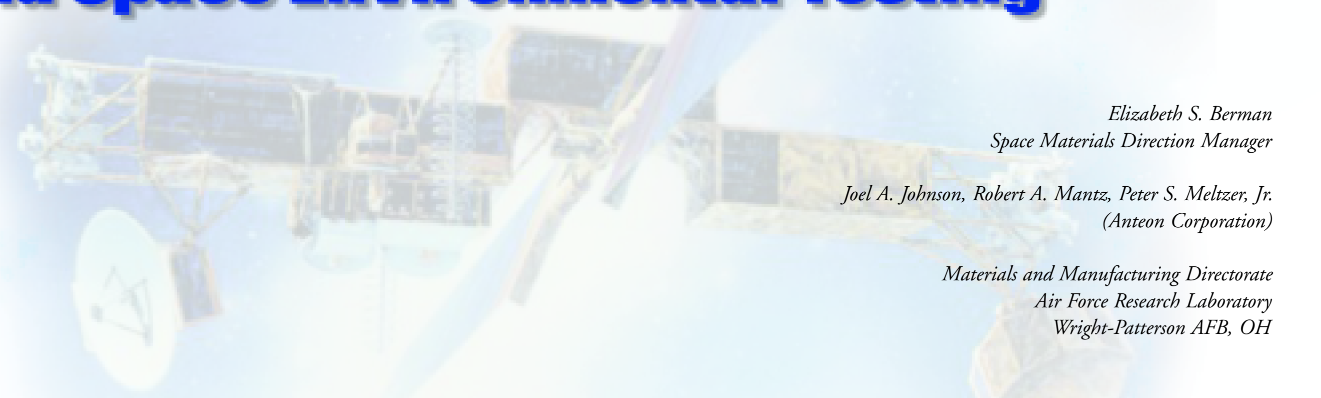
Spacecraft Materials Development Programs for Thermal Control Coatings and Space Environmental Testing



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INTRODUCTION

From planet Earth, the boundlessness of space may seem tranquil enough, yet this same environment is filled with a potentially deadly array of problems for both manned and unmanned spacecraft. Even before mankind soared into the heavens, scientists and engineers knew space was a harsh environment, prone to remarkable fluctuations in radiation levels and temperature, either of which by themselves, or in combination, could cripple or disable a spacecraft over a period of time, or even instantaneously. One of the crucial challenges was finding efficient and cost effective ways to protect a spacecraft's critical subsystems (e.g., power supplies, life support systems, sensitive electronics, communications equipment and sensors), as well as the spacecraft structure, from an unforgiving and dynamic environment.

Protecting spacecraft and their working components from the harmful effects of extreme temperatures (a prime concern of design engineers) is no simple task. This is the main function of the spacecraft's thermal control system (TCS). A well-designed and properly operating TCS is essential to any spacecraft, given the varying amounts and forms of thermal energy bombarding it at any given time. The principal forms of energy include solar radiation, albedo (electromagnetic radiation reflected off of spacecraft surfaces), heat generated by onboard equipment, and earth-emitted infrared (IR) rays [1].

The challenges imposed by the harshness of space become even more pronounced when one considers the extreme shifts in temperature endured as orbiting spacecraft repeatedly pass through day and night, a scenario referred to as "thermal cycling." A satellite in low-earth orbit, for example, must survive temperature swings from –80 to +80° Celsius (a range of about 288° Fahrenheit) approximately every 90 minutes; not once, but tens of thousands of times during its operational lifetime, all while continuing to perform its mission!

A spacecraft's TCS can be categorized as *passive*, *semi-passive*, or *active*. The most prevalent of the three forms of thermal control for space environments, *passive* subsystems were initially developed in the 1960s, relying heavily on reflective coatings such as paints and mirrors. Passive subsystems may also employ multilayer insulation (MLI), phase-change devices, and radiators. *Semi-passive* subsystems go one step further, incorporating simple temperature-activated controls to open or close conductive paths. Heat pipes and louvers are sometimes used in semi-passive subsystems [2]. *Active* subsystems, by comparison, use heaters and mechanical refrigerators, while *advanced* active subsystems would have the ability to change a spacecraft's heat rejection capability as required in real time. This article limits its discussion to the work of the Air Force Research Laboratory's Materials and Manufacturing Directorate (AFRL/ML) in passive and active thermal control systems.

TCS can vary from one spacecraft to another, depending on the spacecraft's mission and other key factors. However, all share the basic objective of maintaining equipment temperature in a specified range throughout a spacecraft's mission life, thus ensuring optimum performance when equipment is operating, and avoiding damage when not in use. The thermal control function ensures stable temperature levels for delicate electronics and optical components, minimizes temperature gradients between units and along structural elements, and maintains boundary temperatures at interfaces between subsystems[3] (please refer to the sidebar in this article for more information about heat transfer fundamentals).

MATERIALS AND MANUFACTURING DIRECTORATE'S CRITICAL ROLE

Thermal control technologies are developed through careful design, analysis, and testing, and by determining and managing the factors that influence mission success. All of this must be accomplished using available resources within the constraints of the space environment [4].

Scientists and engineers at the Air Force Research Laboratory's Materials and Manufacturing Directorate (AFRL/ML) at Wright-Patterson AFB, OH are currently involved in multiple highly innovative research and development programs aimed at improving thermal control technologies. Through in-house efforts and contracted work with industry, they hope to increase the operational life for spacecraft in geosynchronous earth orbit (GEO) threefold. This translates into a service life increase from an average of five to seven years to a minimum of 15 years. At the same time, they are trying to realize these improvements, while significantly upgrading system performance to meet the needs of smaller, higher-powered satellites and other advanced space-based systems envisioned for the 21st century.

THERMAL CONTROL COATINGS RESEARCH AND DEVELOPMENT

The Directorate's *in-house* research and development effort in passive TCS, "Improved Passive Thermal Control Coatings," is being funded by the National Aeronautics and Space Administration (NASA) and executed by the Directorate's Coatings Research Group. The Directorate's *external* research and development efforts in active TCS include: "Conducting Polymer Electrochromic Cell Thermal Control Surface" and "Selectable Wide-Range Epsilon and Alpha Thermostate via Electronically-Controlled Reflectance (SWEATER) for Spacecraft," currently underway at Physical Sciences Incorporated (PSI), and the "Conformal Appliqué for Thermal Control in Space" research and development effort at Sensortex, Inc. The last two are Air Force Small Business Innovation Research (SBIR) projects.

Passive Thermal Control

Current state-of-the-art thermal control systems for spacecraft use passive technology. The absorptance (i.e., amount of solar energy absorbed and turned into heat) and emittance (i.e., capacity to emit IR energy for cooling) of these materials is fixed at the time of application and are a function of the raw materials used and the processing techniques employed in applying them to the space hardware. The primary change that occurs to these materials in-service is degradation of the physical and optical properties due to the harsh space environment. For passive thermal control paints, the change in solar absorptance goes from initial values of 0.15-0.20, to final values in excess of 0.4 after five to seven years of service. For a long in-service life, the TCS must be designed for the higher absorptivity value (i.e. 0.4), which means a larger, heavier, more expensive TCS.

Researchers in ML's Nonmetallic Materials Division (Nonstructural Materials Branch) are actively engaged in an in-house research project, co-funded by NASA, to improve the performance of passive thermal control coatings (TCC) through weight reduction and improved end-of-life properties*. The researchers are working to reduce film thickness and lower the specific gravity (i.e., density) of the coating. They are also working to improve end-of-life solar reflectance properties by using materials with lower overall solar absorptance, and which do not degrade significantly when exposed to the space environment. Improvements in end-of-life properties will lead to additional weight reductions, given the smaller thermal radiator surface area required.

Since it is very difficult to qualify new materials for space applications, the in-house research team has begun by optimizing passive TCCs through formulation changes of existing material combinations. A diffuse reflective coating, for example, requires a binder (typically made of potassium silicate or methyl silicone) and a pigment with a high refractive index (such as zinc oxide) to scatter incident radiation back out of the film, so that it does not pass through and possibly become absorbed by the substrate. These coatings are noticeably bright white in appearance. For a given combination of materials, the scattering efficiency (i.e., the percentage of incident light that gets reflected per unit film thickness) is dependent upon two major factors: the pigment volume concentration (PVC) and the pigment particle size distribution. Intuitively, as the PVC increases, one would expect the scattering efficiency to increase. However, after a certain PVC is reached, there is a point at which the pigment particles begin to crowd together and the scattering efficiency is actually *reduced*.

Continuing to even higher PVC's, there is a point at which there is just enough volume of binder present to fill-in the interstitial volume between the pigment particles, referred to as the critical PVC or CPVC [5]. At PVCs above the CPVC, voids are now present in the film due to the insufficient volume of binder present. These voids assist in the scattering of incident light and the efficiency suddenly increases once again; however, this is often at the price of poor physical properties

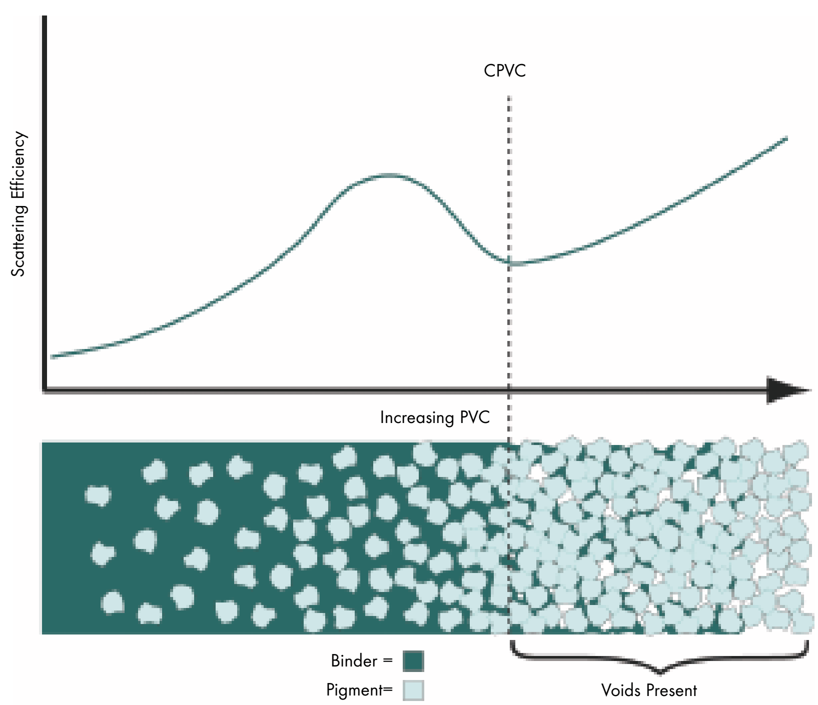

Figure 1. Scattering Efficiency is a Function of Pigment Volume Concentration.

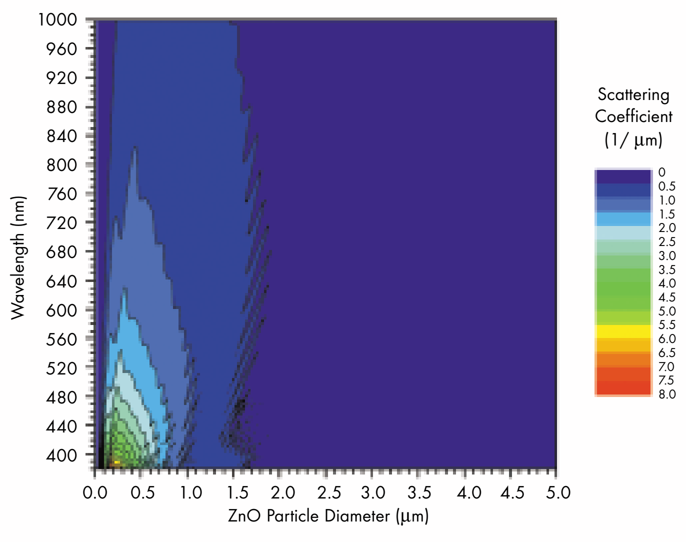

Figure 2. Scattering Coefficient is a Function of Both Particle Size and Incident Wavelength.

due to the very small amount of binder present. Figure 1 depicts this relationship.

The current passive TCC in widespread use is very porous because it is formulated above the CPVC. These porous surfaces are easily contaminated by dust and oils that are extremely difficult to remove and can significantly increase solar absorptance. ML researchers are investigating coatings formulated *below* the CPVC to reduce porosity, while maintaining the ability to use minimal film thickness. An added benefit is that the weight of films with identical thickness is lower because there is a lower volume concentration of the high-density zinc oxide (ZnO) pigment.

The particle size of the pigment also plays an important role in light scattering efficiency. The researchers have used Mie scattering theory[6] to determine the optimal particle size of ZnO pigment to be used in a thermal control coating (TCC) (Figure 2). The results of the modeling indicate the optimal particle size of ZnO is between 0.25 and 1.50 microns. Particle size analysis of the ZnO pigment currently in use showed the presence of ZnO particles and clusters between three and five microns. Since then, ML researchers have investigated the performance of a ZnO pigment whose size falls within the optimal range and have obtained coatings with equivalent solar reflectance values using thinner, lighter weight films. These coatings are being evaluated for accelerated exposure durability.

One of the disadvantages of using a high refractive index material like ZnO as a pigment is the associated strong UV absorption characteristic. A significant amount of solar energy resides in the UV region (200-380 nanometer (nm) wavelength) and coatings that use ZnO absorb nearly all of this energy, which can be transformed into heat or ultimately lead to the chemical degradation of the TCC. An ideal TCC would reflect all incident light ranging from UV to visual (VIS) to near infrared (NIR). Unfortunately, there is a very limited selection of space-stable coating materials that are UV-transparent; thus innovative methods are needed to obtain such highly reflective coatings.

One method of achieving this is to introduce voids (in a controlled manner) into the binder. In this case, scattering is the result of the binder-void refractive index difference rather than the binder-pigment difference. ML researchers are investigating synthesis of hollow silica (SiO_2) spheres of appropriate size for this purpose. When incorporated into a UV-transparent binder such as potassium silicate, the internal voids of the hollow silica spheres promote scattering without introducing film porosity. Additionally, because silica is also very UV-transparent, this coating design would be capable of extended reflection into the UV region (Figure 3). Since almost no incident solar energy would be absorbed, there should be little driving force for exposure degradation either. While coatings using this technique may require a larger film thickness, the overall weight would be lower due to the use of voids in place of a dense pigment. The result of these research efforts will be a TCC that has lower overall solar absorptance and weight, while lasting longer than the current state of the art coating.

Active Thermal Control

Due to passive thermal control's limitations, there is a strong need for *active* thermal control in some spacecraft. Active thermal control manages the effects of sudden changes to incident radiation experienced in the space environment. Active spacecraft TCS responds in real-time to these changes by adjusting the level of power-assisted cooling. Active thermal control can offer several advantages over passive thermal control. First of all, large temperature swings in a spacecraft, resulting from sudden changes in the space environment, can be reduced to just a few degrees. While there are no power requirements for passive TCCs, the power requirements for active devices (currently under development) can be reduced by at least one order of magnitude over current state-of-the-art systems, (e.g. louvers). ML presently has three contractual programs under way to develop these devices.

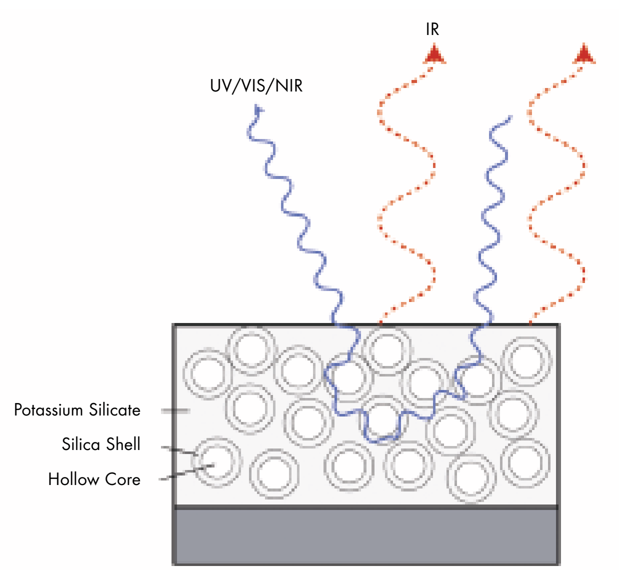

Figure 3. Schematic Cross-Section of a Thermal Control Coating that Uses Hollow Silica Particles to Backscatter Incident Solar Energy via the Presence of Controlled Voids.

Variable Emittance Materials Using Conducting Polymers

The first contractual effort involves variable emittance materials. The program is entitled "Conducting Polymer Electrochromic Cell Thermal Control Surface" and focuses on conducting polymer materials for the electrochromic stack supporting the variable emittance function. Under this concept, changes in emittance are performed in real time using the electrochemistry of the selected materials through an applied voltage. To date, this research and development effort has successfully demonstrated the proof-of-concept, and has also completed the cell design. Development of solid-state electrochromic devices with electronic leads and connectors is under way, including the development of the device's outer window.

Voltage cycling stability testing is also under way. Space environmental effects materials qualification testing has yet to be completed. Passive space flight testing for a minimum of three years in duration is in progress on the International Space Station as part of the Materials on the International Space Station Experiment program (MISSE) and active space flight testing opportunities are currently being considered.

Selectable Wide-Range Epsilon and Alpha Thermostat via Electronically-Controlled Reflectance (SWEATER)

SWEATER is the Directorate's second contracted active thermal control device R&D effort. The objective of this Space-Based Infrared (SBIR) program is to develop space-stable thin-films, and to build and optimize prototype active thermal control devices for both variable absorptance, and variable emittance. Phase I of the SBIR was implemented to identify potential candidate materials. Phase II, recently initiated, will further develop these materials into viable devices and will include simulated space flight testing.

The SWEATER program could lead to significant improvements in spacecraft thermal management by reducing temperature variation, heater power, weight, and cost with the additional application of IR signature control. To date, this program has successfully demonstrated the feasibility of the variable solar absorbtance device concept, including the reversible electrodeposition of reflective metal ions. The team has demonstrated that the lower and upper limit-controlled solar absorptance is dependent upon the quality of metal ion deposition. The research team has analyzed the feasibility of the variable emittance device concept using computer modeling and further analysis is also planned.

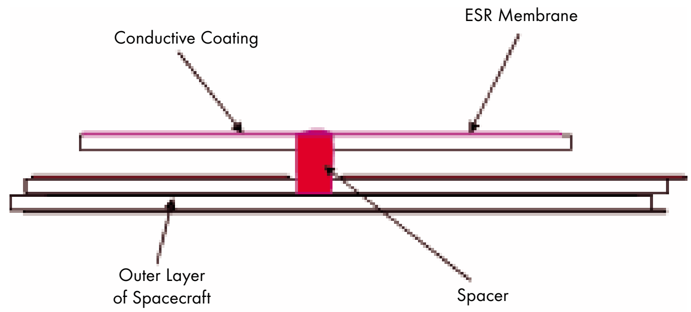

Figure 4. Micro-ESR Structure[7].

Conformal Appliqué for Thermal Control in Space

The objective of the third effort, the "Conformal Appliqué for Thermal Control in Space" SBIR program is to develop an electrostatically switched radiator (ESR) appliqué for tunable emittance (between 0.2 and 0.8). The appliqué system is expected to provide a minimum of 15 to 20 years in-service thermal management within the low-earth to geosynchronous environments, superior heat transfer between the spacecraft and the external space environment, and improved cost-effectiveness. Phase I of this program identified potential candidate materials. The goal of Phase II (recently initiated) is to further develop these materials into viable devices, complete simulated space flight testing and, if possible, undertake and complete actual space flight testing in conjunction with NASA's ST-5 space flight experiment.†

The ESR operates by actuating a thin compliant membrane, typically a thin polymeric film, in and out of contact with the surface of the spacecraft using an applied voltage (see Figure

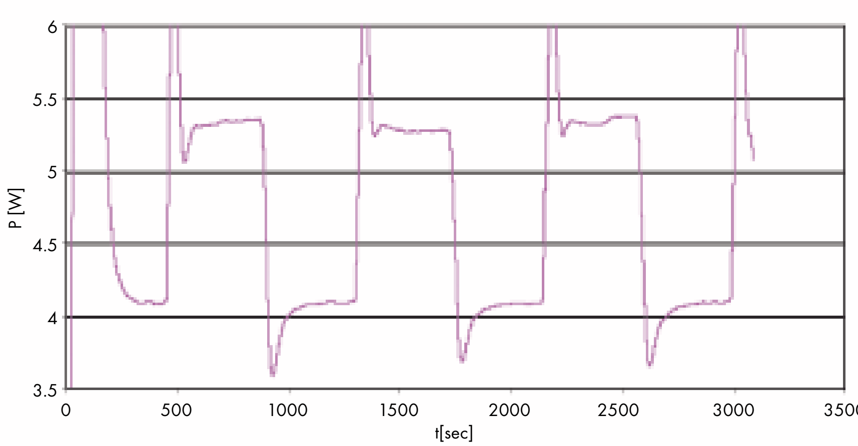

Figure 5. Results on Conductive Membrane with Insulating Base. This is a Plot of Radiated Power versus Time, with Voltage being Alternately Applied to the Sample (Higher Power) and Removed (Lower Power).

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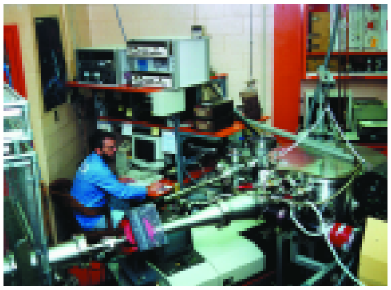

Figure 6. Materials and Manufacturing Directorate's Space Environmental Effects Test Facility.

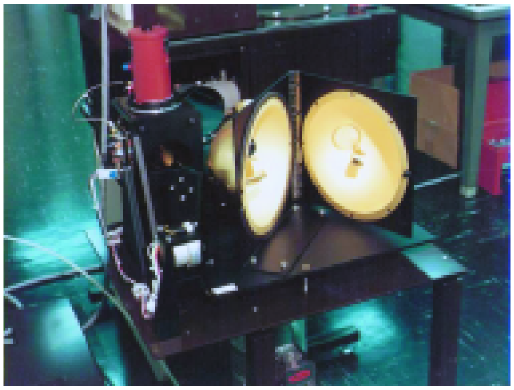

Figure 7. Optical Measurements Facility with Front View of the Facility's Spectrophotometer.

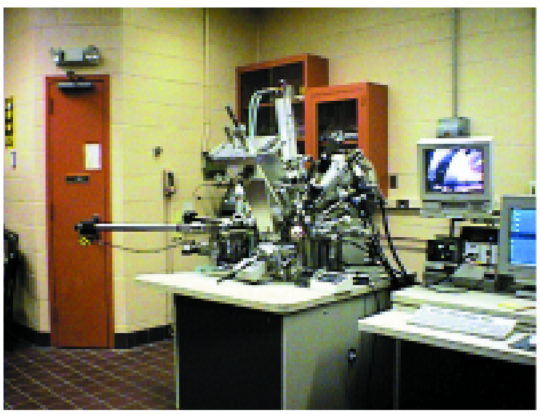

Figure 8. Materials Characterization Laboratory Showing X-Ray Photoelectron Spectroscopy (XPS) Instrument.

4). When in contact, heat is conducted from the spacecraft skin to the radiation membrane, where it is radiated out to space. Without the applied voltage, the membrane loses contact, stopping heat conduction, and thereby reducing the emitted radiation. There are very stringent requirements for this membrane. It must be very thin and flexible to ensure low operating voltage requirements. At the same time, it must have high thermal absorption (emissivity) with low optical absorption, and must also have an outer conductive layer.

A larger ESR device, previously developed on another program, uses a conductive paint to apply voltage to the membrane, which is satisfactory for those devices but is too thick for the desired micro-ESR that this program is centered around; hence, other options are being investigated. The most promising alternative is the use of a transparent conductor,

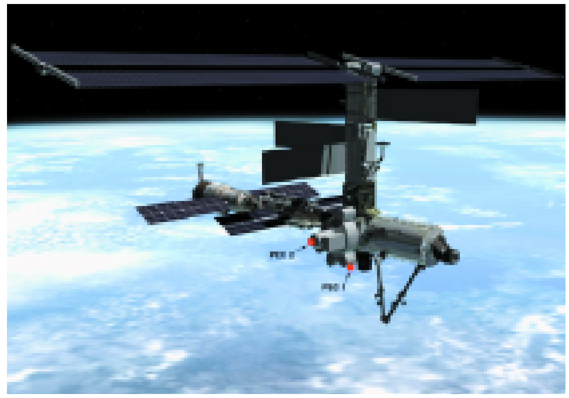

Figure 9. Location of Two Passive Experiment Carriers (PECs) on International Space Station.

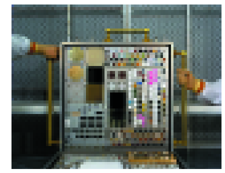

Figure 10. PEC Showing Specimens.

such as indium-tin-oxide (ITO), over-coated with an anti-reflection coating. This formulation results in a visually transparent film with high emissivity. A second approach uses a polyimide layer filled with conductive carbon black. Along with a high emissivity, this structure unfortunately also has a high solar absorption, making this approach unsuitable for use in actual devices but suitable for demonstrating proof-of-concept. Thus far, the experimental results for this approach have been encouraging.

The ESR system requires a space environment to operate; therefore, it is necessary to simulate these conditions for testing. A contractor has developed an experimental chamber, which employs an "Emissivity Measurement System" for this purpose. This is a calorimetric system, whereby lost heat is measured by the amount of electrical heat required to maintain the sample at a constant temperature.

Measurements on a carbon black filled membrane, using this space-like environment test, are shown in Figure 5. Since the carbon filler makes the sample conductive, no additional electrode is required. Voltage is alternately applied to the sample (high radiated power) and removed (low radiated power). This shows a change in radiated power of 1.22 watts with electrical switching, with an effective change in emissivity of 0.5. These test results are actually quite good in comparison to existing technologies. However, changes in the film thickness and composition, planned during Phase II of this SBIR program, should improve performance even more – perhaps with emissivity changes of up to 0.8, resulting in effective emissivities ranging from 0.1 to 0.9.

SPACE ENVIRONMENTAL EFFECTS CHARACTERIZATION

The Directorate's testing facilities consist of three components: (1) the space environmental effects test facility (Figure 6), (2) the Optical Measurements Facility (Figure 7); and (3) the Directorate's Materials Characterization Laboratory equipment (Figure 8). The space environmental effects test facility simulates the GEO environment, approximately 22,000 miles above the Earth's surface, complete with ultraviolet (UV) radiation and electron exposures. Pre- and post-measurements of the simulated space environment are performed in the Optical Measurements Facility and the Materials Characterization Laboratory. Actual onboard space environmental testing of new materials is conducted as space flight opportunities are available. Many new thermal control materials are currently being tested on MISSE, managed by ML in conjunction with NASA and industry (Figure 9 and Figure 10) [8].

CONCLUSION

The Air Force is much better positioned to meet its major objectives for the 21st century through enabling ML programs in thermal control coatings and space environmental testing. ML is actively supporting the Air Force's migration to space, and innovative research and development programs are in place to meet both near and long-term Air Force spacecraft needs for thermal management. Both programs have the potential to dramatically improve the performance and durability of space-based systems supporting the Air Force mission.

Continuing research and development in these technologies is critical to qualification and implementation of improved passive and active thermal control systems. Innovations in thermal control technology for spacecraft will have positive implications for the private sector as well, directly impacting the expected lifetime of commercial satellites.

NOTES AND REFERENCES

* Thermal control systems are designed to fully protect spacecraft for the entirety of its service life. To do this, engineers must account for how much the TCS' protective capabilities degrade over that time, and size the system based on the predicted properties at the *end-of-life*. This means that most TCS are over-designed to insure thermal protection through end-of-life (degrading from a performance level of 'extremely good' to 'adequate'). If future TCS are made to degrade less, than it won't be necessary to overdesign their systems as much, saving

Heat Transfer Mechanisms

Thermal control of spacecraft is all about managing heat transfer into and out of systems and vehicles. For the uninitiated, we offer this brief primer on the major modes of heat transfer and what role each plays in thermal control management.

There are three major modes of heat transfer: *conduction*, *convection*, and *radiation*. Conduction is the primary mechanism by which heat propagates through solids. The second law of thermodynamics dictates that heat travels from a hotter point to a colder point. With few exceptions, the temperature gradient through a solid is linear in profile (Figure A).

Convection is the primary mechanism by which heat propagates from a solid via moving fluids (both liquids and gases). Convective heat transfer rates tend to be several orders of magnitude higher than conduction for similar temperature gradients (Figure B).

Radiation is the most complex (and least understood) of the three mechanisms. Unlike conduction and convection, radiation does not require matter as a transfer medium (it's actually more efficient in a vacuum). Moreover, conductive and convective heat transfer are exclusively driven by the size of the temperature gradient across the transfer area – radiant heat transfer depends not only on the gradient, but on the absolute temperature of the source material as well. While any electromagnetic transmissions, from cosmic rays to radio waves, may be classified as radiation, only those in the wavelength range of 100 nm to 100,000 nm (from near-UV through visible light to IR) may be considered *thermal* radiation. For an exposed spacecraft component, the incoming thermal

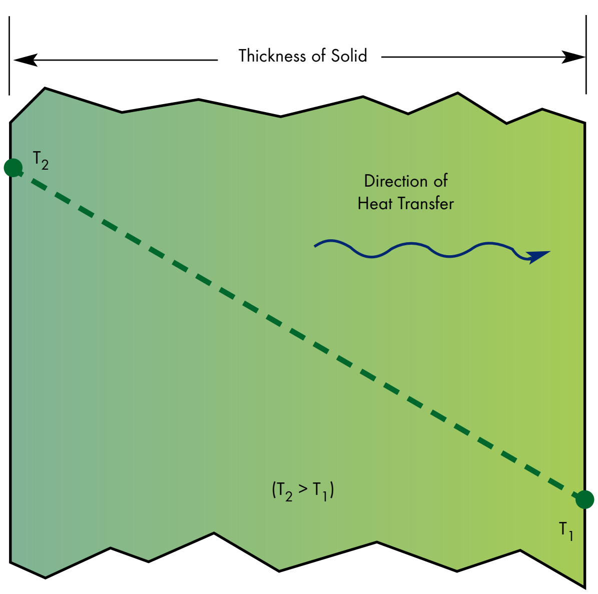

Figure A. Conductive Heat Transfer.

money and improving reliability.

† Part of NASA's New Millennium Program to develop and test advanced technology in space flight, Space Technology 5 (ST-5) is an effort to fabricate microsatellites. The mission, scheduled sometime in 2005, will launch multiple miniature spacecraft (known as *small-sats*) to demonstrate and flight-qualify several leading edge technologies which measure solar and magnetic effects in the atmosphere.

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[6] C.F. Bohren, and D.R. Huffman (1983) Absorption and Scattering of Light by Small Particles. John Wiley & Sons, Inc.: New York, NY. (Note: The Mie scattering theory is a comprehensive mathematical-physical theory pertaining to the scattering of electromagnetic radiation by spherical particles, developed by Gustav Mie in 1908)

[7] W. Biter, "Thermal Control Using Multi-Spectral Switching" (Micro-ESR structure drawing), http://www.winbmdo.com/scripts/sbir/abstract.asp?log=0159&Phase=1&Ph1Yr=96&firm_id=2096&int=96

[8] "Overview: Spacecraft Materials Development Programs for Thermal Control Coatings & Space Environmental Testing" (briefing photos), Air Force Research Laboratory Materials and Manufacturing Directorate, March 14, 2003

radiation (mostly from the sun) is either absorbed by the constituent material (which heats it up), reflected back off into space, or is transmitted through the medium. These three characteristics are known as *reflectivity*, *absorptivity*, and *transmissivity*, respectively (Figure C).

Heat Transfer in the Space Environment

For Earth-orbiting space systems, thermal radiation is the primary heat transfer mechanism (conduction is an important secondary one). Convection is negligible in the vacuum of space. As an object in space absorbs radiant energy, the object's temperature begins to rise. Simultaneously, the object emits some of this energy back out into space as thermal radiation – this property is known as *emissivity* (ε). The amount of radiation emitted is a direct function of the object's temperature. As the object's temperature increases, so does the emittance. The object's temperature will rise until eventually the absorptance rate equals the emittance rate – at this point, the object has reached an *equilibrium temperature*.

Each TCS uses these principles to serve their own application: some systems are designed to cool components, others to heat them, and still others to maintain temperatures in some critical range. AFRL/ML, NASA, and industry must examine each application carefully and devise a strategy that best protects the vehicles and ensures the continued nominal performance of their subsystems.

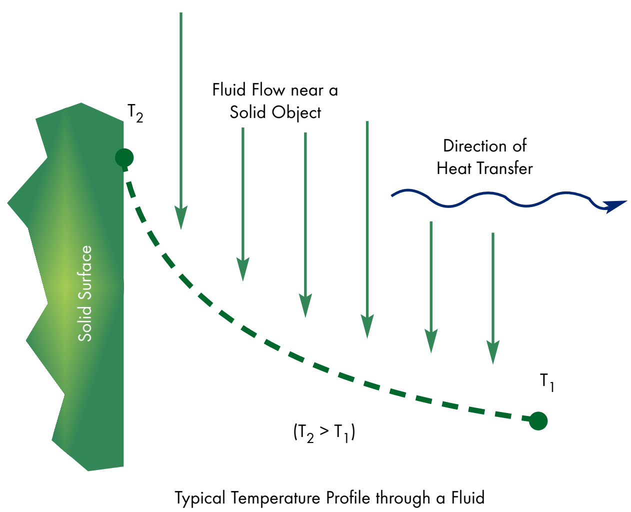
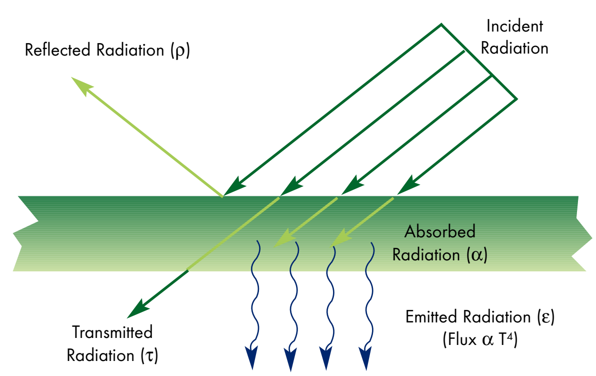


Figure B. Convective Heat Transfer.



For any given unit of incident radiation, the following relationship is true:

$$\rho + \tau + \alpha = 1$$

Figure C. Radiant Heat Transfer.

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Advanced Materials and Processes for Large, Lightweight, Space-Based Mirrors

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The use of monolithic glass to produce large, rigid segmented members for lightweight space-based mirror systems has reached its limit due to the long lead times, high processing costs, and launch load/weight requirements. New material solutions and manufacturing processes are required to meet the Air Force's directed energy weapons, reconnaissance/surveillance, and secured communication needs. Mirror structural substrates made out of advanced composite materials (metal, ceramic, and polymer), foams, or microsphere arrays should allow for CTE and modulus tailorability, low-density, high strength, stiffness, and toughness. Due to the multi-phase complexities of these new systems, mechanical polishing will be difficult. This article introduces some of the issues surrounding the materials and processes traditionally used to fabricate mirrors for space applications, and also covers the evolution from conventional materials and processes to newer concepts for use in space-based mirrors. Selected material and process approaches are detailed as well.

THE NEED FOR ADVANCED MATERIALS AND METHODS

Large, lightweight, high precision mirrors are critical for enhanced surveillance/reconnaissance missions, directed energy weapons and communication systems, laser radar systems, X-ray and UV telescopes, as well as large astronomical telescopes. The Department of Defense (DOD), the National Aeronautics and Space Administration (NASA), and other US Government agencies have developed concepts for airborne and space-based systems that will require mirrors ranging in size from 0.1 to 100 meters in diameter. In all of these applications, mass, size, natural frequency, and reliability are major issues due to launch and flight constraints as well as anticipated life times.

Cost, production infrastructure, and scheduling have also become important technology drivers in some missions where large surface area mirrors are needed. For example, a primary mirror for an airborne directed energy system might consist of a monolithic design with a diameter up to 1.5 meters (allowing it to fit inside existing airframes). In such a case, the mirror is shielded or encased within the airframe, thus the mirror's fracture toughness would not be a major issue. In such circumstances, existing lightweight glass mirror technology might suffice[1]. In contrast, a space-based directed energy system would require a constellation of very large mirrors, 10 to 15 meters in diameter. They would use a segmented design with segments no larger than roughly 3.25 meters (so they could be stowed in the Space Shuttle cargo bay or a launch vehicle shroud). Once launched to proper orbit, these segments would need to be assembled or deployed. To meet the payload weight constraints of launch, the mirror would also have to be very lightweight (with an areal density (mass per unit surface area) of less than 15 kg/m^2). The reliability and robustness of these mirror sections are major concerns because they would be unshielded (open to the space environment) and thus subject to high launch loads, in-space assembly damage, and micrometeor impacts. Most likely, monolithic glass mirrors would not be able to meet these requirements; hence the need to develop advanced mirror materials and design practices.

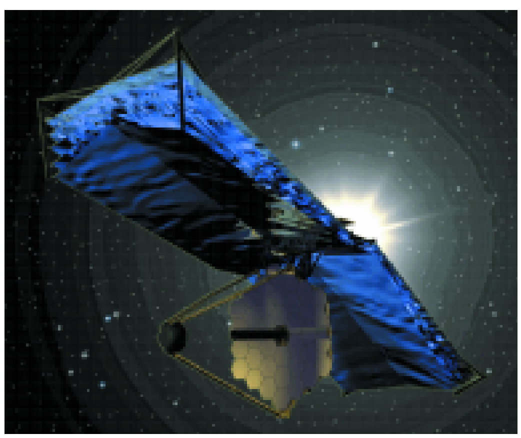

Image courtesy of NASA

Figure 1. James Webb Space Telescope – Being Constructed to Replace the Hubble Space Telescope.

To meet the anticipated demand for space-based applications, the US industrial base of aerospace contractors would require the capacity to manufacture approximately five to seven 10-meter diameter primary mirrors (segmented) per year for a period of 15 or 20 years. Unfortunately, the infrastructure needed to meet such a large production quantity does not currently exist in the US. Therefore, substantial government and corporate investment would be required to meet this goal. Some of this infrastructure investment could be shared by NASA, as long as common goals could be achieved (e.g. the mirrors could be cooled to cryogenic

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temperatures without increasing their figure or finish distortions). They could be employed in systems such as the James Webb Space Telescope (Figure 1), which is envisioned to replace the Hubble Space Telescope.

TRADITIONAL MATERIALS AND PROCESSES

Monolithic Glass Mirrors

Silica-based glasses have been used for hundreds of years as both the optical and structural substrate for mirrors. Glass makes a good optical substrate due to its low softening point, low hardness, and its absence of a grain structure (amorphous). This allows it to be formed, ground, and polished into complex shapes with precise figure ($\cong \lambda/20$ RMS[*,†]) and very smooth surface finishes (as low as $\cong$ 3Å RMS). Once the figure and finish requirements are met for a particular application, the mirror is then coated with a very thin metal film which provides its reflective characteristics.

Another benefit for using glass in mirror designs is that its amorphous structure allows for a wide variation in chemistries. Varying the chemical composition of the elements contained in the glass is a method used to adjust the coefficient of thermal expansion (CTE) to values approaching zero at various use temperatures. These mirror glasses provide dimensional stability (of the mirror figure) with respect to the thermal variations of the environment. A brief review of glass chemistry shows how this was made possible.

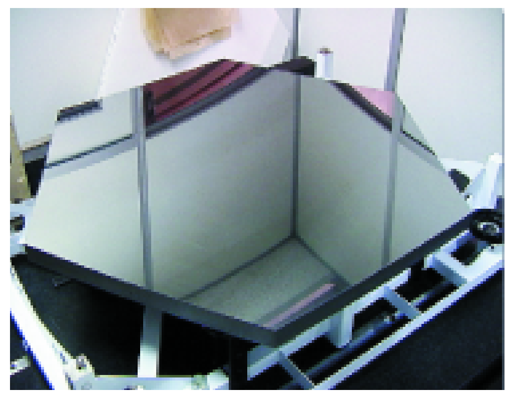
Silica-based glass is an inorganic material with a metastable amorphous structure (no long range order). Most glasses are produced by supercooling their liquids to a rigid condition without crystallization. Some glasses are prepared without cooling from the liquid state such as vapor grown or solution grown glasses. In either case, the atoms of a silicate glass form a continuous framework of silicon and oxygen atoms tetrahedronally bonded together at their corners. The bonds are strong, but they have large variations in the Si-O-Si bond angle. Such a random network is not necessarily uniform, and local variations in density and structure are to be expected. This variability in local density and bond angle allows the absorption of thermally inducted vibrational energy through transverse modes of vibration and the adjustment of bond angles, resulting in a low CTE.

Corning Glass uses a vapor growth process and a chemical composition employing fused silica (SiO_2) and 7% (by weight) Titania (TiO_2) to produce its Ultra Low Expansion (ULE) glass [2]. One of the contractors under Air Force (AF) sponsorship recently produced this composition by a sol-gel approach [3]. The CTE of a glass can also be tailored by the homogeneous precipitation of negative CTE crystalline phases throughout the glass matrices. This is the case with Zerodur glass [4], a glass–ceramic system containing Li_2O, Al_2O_3, and SiO_2 (LAS) with a small amount of TiO_2. ULE and Zerodur both suffer from very low thermal conductivity, strength, modulus, and fracture toughness. Since they can be polished to a complicated figure with a very smooth surface finish, glasses such as ULE and Zerodur are good optical surfaces. However, since they both possess poor mechanical properties they may not be the best material choice for a space-based mirror.

To surmount the aforementioned shortcomings in mechanical properties, thick and heavy mirror designs have typically been used along with good handling and mounting practices. Reliability and robustness were assured in space-based systems by encasing mirror systems into metallic tube structures. However, in future airborne and space-based mirror systems, where weight and size are constrained by payload requirements, this shielded approach, and high areal density design may not be feasible. Non-shielded, low areal density designs may be required to meet system goals; and robustness must be provided by either new structural substrate materials (with high modulus, strength, and fracture toughness) or with new hybrid designs.

Metallic Mirrors

Because they are easily formed, machined, polished, handled, and are relatively inexpensive, metals like aluminum and nickel have been used as mirror materials in terrestrial applications for years. Additionally, most metals are inherently highly reflective, so they do not require coatings to yield high broadband reflectivity. Unfortunately, they generally have high CTEs at ambient temperatures, which limit their applications. However at cryogenic temperatures below 70°K, beryllium has a near zero CTE. This along with its low density, high stiffness, and cryogenic-thermal conductivity make it a desirable mirror material for high-resolution infrared imaging. Beryllium's utility is compromised by its high cost, toxicity, slow machineability, and anisotropic behavior due to its hexagonal crystal structure. Processing by standard metallic hot working methods such as forging and rolling results in texturing that cannot be homogenized through recrystallization. This textured grain structure results in an anisotropic modulus and thermal expansion behavior of the mirror substrate. Only powder processes such as hot isostatic pressing, vacuum hot pressing, sintering, or vacuum plasma spray will yield a randomly oriented grain structure that shows isotropic behavior (Figure 2).[5, 6, 7]



Courtesy of NASA

Figure 2. A 1.4 Meter Beryllium Mirror.

Metals can also be used to create the optical substrate, which is the polished material directly between the reflective surface and the structural substrate. Several manufacturers have used polycrystalline silicon as an optical substrate (also known as a mirror cladding). Its isotropic behavior (diamond cubic structure), low density and CTE, high thermal conductivity and excellent polishability make it a good candidate for an optical substrate [8]. Polycrystalline silicon can be fabricated using melt/solidification, sintering, plasma spraying, physical vapor deposition (PVD), and chemical vapor deposition (CVD). Highly polishable single crystal silicon from the electronics industry has also been used as an optical substrate material on

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a flat mirror, but its size is limited to approximately 12 inches by single crystal growth methods. A detriment to the use of silicon is that it has a low modulus and an affinity for atomic oxygen, which may limit its applicability for certain missions.

NEW MATERIALS AND PROCESSES

Increasing the size of mirrors for space applications requires that new materials and processes be developed to reduce the areal density as compared to monolithic glass and metallic mirrors. One approach that has been under development for quite some time involves the use of monolithic glass sheets that are bonded to a lightweight honeycomb core. Since an internal honeycombed structure is used, this approach allows for the same performance as a monolithic glass mirror but at a greatly reduced weight. Another approach that has seen quite a bit of development uses monolithic silicon carbide fashioned using various fabrication techniques. Both of these methods are discussed further in the following sections.

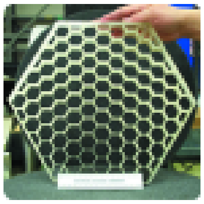
Lightweight Monolithic Glass Mirrors

Significant effort has been made over the past twenty years to reduce the weight of airborne and space-based glass mirrors. These efforts were driven by needs to reduce launch costs, decrease thermal mass (to equilibrate temperatures in shorter times), and to minimize the weight and complexity of the support and handling equipment.

The Hubble Space Telescope mirror was a lightweight design. It was produced using a frit bonding process to join individual ULE glass plates to create an open-faced honeycombed core structure[5]. The core was then frit bonded between two ULE glass face-sheets to produce a lightweight mirror blank. The mirror blank was ground, polished, and vapor coated with aluminum to create a visible light reflective surface. This mirror is 2.4 m (8 ft) in diameter and weighs 828 kg (1820 lbs). It has an areal density of approximately 200 kg/m^2. The major problems encountered in building this mirror were thermal distortions and uneven stresses in the plates and joints. Additionally, the processing method was extremely labor intensive, time-consuming, and expensive.

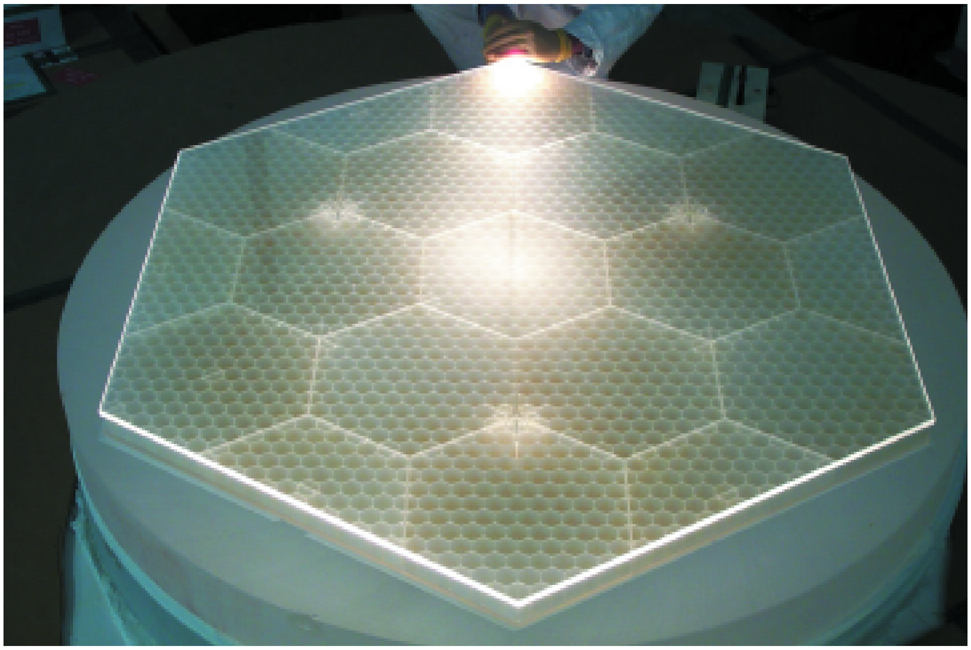
Many programs have attempted to overcome the processing difficulties experienced while building the Hubble mirror and to develop methods/processes to substantially reduce the areal density to less than that of the Hubble mirror. Most recently, the Advanced Mirror Systems Demonstrator (AMSD) program (run by NASA's Marshall Space Flight Center), a jointly funded effort by the Air Force, NASA, and the National Reconnaissance Office (NRO), attempted to advance the state-of-the-art in large, lightweight mirrors[5, 9].

In the AMSD program, an abrasive water jet (AWJ) milling technique was used to fabricate thin-walled, open-ended, honeycomb core structure out of bulk ULE glass (Figure 3). The front and back faceplates were attached using a low temperature fusion bonding process; producing a honeycomb sandwich-type design. A 1.4-meter wide hexagonal mirror segment is shown in Figure 4. This lightweight glass mirror segment was then attached to a carbon fiber-reinforced composite reaction structure with 16 actuators. This total mirror system has an areal density of about 12 kg/m^2. However, the contractors appear to have reached the lower limit in areal density that one can expect for a monolithic glass mirror. Any additional reductions would have to come though hybrid material approaches, new materials, or composites. The AMSD



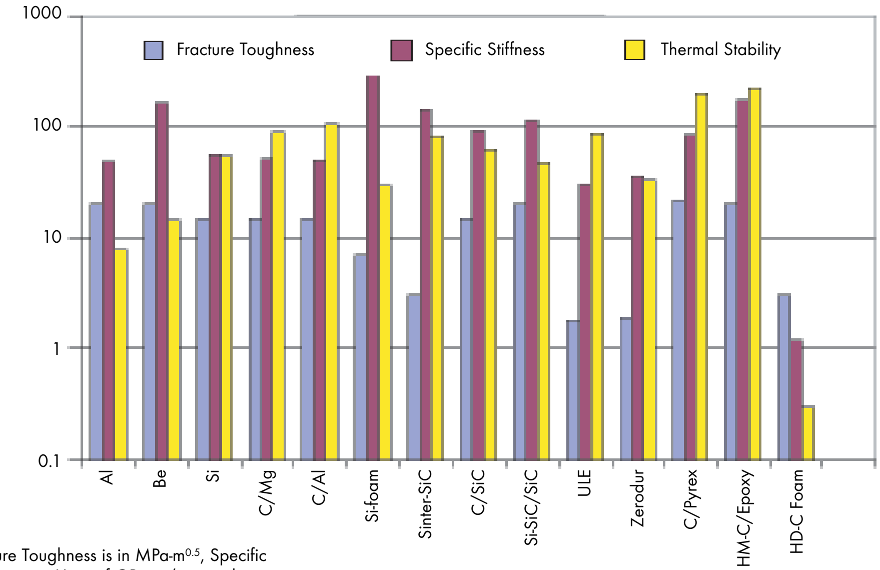
Courtesy of NASA

Figure 3. ULE Honeycomb Core Produced by AWJ Milling in the AMSD Program.



Courtesy of NASA

Figure 4. Kodak's 1.4 Meter Lightweight Glass Mirror Segment.



Fracture Toughness is in $MPa\text{-}m^{0.5}$, Specific Stiffness is in Units of GPa-cc/gm, and Thermal Stability[§] (k/α) in W/m-ppm.

Figure 5. A Comparison of Parameters for a Variety of Mirror Substrate Candidate Materials.

contractors were also very successful in reducing the cost and fabrication time of a glass mirror to half that of a comparable Hubble mirror.

Silicon Carbide-Based Mirrors

Silicon Carbide (SiC)-based materials are promising for use as structural substrates in large mirrors because of their high specific stiffness (high modulus and low density) and their low thermal distortion susceptibility (low thermal expansion and high thermal conductivity) (Figure 5). However, there are many different types of SiC-based materials, and each will polish differently producing variability in surface figure and finish. This variability comes from the differences in hardness and modulus between the phases present, their crystallography, and morphology.

Pure SiC can be grouped into two crystalline forms: 1) alpha (α-SiC), which has a rhombohedral or hexagonal structure and is produced when the formation or processing temperature exceeds 2000°C; and 2) beta (β-SiC), a face-centered cubic phase that is formed by processes that occur below 2000°C. The best surface finish for crystalline SiC would be expected from a dense, fine equiaxed grain, single-phase, β-cubic structure because its hardness, strength, modulus, and thermal expansion behavior should be isotropic and the grain shape equiaxed.

The highest density, smallest grain size, single-phase β-SiC is produced by controlled re-nucleation using a CVD process. Since the deposition rates are rather slow, β-SiC is mainly used for depositing thick coatings or claddings (the optical substrate) onto less expensive, less dense, sintered, or siliconized (excess silicon) SiC based materials (the structural substrate). The polishability of CVD β-SiC cladding material is limited by its high hardness. Too high a pressure on the polishing tool causes quilting-type print-through effects on lightweight honeycomb core structures, while too low a pressure increases the polishing time making it uneconomical.

However, β-SiC mirrors can be fashioned through other techniques. Lightweight, near net-shaped β-SiC mirrors are produced by taking a special grade of graphite and machining it to the desired structure followed by conversion of the graphite to silicon carbide through a gas phase reaction. This reaction process has a very small but predictable dimensional change. The as-converted β-SiC structure has approximately 20% porosity. This mirror substrate is then cladded with CVD β-SiC to make a 100% β-SiC mirror. It is then polished using conventional optical polishing.

Sintering of pure alpha (α-SiC) particles to full density is difficult unless both sub-micron powders and sintering aids are used. Powders and binders are usually mixed and isostatically pressed at room temperature into a green body[‡] blank. The green body can then be machined into an oversized geometry that is predicted by sintering shrinkage models. The oversized, machined green body part is then sintered above 2100°C, resulting in approximately 17% linear shrinkage. The sintered SiC component is approximately 97% dense and contains 98 to 99% α-SiC, depending upon the amount of sintering aids used. Sintered SiC produced by Boostec in France[10] has a morphology consisting of 5 µm grain size with 3% porosity showing up as 1 to 2 mm voids along particle boundaries. A 1.3 m sintered SiC demonstration mirror has been produced for the first near-IR telescope [11].

For optical applications at shorter wavelengths, sintered SiC is coated with CVD SiC and the blank is ground, polished, and etched by an ion plasma beam. This Boostec-sintered (α-SiC) technology has recently been acquired in the USA by Coors Tek in Boulder, Colorado [12].

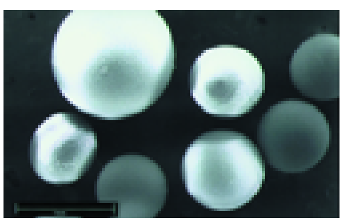
Two-phased, siliconized-SiC is produced by several methods. The first method uses slip cast (α-SiC) powders followed by sintering until they are approximately 60 to 80% dense. This preform is then infiltrated with silicon metal by either gas phase deposition or liquid infiltration to fill the open porosity. The second method involves slip casting SiC with carbon particulates in a polymer binder that decomposes to a carbon network upon vacuum calcination. The calcined SiC/C body is then exposed to either Si vapor or molten Si to convert the carbon phase to SiC through a reaction bonding process. Any remaining porosity is then filled with silicon metal. This method is used by several manufacturers to produce mirror substrates and optical support components. Both methods produce a two-phased (SiC+Si) continuous structure that is intertwined. The latter process is used to produce siliconized α-SiC mirrors [13, 14].

NEW RESEARCH DIRECTIONS

There are many other approaches that are being considered for developing space-based mirrors. Some of these approaches are similar to the lightweight monolithic glass mirror discussed above, in that a lightweight core is used to reduce the total mass of the mirror. Included in these emerging technology approaches are glass mirrors with a lightweight core fashioned from glass microballoons bonded together with glass deposited using sol-gel techniques. Other methods involve using various types of foam materials or composites. The following sections discuss these approaches.

Lightweight Glass Mirrors

Sol Gel and Microballoon Arrays: The Air Force Research Laboratory's Materials and Manufacturing Directorate (AFRL/ML) is sponsoring research to create near zero CTE glass sol-gels for use as bonding agents, surface coatings, and claddings. Additionally, they are fabricating near zero CTE glass microballoons that can be bonded by sol-gel deposited glass, thus forming a microballoon array (Figure 6). Lightweight glass mirrors will be fabricated by bonding ULE glass face-sheets to cores made from microballoon arrays. This design should result in low areal density mirrors that are more robust than current honeycomb web designs. The sol-gel chemistry approaches could also allow for the incorporation of nano-particles or nano-fibers to increase the tensile strength, modulus, and fracture toughness of the glass. Sol-gels could also be used to build up glass claddings on glass ceramic composite mirrors or mirrors made of other materials. Near zero CTE glass micro-balloons could also be used for CTE control and strengtheners for polymer-based composites.



Courtesy of NASA

Figure 6. Near Zero CTE Glass Spheres.

Mirrors Constructed from Foams

An open cell foam structure can provide structural support to a dense facesheet without sagging, hence eliminating distortions as seen in web-based mirror architectures. Foams also allow for a substantial decrease in mirror weight. Foams have been produced out of a variety of materials including aluminum, silicon, silicon carbide, and carbon. Foams can also be formed by the intermixing of hollow spheres of glass with a polymer matrix, thus making a substance referred to as syntactic foam. Below you will see examples of these types of materials.

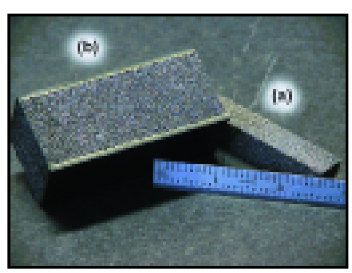
Silicon Foams: Silicon foam can be produced by several methods, including a displacement reaction between carbon foam and SiO vapor.

$$SiO_g + C_{foam} \rightarrow Si_{foam} + CO_g$$

It can also be produced by the diffusion of carbon through a chemical vapor infiltrated silicon surface coating that has been deposited onto the ligaments of open cell carbon foam. The latter process has been used to convert machined carbon foam preforms into net-shaped silicon foam preforms[7, 15]. The surface of the silicon foam is then coated with silicon particulate slurry or by CVD silicon until the surface pores are closed off. A fully dense optical silicon substrate is then applied using CVD, and the surface is polished to the appropriate figure and finish.

Glass/Ceramic Syntactic Foams: Composite materials made from glass, ceramic, or polymer microballoons with polymer resin matrices, broadly known as syntactic foams, are showing great promise for space-based mirror systems. Essentially, they are highly filled polymer systems where the fill material is made up of very small hollow spheres (2-100 µm diameter). Ceramic and glass microballoons are of special interest for use in mirror systems. These types of microballoons can have very low CTE and are relatively stiff compared to their bulk densities.

Syntactic foams typically have low densities. Most advertised syntactic foams, however, are essentially nonporous since all interstitial spaces between microballoons are filled with resin. A significant portion of the density of the composite is made up of resin. For a low density, lightly loaded mirror, the resin's only purpose in the composite is to serve as a binder of sufficient structural integrity for the expected mechanical and thermal load. Any more resin would increase the density and CTE, as well as the cure shrinkage of the whole composite. Recent research at AFRL/ML has developed a methodology to produce syntactic foam composites with very low resin content, hence minimum density[16].



a) Carbon foam.
b) Carbon foam sandwich with ordinary composite laminate face-sheets top-coated with a layer of multi-walled nanofibers embedded in a polymer matrix.

Figure 7. Carbon Foam Examples.

Carbon foams: An exciting new material with potential applications to space-based mirrors is carbon foam. There are a variety of manufacturers that produce a wide range of carbon foam products. These foams can be tailored (density and morphology) to some degree during manufacturing to display moderate stiffness, moderate compressive strength, low density, low CTE, low or high thermal conductivity, and high or low electrical resistivity. They typically show in-plane isotropy on a plane perpendicular to the foaming direction [17]. Research is currently underway to engineer a better microstructure to improve the compressive, tensile, and shear strengths of these foams. Additionally, work is ongoing to identify methods for closing off the porous surfaces, adding a polishable substrate, strengthen attachment locations, and protecting the surfaces from atomic oxygen. Possible solutions to this problem include functionally grading the materials, adding a facesheet to cover up the pores, or adding a cladding material to fill up the surface pores. Figure 7 shows two examples of carbon foam, including one with facesheets of ordinary composite laminate with a topcoat of multi-walled nanofibers bonded by an epoxy matrix. Hybrid mirror designs using low CTE glass sols as the close-off and optical substrate materials are also being considered.

Composite Mirrors

Organic Matrix Composite Mirrors: Organic matrix composites made with conventional carbon fibers have been considered for use in space-based mirrors for quite some time. They exhibit many properties that are extraordinarily good for mirror systems. They have a high specific stiffness and depending on fiber choice, they can have good in-plane thermal conductivity. Most importantly, carbon fiber composites can also be designed with near zero CTE for a space-based mirror. Many problems exist, however, with using these materials for mirrors. Polymer resin systems can be sensitive to a variety of environmental factors that put into question their long-term stability. Highly uniform and consistent raw materials (composite prepreg – uncured fiber/matrix sheets) can be difficult to achieve. Finally, the multiphase nature of the composite causes a fiber-print-through phenomenon, which deleteriously affects the surface finish of the optic**. It is important to note that this problem affects all classes of composite materials, not just organic matrix composites. A large PMC mirror (with an areal density of 10 kg/m^2) produced for NASA Jet Propulsion Laboratory (JPL) is shown in Figure 8.

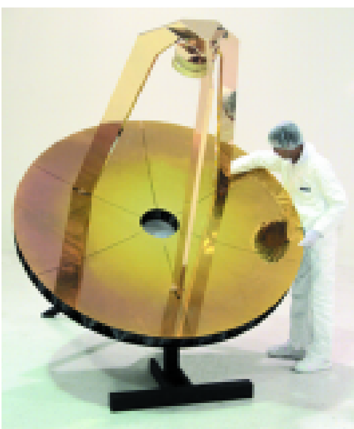
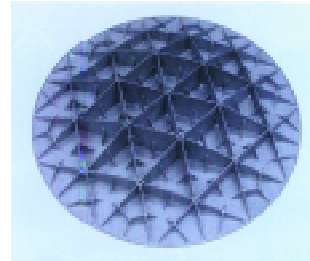


Figure 8. A 2-Meter Polymer Matrix Composite Mirror Produced for NASA JPL.

Ceramic Matrix Composite Mirrors: The desirable features of CMC mirrors are that their CTEs and areal densities are low while their strength, modulus, and fracture toughness are high. High strength and fracture toughness will be needed for durability and robustness in unshielded space-based mirror systems, such as the James Webb Telescope and the Space-Based Laser. Survivability and longevity requirements will demand fielded mirrors be made of highly durable and stable materials. Therefore, as a community we need to continue to invest in scaling up these composite mirrors to very large sizes while assuring thermal-mechanical stability.



Courtesy of NASA

Figure 9. The Back Side of the 500 mm C/SiC Mirror with an Areal Density of 8 kg/m^2.

Many DOD and NASA organizations have sponsored numerous businesses to develop carbon and SiC fiber-reinforced SiC and siliconized SiC matrix composites. These ceramic matrix composites (CMCs) have been fabricated in both continuous and discontinuous fashion by numerous companies using a variety of processing routes. As in glass composites, carbon fiber reinforcements allow for CTE and strength tailorability, but polishability problems arise when a weak carbon interfacial coating is deposited on the fibers to promote crack deflection and improve fracture toughness. Polishability is improved by adding a thick cladding of dense CVD β-SiC to form an optical substrate.

Many processes can be used to fabricate structural CMC substrates using chopped carbon fibers coated with a carbon interfacial layer and bonded together in a SiC matrix. For example, AIBG and ECM from Germany, molds a mixture of SiC and C particles, polymer binder, and chopped carbon fibers (with and without interfacial coatings) into a blank. The mirror blanks are then heat treated under vacuum to form a porous graphitized green body. The green body is easily machined into a lightweight shape using standard CNC milling equipment. It is then infiltrated under vacuum with liquid silicon to form a C/SiC composite structure. [6,7], (Figure 9). It is claimed that there is no noticeable shrinkage in the infiltration/conversion process with virtually no residual stresses left in the mirror. The composite is then rough ground and cladded with slurry to form a SiC+Si surface layer that is polished to a surface roughness of 2 nm. Other fabrication methods use chemical vapor infiltration to densify a preform of carbon or silicon carbide fibers. These composites are then clad with either CVD β-SiC, PVD Si, or melt replication with Si to form the optical substrate.

Metal Matrix Composite Mirrors: Continuous and discontinuous carbon fiber-reinforced magnesium and aluminum matrix composites are currently being studied as possible mirror structural substrates[7,18,19]. As previously mentioned, the volume fraction of carbon fibers can be varied to tailor the net CTE in a composite material. It can also increase the strength, modulus, thermal conductivity, and fracture toughness of the base material. Carbon-reinforced aluminum and magnesium matrix composites are highly machineable to a lightweight configuration without warpage. These structural substrates are then coated with a CVD-Si

Courtesy of NASA

Figure 10. Three-Inch Diameter C/Al and C/Mg Mirrors.

cladding and polished to a surface roughness of 10 angstroms RMS (Figure 10).

CONCLUSIONS

For many situations, monolithic glass remains the material of choice for mirrors, due to its ease of fabrication, high precision on curvature, roughness amplitudes much less than the wavelength range of light, and very low distortions arising from thermal fluctuations due to low thermal expansion. The AMSD program has shown that monolithic glass mirror designs can be lightened to around 15 kg/m^2 and their cost reduced substantially compared to Hubble-based technology. However, many believe that current glass technology is fast approaching its theoretical limit, and that any further substantial reduction in areal density would require hybrid mirror designs. It is anticipated that an order of magnitude increase in fracture toughness, compared to monolithic glass, would be required in large segmented mirror designs for unshielded space-based applications. The high fracture toughness is desired to avoid catastrophic mirror failure due to assembly accidents and micrometeoroid impact damage.

The future needs of the Air Force and the Department of Defense will also require reductions in lead times, processing costs, and launch load/weights. New materials and processing methods for providing mirrors are needed. Mirror structural substrates made out of advanced composite materials (metal, ceramic, and polymer), foams, and microsphere arrays do allow for CTE and modulus tailorability, low-density, high strength, stiffness, and toughness. Small-size mirror structural substrates have been fabricated from these new emerging materials, but scaling to 2- or 3-meter segments will require new resources, both in time and funding. Producing the surface finish and figure requirements needed for visible quality optics from these multi-phase complex systems will be difficult. New methods of polishing, replication, and sol-gel or polymer spinning will be required to produce quality optical substrates. Finally, research will be required to produce uniform, stress free reflective coatings and dielectric stacks on such large mirror systems.

In this article we have addressed the majority of existing mirror technologies as well as the current research areas and their related technologies. While not all-inclusive, our discussion highlights the important issues relating to constructing large mirrors for use in space. For additional information on specific programs and materials approaches we refer the reader to the references.

NOTES AND REFERENCES

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* λ denotes the wavelength of incident electromagnetic radiation (mainly visible light in the case of optical mirrors)

† *Root Mean Square* (RMS) – a statistical averaging function that characterizes the relative roughness of a surface.

§ Thermal Stability (k/α) is defined as the thermal conductivity (k) divided by the coefficient of thermal expansion (α). In SI units, k is expressed in W/m-K, α in ppm/K.

‡ Powder ceramics (and powder metals) are frequently processed by pressing them into a preformed shape known as a blank, or a *green body*. Green bodies are subsequently processed to final form by densifying them (typically by sintering or vitrification).

** *Fiber print-through* is caused by a mismatch in properties between the fibers and the resin matrix binding them together. The resin will shrink upon cure while the fibers do not change shape. The resin shrinkage and CTE/CME mismatch combine to form valleys in the resin-rich zones between adjacent fibers, resulting in significant surface roughness. This fiber print-through phenomenon affects a composite mirror whether it was polished or replicated except in the case where the use temperature is exactly the same as the manufacturing/or polishing temperature.

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Dr. David H. Mollenhauer's technical career has largely focused in the area of experimental mechanics. He received a BS in Aerospace Engineering in 1990 from Texas A&M University. As part of the Air Force Palace Knight program, he received his MS in Engineering Mechanics from Virginia Tech in 1992, and subsequently earned his PhD there in 1997. During his tenure at AFRL, he developed a state-of-the-art photomechanics laboratory at the Materials and Manufacturing Directorate. Using moiré interferometry, he has extensively examined the surface behavior of drilled and molded holes in laminated composites; and quantitatively measured the micromechanical behavior of model composite systems. The results of his work spawned great interest in a newly developed composite analysis method, known as BSAM. Contact information: david.mollenhauer@wpafb.af.mil.

Recent US Patents

The following is a list of patents issued by the United States Patent and Trademark Office in the areas of materials and space. They are organized into subject areas. Interested readers can obtain further information by accessing the Patent Office's website: http://www.uspto.gov.

SPACECRAFT STRUCTURES

6,679,456 Spacecraft protected by a coating including pyroelectric/ferroelectric particles, and the coating material
6,695,261 Shock isolation system for spacecraft fairing

POWER

6,689,949 Concentrating photovoltaic cavity converters for extreme solar-to-electric conversion efficiencies
6,706,962 Hybrid solar cells with thermal deposited semiconductive oxide layer
6,717,045 Photovoltaic array module design for solar electric power generation systems

SENSORS

6,717,228 Infrared image sensor with temperature compensation element
6,678,048 Information-efficient spectral imaging sensor with TDI
6,682,638 Film type solid polymer ionomer sensor and sensor cell
6,714,345 Semiconductor optical amplifier providing high gain, high power and low noise figure
6,704,138 Low-noise, high-power optical amplifier
6,717,544 Radar sensor

LAUNCH

6,695,256 Cryogenic propellant depletion system for a launch vehicle
6,685,141 X-33 aeroshell and bell nozzle rocket engine launch vehicle

THERMAL MANAGEMENT

6,689,471 Thermal management device and method of making such a device
6,711,904 Active thermal management of semiconductor devices

THERMAL PROTECTION

6,716,539 Dual microstructure thermal barrier coating
6,689,470 Thermal protection system
6,691,505 Fiber-reinforced rocket motor insulation

ROCKET

6,711,901 Rocket motor nozzle assemblies having vacuum plasma-sprayed refractory metal shell throat inserts, methods of making, and rocket motors including same
6,705,076 Rocket thrust chamber
6,701,705 Gas-walled rocket nozzle
6,679,965 Low density composite rocket nozzle components and process for making the same from standard density phenolic matrix, fiber reinforced materials
6,673,449 Net molded tantalum carbide rocket nozzle throat and method of making

CRYOGENICS

6,681,589 Space suit backpack using solid adsorbents for cryogenic oxygen storage, freeze out of carbon dioxide and moisture, and ice heat sink

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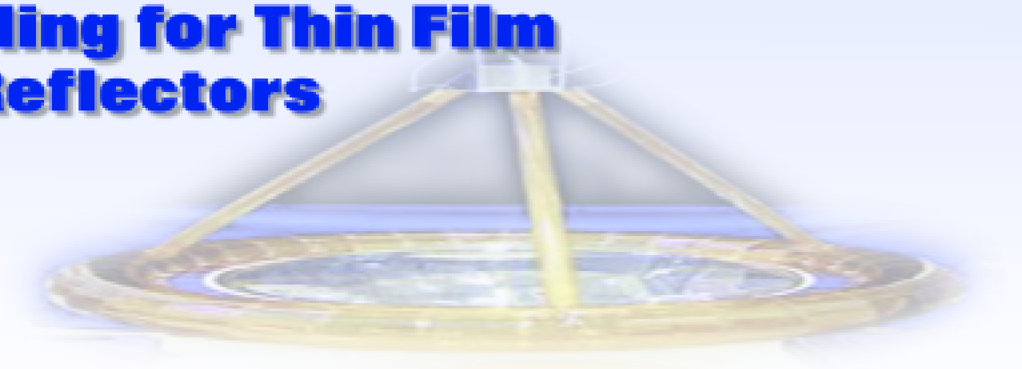
Precision Tooling for Thin Film (Membrane) Reflectors



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Any discussion about placing new systems into space is at its heart, a discussion of the respective enabling technologies which facilitate or make possible their deployment. Among these enablers are materials, manufacturing methods, and fabrication facilities. State-of-the-art tooling is part of any up-to-date facility. This article describes the innovative design approach, fabrication processes, and materials that SRS Technologies and the Air Force Research Laboratory's Materials and Manufacturing Directorate (AFRL/ML) are developing for precision tooling directed toward the production of polymer-based thin film (membrane) reflectors for use as inflatable light weight antennas, solar power concentrators, and imaging optics. The designs and tooling will ultimately support production of polymer thin films for a proposed Picosat Space Inflatable Reflector Experiment (PSIREX) space flight experiment (FE) and ongoing terrestrial radio frequency (RF) antenna development and testing. The precision tools are also being investigated for use as substrates for the lay-up of composite structures.

Although small, high-quality reflectors are available, adaptive optics technology is not yet at a significantly mature stage to resolve the optical aberrations usually observed in large inflated membrane structures. Smaller reflectors on the order of one meter or less in diameter have been produced in an affordable tooling approach and the capability to produce precision tooling from conventional metallic materials has existed for some time. However, as the size of the reflector increases, the cost of preparing a stable metallic tool for manufacturing becomes cost prohibitive. So from the programmatic viewpoint, the relatively high cost of conventional materials and processes has been a limiting factor, especially for large aperture tooling. As an example, one estimate for fabrication of a single four-meter aperture tool made from conventional metallic materials and finishing processes exceeded $3 million.

There are also technical challenges surrounding the use of conventional metallic tooling materials. Materials compatibility is a typical issue when advanced polymers are produced upon precision tools. A mismatch in the coefficient of thermal expansion (CTE) between the tool and the polymer thin film can cause the film to pre-release during the thermal cure, tear during thermal cycling, or tear when releasing the film from the metal tool; even when release agents have been properly applied.

Another technical challenge involves tool dynamics. SRS and AFRL/ML (referred to hereafter as ML) digital photogrammetry shape measurement tests of conventional tooling have shown that significant tool shape changes can occur as a result of thermal cycling. Some of this movement can be classified as thermal stress relief, but some movement is clearly dynamic. These tool shape changes ultimately produce off-dimension thin films that degrade the performance of the application as well as the future utility of the tool. In some cases, the tool surface coating (over conventional materials) degrades (cracks) as a result of thermal cycling and CTE mismatches. The innovative tooling research and development in progress addresses the programmatic and technical issues through the selection of materials and fabrication processes that are CTE compatible, have demonstrated the ability to retain their precision shape and surface quality through repeated thermal cycles, and are cost effective.

FABRICATION OF PRECISION TOOLING

Over the last 15 years, SRS has partnered with ML and NASA to develop thin film polymer concentrator technology, including the respective precision tooling. In recent years, AFRL has focused an increasing

Figure 1. **One-Meter by Two-Meter Off-Axis Mandrel and Thin Film Polymer Concentrator.**

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Figure 2. **Four-Meter by Six-Meter Off-Axis Tool and Prototype Test Hardware.**

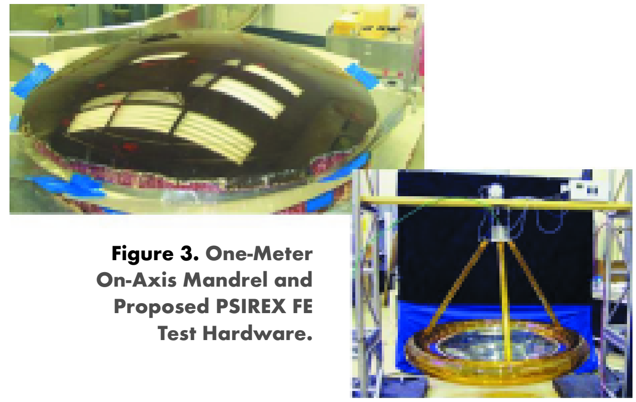

Figure 3. **One-Meter On-Axis Mandrel and Proposed PSIREX FE Test Hardware.**

amount of attention upon the development of precision tooling technology. In 2001, SRS and ML successfully developed a prototype 1-m x 2-m off-axis* tool that was utilized to produce precise, tear-resistant polymer films. Figure 1 shows the prototype tool and the thin film concentrator that was manufactured. An outgrowth of that technology has been the ongoing fabrication of a 4-m x 6-m off-axis tool. Figure 2 shows the tool along with prototype test hardware. The latest effort is a 1-m on-axis* tool for the proposed PSIREX FE. The PSIREX FE mandrel and test hardware are shown in Figure 3. Fabrication of these tools should be completed in CY03.

DESIGN AND MATERIALS

The design of the PSIREX FE tool began with a general description of the FE and an initial set of tooling specifications, as shown in Figure 4. The fundamental objective of the PSIREX FE is to verify deployment of a thin film concentrator and then characterize the shape of the reflective surface. One of the explicit specifications was a 1m-class aperture. A grid projection optical measurement apparatus (similar to a Ronchigram or Hartmann) was selected for the FE shape characterization technique, which led to the selection of a spherical-shaped reflective surface. A focal number† target value of 0.5 was selected based on geometric ray trace analysis of the grid projection apparatus. By using the FE specifications, an approach and set of tooling requirements were spawned.

As a tooling design objective, non-conventional materials were selected that met the tooling requirements and addressed the programmatic and technical issues. An aluminum skin honeycomb was chosen as the base because of its inherent flatness and strength and relatively high temperature rating, and a high temperature honeycomb material (Nomex) was chosen for the tool core. This material has a combination of high compressive stress, high temperature rating, and good dimensional stability.

A specially formulated anhydride was chosen as the substrate material. This thermosetting polymer material possesses good properties for machining and surface finishing. A specially formulated high temperature phenolic resin was chosen for the surface coating material. The performance of each of these materials (individually and assembled) was proven through prototyping and extensive testing. Finally, a tooling design with material and surface finish specifications was created.

Depending on the application, SRS sometimes employs a tooling shape optimization algorithm that calculates the anticipated deformations of the deployed thin film concentrator that result from thermal and pressure loads. These deformations are then compensated for in the shape of the tool. The optimization process is further described in Figure 5. The PSIREX tool was not optimized in order to support correlation of the film shape characterization data with the mandrel shape.

FABRICATION PROCESS

Following design and materials selection, the fabrication process for the PSIREX tool was defined and implemented with only minor deviations from the original process. The PSIREX tool process itself is a deviation from the similar process currently being used in fabrication of the large aperture

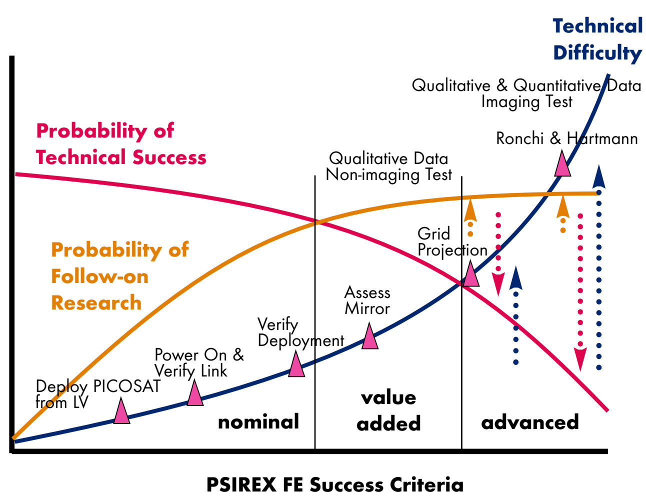

Figure 4. **PSIREX FE Specifications.**

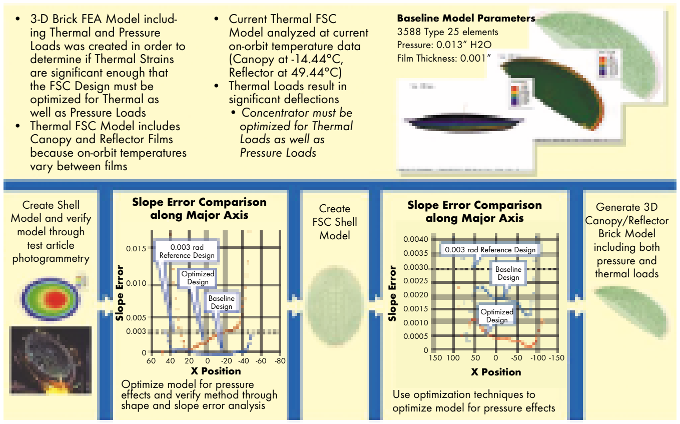

Figure 5. **Optimization Process.**

(4-m x 6-m) off-axis tool being fabricated for AFRL (shown in Figure 2). The differences between the PSIREX tool process and the 4-m x 6-m tool process are primarily due to scaling issues. The mass, outside dimensions and handling requirements of the 4-m x 6-m tool require a more robust base; plus, the PSIREX has an objective to eliminate all hand finishing of the surface, whereas the 4-m x 6-m tool seeks to minimize hand finishing. The 4-m x 6-m tool is currently in the surface finishing phase and the PSIREX tool is operational, as shown in Figure 2.

DESIGN VERIFICATION

During the PSIREX tool fabrication process, the design was verified via shape and surface finish measurements at three critical junctures: a rough verification following machining of the core, a coordinate measurement machine (CMM) measurement following substrate machining, and a second CMM measurement, following surface coating and two thermal cycles. Surface measurements, via a profilometer, were specified following substrate machining and surface coating. SRS also uses digital photogrammetry to perform shape measurement of both tools and concentrators.

ISSUES

The cost effectiveness of the precision tooling that is manufactured using non-conventional materials and respective processes will be assessed versus historical data for conventional tooling and a market assessment to see what customers are willing to pay for the precision tooling. Certainly, the design and quantity of material for each unit is unique and multiple orders per design are not anticipated. However, for this given design approach, the material selection, and fabrication process would be identical for each tool. This would also be true for conventional tooling approaches; hence the anticipated reductions in material cost, fabrication labor, and machine time should translate into lower tooling costs.

The ultimate qualifier for these tools is the polymer thin film product that is produced. Based on the prototype results, the research and development team expects the polymer thin films to meet the design requirements. To be sure, a correlation will be developed between the quality of polymer thin film product and the tool to verify the film fabrication process.

FUTURE TOOLING

The advent of new materials will undoubtedly benefit the precision tooling market. Advanced polymers will require increasingly precise tooling with longer life and a broader temperature range to support thermal cycling. Coated polyimide foams are currently being developed as core/substrate materials that are very lightweight and perform at high temperatures. New "designer" polymers will be tougher and more tear resistant, while also allowing more control of the CTE. Thermal cycling requirements may be reduced through the development of chemical curing technology. Finally, the whole tooling concept may be redefined, if the manufacture of precision pressure-formed thin films proves feasible.

SUMMARY / CONCLUSIONS

Based on the prototype results and the fabrication cost of the PSIREX tool, the innovative materials and processes that are being developed are cost effective, programmatically capable, and technically compatible. The research and development team anticipates that the tool will maintain precision shape through multiple thermal cycles. They further anticipate that the surface finish will not significantly degrade through a typical duty cycle of 25 thermal cycles and that polymer films will not tear during thermal cycling and will release properly. The greater than 300°F maximum soak temperature is sufficient for many applications, but higher soak temperatures are still needed.

NOTES AND REFERENCES

* Concentrators, reflectors, and other precision components with circular geometries are fabricated on rotating fixtures known as mandrels. Until recently, most of these components were affixed to their tools via the mandrel's centrally rotating shaft – these are known as *on-axis* tools. The major benefit of on-axis tooling is that it ensures radial symmetry for components manufactured in this manner. However, the presence of a central axle may interfere with the manufacture of some precision components, so an alternate fixturing method of mounting circular components (concentrically around the perimeter) was developed where there was no axial interference. These fixtures are known as *off-axis* tools, which while mounted coaxially relative to the fixture's rotation, are not affixed to an axle. Note in Figure 2 there are several examples of off-axis mountings – either by riggings or rollers. Conversely, Figure 3 shows a more traditional on-axis tool.

† The *focal number* is the ratio of the focal length (distance from the lens surface to the focal point) to the aperture diameter. It is also known as the *focal ratio*, or the *focal stop* (commonly known in photography as the *f-stop*).

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Ms. Marilyn R. Unroe is a Program Manager and Research Chemist with the Polymer Branch of the Materials and Manufacturing Directorate (AFRL/MLBP), Wright-Patterson AFB, OH. She has over 20 years experience in basic polymer synthesis research and applied development of polymeric materials for aircraft and aerospace applications, all within the Polymer Branch of AFRL.

AMPTIAC SENDS ITS THANKS

Mr. Henry Johnson donated over 630 reference books, government technical reports and other documents. Mr. Johnson is an alumnus of the Air Force Research Laboratory's Materials and Manufacturing Directorate, who last served as the Chief of the Metals Branch in the 1980's (AFRL/MLLM). After he left the Air Force, Mr. Johnson continued to advocate metallic materials as the President of Materials & Manufacturing Tech Inc. Throughout his career, he collected many documents on metallic materials. Many of the reports he donated date back to the early days of the space race. These documents will help the government save both time and money by preserving valuable data.

Dr. Stuart Schwab has quite generously donated over 70 reports from his personal technical library, accrued over the past 20 years as an active participant in the development of defense technology. The reports Dr. Schwab forwarded focus on high temperature composite materials, both ceramic matrix and carbon-carbon composites, for advanced engine and thermal protection applications.

Don't let your work become part of a landfill – you've no doubt seen this message in past issues of the AMPTIAC Quarterly. It is part of our continuous campaign to preserve and maintain the invaluable and irreplaceable material research data generated by the DOD, contractors, and universities over the previous decades. We regularly receive donations from principals in the defense materials communities, which augment and enhance AMPTIAC 's library of now more than 220,000 volumes. As a semi-regular feature of the newsletter, we would like to acknowledge some of the exceptional donations made by our readers. By donating their work to us, it now also becomes available to you – the users of the community!

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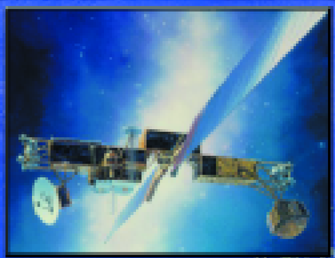

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