http://amptiac.alionscience.com/quarterly

AMPTIAC

QUARTERLY
Volume 8, Number 1
2004

Materials in Space

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

AMPTIAC is a DOD Information Analysis Center Administered by the Defense Information Systems Agency, Defense Technical Information Center

http://amptiac.alionscience.com/quarterly

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

Editor-in-Chief
Christian E. Grethlein, P.E.

Special Issue Editor
Jeffrey D. Guthrie

Creative Director
Cynthia Long

Information Processing
Judy E. Tallarino
Patricia McQuinn

Inquiry Services
David J. Brumbaugh

Product Sales
Gina Nash

The AMPTIAC Quarterly is published by the Advanced Materials and Processes Technology Information Analysis Center (AMPTIAC). AMPTIAC is a DOD sponsored Information Analysis Center, administratively managed by the Defense Information Systems Agency (DISA), Defense Technical Information Center (DTIC). The AMPTIAC Quarterly is distributed to more than 15,000 materials professionals around the world.

Inquiries about AMPTIAC capabilities, products and services may be addressed to

David H. Rose
Director, AMPTIAC
315-339-7023
email: amptiac@alionscience.com
url: http://amptiac.alionscience.com

We welcome your input! To submit your related articles, photos, notices, or ideas for future issues, please contact:

AMPTIAC
ATTN: CHRISTIAN E. GRETHLEIN
201 Mill Street
Rome, New York 13440

PHONE: 315.339.7009
FAX: 315.339.7107
email: amptiac_news@alionscience.com

Ceramic Materials for Reusable Liquid Fueled Rocket Engine Combustion Devices

Captain Steven Steel
Materials And Manufacturing Directorate
Air Force Research Laboratory
Wright-Patterson AFB, OH

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).

http://amptiac.alionscience.com/quarterly

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

http://amptiac.alionscience.com/quarterly

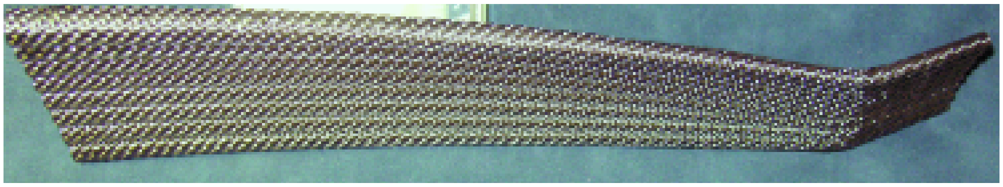

Figure 2. **Carbon Fiber Preform for Bell Nozzle Segment.**

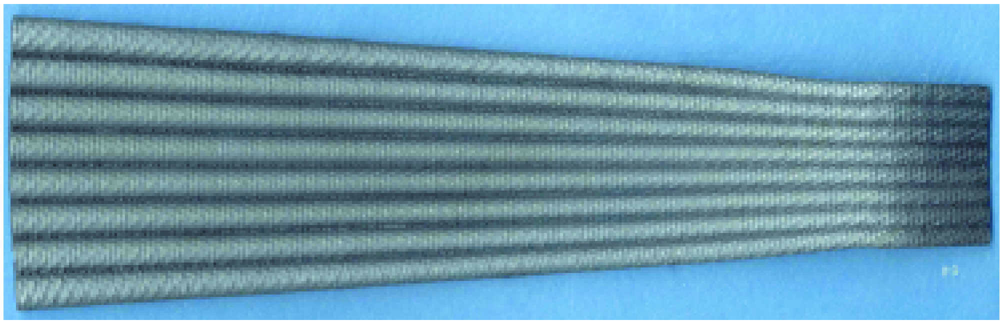

Figure 3. **C/SiC Bell Nozzle Segment.**

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

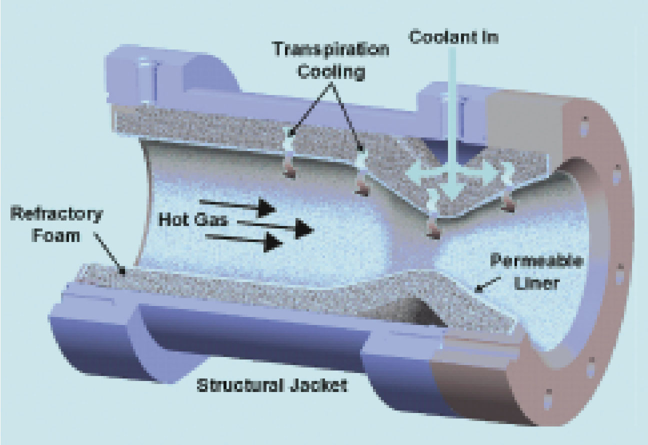

Figure 4. **Transpiration-Cooled Thrust Chamber Concept.**

http://amptiac.alionscience.com/quarterly

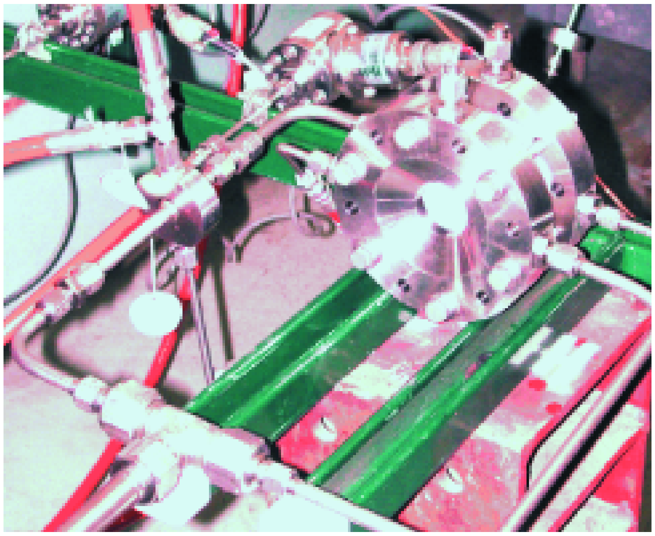

Figure 5. Permeability Testing of Cylindrical Specimens.

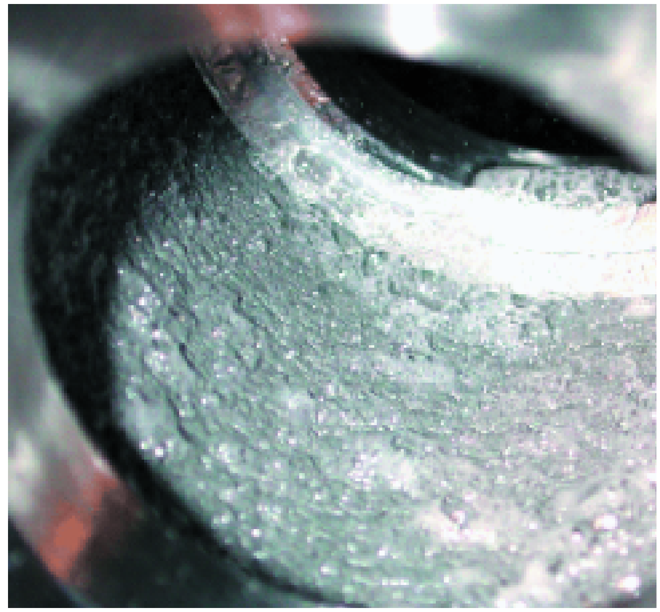

Figure 6. Soap Bubbles Show Gas Flow Pattern.

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.

http://amptiac.alionscience.com/quarterly

http://amptiac.alionscience.com/quarterly

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.

Overworked? Overloaded?
Could you use some materials engineering help?

AMPTIAC can provide answers to materials-related technical questions.

Here's how it works: You contact our inquiry manager with the problem. The inquiry manager discusses the problem with you to make sure we understand exactly what you need. He then assigns the task to an AMPTIAC technical expert with knowledge and experience of the discipline in question.

AMPTIAC maintains the DOD's knowledge base in advanced materials; nearly 220,000 technical reports addressing all classes of materials. Our database contains information on properties, durability, applications, processes, and more. Plus if we don't find it in our resources, we also have direct access to NASA and DOE databases. With this tremendous amount of data, our engineering staff can save you time and money by quickly providing you with off-the-shelf information or technical solutions that directly meet your needs.

For smaller inquiries and bibliographic searches we can provide you some information free of charge. Larger efforts are on a cost-reimbursable basis but under no circumstances do we begin work before you accept our quote and issue us a purchase order. For more information on how we can help you, please contact AMPTIAC's Inquiry Services Manager, Mr. David Brumbaugh, at (315) 339-7113.

A Recent Example

A government contractor asked us to locate and compile properties of carbon fiber composites at cryogenic temperature. In less than 2 weeks we:

• performed a literature review • identified 162 relevant technical reports • reviewed the reports and extracted appropriate data • organized 152 pages of data in a binder • and cross-linked the data to a searchable spreadsheet

The resultant data book provided the contractor with valuable information they needed in their effort to design a satellite structure.

http://amptiac.alionscience.com/quarterly