Materials and Structures Research and Development at APL

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This article gives an overview of current work in materials and structures at APL. It is intended to provide a retrospective and prospective look at APL's work, emphasizing several themes including spacecraft engineering, missile engineering, microelectronic technology, composites and advanced materials, and other selected activities. The first two of these themes are relatively broad mission areas that have a long history at APL and for which the Laboratory has a prestigious national and international reputation. The second two themes are technology areas that APL has participated in and applied to spacecraft and missile engineering mission areas as well as new emerging mission areas. Composites and advanced materials are actually quite ubiquitous across the Laboratory and will be described in conjunction with some of the other major theme areas. Microelectromechanical systems, a relatively new initiative, extends our current microfabrication capabilities to a variety of specific applications. Nanotechnology and other activities are also described on a case-by-case basis.

INTRODUCTION

Missile and spacecraft engineering have been the mainstays of APL's work for several decades. Innovation and development of materials and structures in these areas have been driven by our sponsor's system requirements, often from the "top down." Our sponsors, of course, have been various DoD and civilian agencies, principally the Navy and NASA. Our "hands-on" experience, however, is one of the Laboratory's core values, which is important to the effective development of these systems, yet it is sometimes obscure to a view from the "top." Nevertheless, many APL staff have the conviction that it is through "touching metal that we gain our mettle." In this article we hope to convey the essential nature of materials development at APL, particularly our role in applying innovations from the private sector to mission applications in national security and space exploration.

In addition to setting a historical perspective in the two key mission areas, we give several examples of recent work reported at a recent Senior Leadership Team session on Materials and Structures. Requirements for new system capabilities in harsher environments (whether natural or manmade) have continually escalated over the last few decades. These requirements ultimately flow down to the materials used at the very core of these systems. Although it is a cliche to say "better, cheaper, faster," the reality is that there has always been and continues to be an increasing demand for state-of-the-art materials and novel structures, which ultimately improve system performance and cost.

HISTORICAL PERSPECTIVE

APL's earliest efforts in materials and structures began principally with the development of the variable timing (VT) fuze during World War II, followed by work on guided missiles for the Navy in the late 1940s and early 1950s (Fig. 1). Although we grew out of the business of *directly* prototyping guided missiles in the late 1950s, we remain intimately involved in missile guidance, propulsion, and aerodynamics, particularly in assessing contractor performance as an "honest broker" and correcting problems encountered in hardware and system development.

In the 1960s we began a series of tasks evaluating the effects of high-speed missile flight on missile radio-frequency (RF) seeker domes, particularly what is known as boresight error. In simplest terms, boresight error is the difference between actual and measured angle from boresight seen by an RF antenna looking through a radome at a target. As speeds, altitudes, endgame accelerations, and temperatures increased, ever-more exotic materials were introduced while maintaining more exacting tolerances on the electromagnetic properties of these materials (e.g., parameters such as the dielectric constant and loss tangent at microwave frequencies).

By the 1980s, infrared (IR) seekers were introduced for a host of reasons, especially at high altitudes and in the terminal phase of missile trajectories. However, these seekers also brought with them a whole new set of problems having to do with aerothermal shock and high temperatures, which affect IR dome survivability and IR seeker sensitivity. Most recently, they have introduced problems having to do with imaging IR seeker spatial resolution through such parameters as the index of refraction and its variation with temperature and position on the dome, as well as degrading sensitivity via increased scattering and absorption of incident radiation directly in front of the sensor.

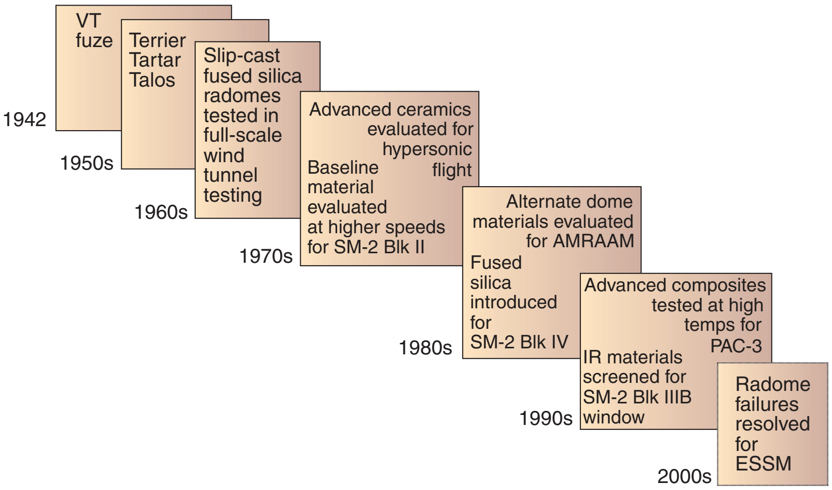

Figure 1. Highlights from the history of missile engineering at APL showing several key developments in materials and structures dating from the genesis of our Navy-sponsored efforts in 1942. Many of these efforts are correlated with the advent of RF, microwave, and IR seeker developments. (AMRAAM = Advanced Medium-Range Air-to-Air Missile, ESSM = Evolved SeaSparrow Missile, PAC = Patriot Advanced Capability, SM = Standard Missile.)

In the future, more demanding capabilities such as the use of aerodynamically conformal windows, multiple spectral bands, and low observable signatures will tax the use of existing and new materials to the limit of what is physically possible. Work described later in the Missile Engineering section covers some of these issues.

Another historically significant stimulus external to the Laboratory on our use of new materials and structures was the advent of the space program, which we entered in the early 1960s (Fig. 2). Spacecraft electronic circuit fabrication demands for smaller size, higher reliability, and significant radiation, shock, vibration, and temperature extremes were major drivers in the search for new and better ways of circuit layout, board materials, and component materials selection. That stimulus continues to drive materials and structures innovations to this day with even greater demands, including cost and scheduling. Recent work presented later in this article on spacecraft engineering describes new developments in materials and structures for lightweight spacecraft and harsher space environments.

Advanced materials, such as composites and refractory crystalline materials, have been introduced more recently in a variety of applications ranging from rocket nozzles to IR seekers to missile airframes. Future plans for hypersonic long-range missiles present the most daunting challenge so far to the guided missile community. Composites are also being used in innovative ways by APL staff to build new antennas and solar panels for spacecraft, which are the subject of recent research and development efforts.

SCOPE OF EFFORTS

Looking at the overall picture of materials and structures used by APL in all applications, we see in Fig. 3 that they span 12 orders of magnitude of scale, from nanometers at virtually atomic dimensions to large-scale structures such as bridges. In between we have the

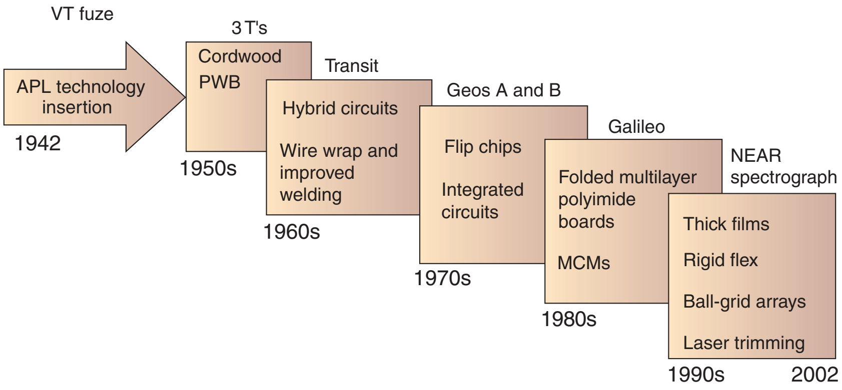

Figure 2. Applications of materials and structures were initially stimulated by APL's involvement in guided missile development, especially in the 1950s with the 3 T's: Terrier, Tartar, and Talos. As we began to get involved with the national space program, however, the need for miniature electronic packaging significantly accelerated our involvement and drove our innovations in applying and packaging microcircuit technology. (MCMs = multichip modules, NEAR = Near Earth Asteroid Rendezvous, PWB = printed wiring board.)

more familiar microcircuit technology as well as structures fabricated in our machine shops using (albeit) nonstandard materials and shapes. Spacecraft are the most notable examples of such applications. Among the newer structures being examined by the Laboratory are microelectromechanical systems (MEMS). This technology is the focus of several new investigations as is some nanotechnology as exemplified by work shown in the boxed insert. Some of these examples are illustrated and explained in the section on newer initiatives in micro- and nanotechnology later in this article. (The boxed insert lists presentations on these topics given for the Senior Leadership Team Technology Review on Materials and Structures).

A plethora of diagnostic techniques exist at APL for testing and evaluating these materials and structures, including nanometer-scale microscopy, imaging, and spectroscopic or spectral analysis techniques, the last, by example, involving acoustic excitations in very large structures picked up by sensitive accelerometers.

We have used traditional macromachining as well as unconventional machining techniques to fabricate both ordinary and exotic materials. In the region of Fig. 3 between photolithography and machining, we hope to close the gap with an in-house capability to perform controllable and repeatable three-dimensional micromachining.

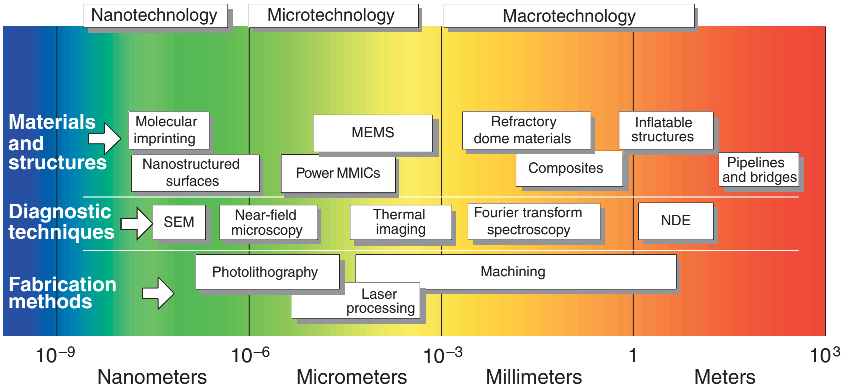

Figure 3. The vast array of APL work on materials and structures covers the regions of scale dubbed nano-, micro-, and macrotechnology, spanning from 1 nm (10^{-9} m) to almost 1 km (10^3 m). Particular examples of materials and structures developed at the Laboratory are highlighted on top, associated diagnostic techniques are highlighted in the middle, and examples of generic fabrication methods are on the bottom. (MEMS = microelectromechanical systems, MMIC = monolithic microwave integrated circuit, NDE = nondestructive evaluation, SEM = scanning electron microscopy.)

CENTERS OF EXPERTISE

Most efforts in materials and structures occur in a handful of key organizational units across the Laboratory. The Research and Technology Development Center staff apply their expertise to solving materials-related issues for major sponsored programs requiring a greater level of investigation than normally planned for the usual systems engineering tasks. They also solve critical research challenges, bringing to bear a considerable expertise and suite of diagnostic tools to analyze materials failures, make improvements in materials, or introduce new materials in system or component development. A wide range of materials problems are addressed including

- Stress-induced fractures on IR domes
- IR transparent materials
- Disbonds in composites
- Transient heat flow
- Surface and interface properties
- Electronic structure of semiconductors
- Phase transitions in liquid-crystal films
- Nonlinear optical response
- Molecular structure effects

A wide variety of characterization techniques, both experimental and routine, are employed including

- Time-resolved IR radiometry
- Nondestructive evaluation
- X-ray crystallography
- Microwave thermography
- Thermoelastic shearography
- Optical fluorescence, scattering, and birefringence
- Scanned-probe, tunneling, etc., microscopy
- Fourier transform IR spectrometry

CURRENT EFFORTS INVOLVING MATERIALS AND STRUCTURES AT APL

Missile Engineering
- *Nose Cone Development and Testing Recommendations*
  - D. G. Drewry and T. D. Wolf
- *High-Temperature Materials Development and Test*
  - J. W. M. Spicer, R. Osiander, A. L. Barrios, and M. J. Neuenhoff
- *An Optical Technique to Sense Thermal Stress in Sapphire*
  - J. Miragliotta and K. R. Grossman
- *Evaluation of Ceramic Matrix Composite Materials for Hypersonic Missiles*
  - T. D. Wolf and S. M. D'Alessio
- *Electromagnetic Window Engineering Analysis and Testing*
  - R. K. Frazer
- *Optical Material Characterization of Infrared Window Materials*
  - M. E. Thomas and D. W. Blodgett

Spacecraft Engineering
- *Development of High Temperature Composite Solar Panels for the MESSENGER Spacecraft*
  - P. D. Wienhold, D. F. Persons, J. E. Jenkins, C. J. Ercol, and T. J. Hartka
- *Advanced Thermal Control*
  - D. S. Mehoke
- *Infrared Wireless Bus Communications for Small Spacecraft: Materials and Structures Issues for Design Optimization*
  - S. C. Walts, W. Schneider, M. A. G. Darrin, B. G. Boone, and P. J. Luers
- *Inflatable Structures Developments for Future APL Spacecraft*
  - C. E. Willey and R. C. Schulze

Micro- and Nanotechnology
- *MEMS Thermal Control Devices*
  - R. Osiander, J. L. Champion, and M. A. G. Darrin
- *Measuring the Mechanical Properties of MEMS Materials*
  - R. L. Edwards
- *Micro-Electro-Mechanical Systems Materials on International Space Station Experiment*
  - M. A. G. Darrin, R. Osiander, and J. L. Champion
- *Xylophone Bar Magnetometer*
  - D. A. Oursler, D. K. Wickenden, L. J. Zanetti, T. J. Kistenmacher, R. B. Givens, R. Osiander, and J. L. Champion
- *Development of Nanostructured Surfaces for Sensor Applications*
  - J. Miragliotta

Other Activities
- *Nondestructive Determination of Rebar Corrosion in Reinforced Concrete Structure*
  - D. W. Blodgett
- *The Effects of Seatback Stiffness on Occupant Kinematics in Rear Impact Collisions*
  - M. Kleinberger, L. M. Voo, M. G. Bevan, and A. C. Merkle
- *Advanced Sonobuoy Project*
  - C. W. Anderson, R. W. Mitnick, D. A. Kitchin, C. W. Kerechanin, and C. A. Boyles
- *Sensing and Sequestering Materials Produced by Molecular Imprinting*
  - G. M. Murray, D. S. Lawrence, D. Schauki, A. S. Perry, C. A. Kelly, O. M. Uy, and H. W. Ko

Another center of expertise is the Missile Engineering Branch of the Air Defense Systems Department, which conducts much of the dome materials and structures work already mentioned. At least two groups in the Missile Engineering Branch are involved: Mechanical Engineering and Electro-optical Systems. Together, they comprise a multidisciplinary team of people who work closely together on thermal, mechanical, structural, and optical problems. They conduct significant modeling and testing on site as well as frequent critical field tests outside of APL. (Another group now in the Power Projection Systems Department has been involved in the electromagnetic characterization of missile structures, especially domes and antennas.)

The characterization of optical, microwave, thermal, and structural properties of missile domes and airframes includes the full spectrum of analytical, experimental, and computer modeling tasks. Among many other examples, these tasks include modeling and measurement of IR signatures, assessment of material ablation and failure, as well as shock, vibration, mass, and loading characteristics of missile domes and airframes. New composite structures are being evaluated for propulsion and airframes by a number of groups. The effects of these structures on guidance, aerodynamics, and propulsion are assessed in depth. Currently, the thermal, structural, and optical evaluation of IR seeker windows is carried out. Measurement of radome-induced boresight error on microwave seeker guidance performance at high temperatures also continues to be assessed because more sophisticated guidance techniques involving the use of multiple frequencies and polarizations are being developed. A wide range of flight, wind tunnel, and ground-based tests are also conducted.

The Technical Services Department (TSD) is the central Laboratory facility for fabrication and evaluation of materials and structures, particularly for spacecraft. The TSD Materials Laboratory embodies a broad spectrum of diagnostic equipment and expertise, which are applied to demanding space, underwater, and missile guidance environments. TSD designs and fabricates biomedical systems, rapid prototypes, state-of-the-art electronics, and high-reliability microcircuits that must survive and function over a wide variety of extreme environmental conditions while meeting more challenging performance requirements. Our key role is not to produce many copies (as in the commercial world), but a single copy (or few copies) that must be very reliable. Available resources and expertise residing in TSD include

- Reliability and failure analysis
- Testing (thermal, mechanical, electrical, radiation, etc.)
- Spectroscopy and image analysis
- Life and stress testing
- Outgassing and contamination
- Surface characterization

The number of full-time staff involved in materials and structures, state-of-the-art structural design, and test and evaluation is approximately 5% of the professional staff, with the major share being approximately equally weighted in missiles, spacecraft, and composite materials. Only a handful of investigators are involved in micro- and nanotechnology.

Our sponsor base is significantly different in character for incumbent programs versus newer initiatives. The established efforts in missile and spacecraft engineering have fewer but larger sponsored programs (e.g., Navy, Ballistic Missile Defense Organization, NASA, and Army), except for advanced technology development (e.g., Defense Advanced Research Projects Agency and Air Force Research Laboratory), which has not been sustained continuously. Newer efforts are funded by a wider range of sponsors, including non-DoD agencies.

CURRENT EFFORTS AT APL

Missile Engineering

The Missile Engineering Development Process

APL's approach to developing a complex missile component such as a supersonic nose cone for the Standard Missile-3 configuration is to apply systems engineering practices. This approach generates a calibrated design and hardware structural/thermal response database that is critical for measuring the robustness of a design. It is also crucial to the identification of technical and programmatic risk areas and their mitigation through testing. Establishing corresponding risk acceptance criteria at key program decision milestones enables a program to smoothly transition from development to qualification and into production.

The integration of fluid, thermal, and structural modeling with component-level testing serves to "calibrate" the necessary analysis and substantiates the modeling assumptions used in designing new structures such as nose cones. Candidate structural, ablative, and insulating materials are screened to gather mechanical and thermal properties needed for improved prediction accuracy and to allow cost-effective testing under the most taxing conditions in a controlled laboratory setting.

Additional testing of the full-scale nose cone system design addresses integrated system response in the areas of mechanical load sharing between components, load transfer through attachment points to the remaining missile airframe, shroud discard, and aero-heating phenomena associated with ablation in high Mach number regimes. Wind tunnel and rocket-assisted sled testing can then be used to fully address critical heat flux in dynamic airflow environments, as well as material degradation from rain erosion.

Composites and Advanced Materials in Missile Engineering

One of the chief long-standing goals of continued missile development is to deploy a very high-speed long-range strike missile. Development of passively cooled, long-range, hypersonic air-breathing cruise missiles for such future tactical offensive missions will require the application of advanced high-temperature ceramic matrix composite materials to the fabrication of integrated engine/airframe structural components. In collaboration with industry, APL will be evaluating the results of short-duration (10–15 s) testing of ceramic matrix composite material samples to be tested in the dual-combustor ramjet (DCR) combustor currently in development at the APL Avery Advanced Technology Development Center. The DCR combustor test apparatus provides flow conditions simulating Mach 6 flight. The results of a missile nosecone test are shown in Fig. 4.

APL has had a significant role in the development of guided missile structures through analytical studies and critical experiments to assess new materials and advanced designs and to validate tactical hardware, particularly focusing on the impact of these structures on missile guidance. A critical development item shared by many of these programs is the radome, and, in some cases, the IR dome (or window). Radome structural integrity under the rapid aerodynamic heating associated with the boost phase of flight is a major concern. Although ceramics are used for high-speed missiles, their brittle behavior and susceptibility to thermal shock often result in the radome being the limiting component of a missile's overall performance.

IR windows are also susceptible to thermal shock and aerodynamic heating (Fig. 5), but many IR transparent materials have relatively low temperature capability and so active cooling systems are employed. A key performance degradation introduced by the sensor window, boresight error, can be altered by aerodynamic heating to such a degree that it leads to the seeker's failure to track the target. APL has made unique contributions to understanding the effects of radome boresight error on missile performance and to demonstrating these effects through careful measurement. The Laboratory's contributions

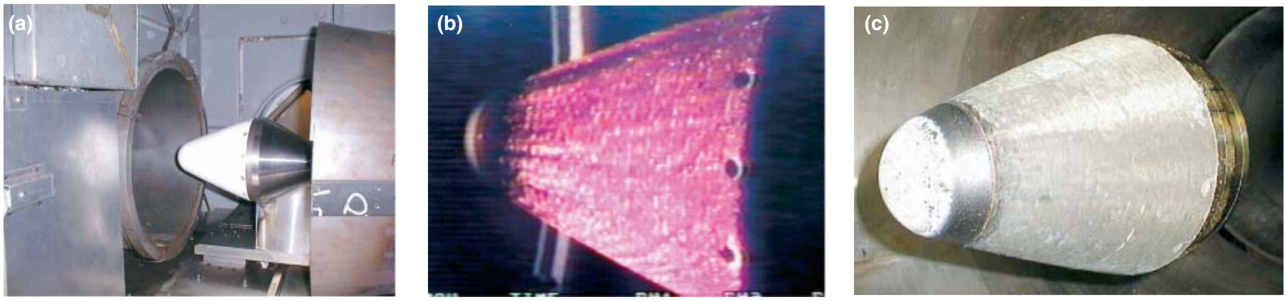

Figure 4. A composite nosecone (a) before a wind tunnel test, (b) under test, and (c) after the test.

have also addressed electromagnetic window survivability, RF performance, and the effects of heated IR domes on IR seeker performance.

Optical materials exposed to stressing missile environments require extensive characterization of their optical and thermomechanical properties to ensure reliable use. High-temperature characterization is especially important and has driven the need for new measurement techniques and apparatus. APL has addressed this need and has validated the corresponding models that represent the experimental results for subsequent incorporation in engineering studies. A good example is the remote measurement of spatially resolved IR missile dome temperature using noninvasive longwave-imaging pyrometry. Knowledge of the optical properties of a window is also useful in determining the optimal window shape. For high-speed missiles this is called conformal optics, an important current research and development area because no manufacturable window material shaped as a hemisphere can survive the expected harsh environment.

APL has also developed new diagnostic techniques to sense thermal stress in sapphire dome materials for high-speed missiles. It is well known that chromium ions in a sapphire crystal will fluoresce when excited by visible radiation in the ≈500-nm (blue-green) wavelength region. The peak position, bandwidth, and intensity of the 690- to 700-nm (deep red) optical fluorescence bands can be used to characterize the environment of the sapphire crystal, providing information on parameters such as lattice spacing and mechanical strain. Careful experiments have been conducted to decouple temperature and mechanical stress effects on the fluorescence spectral characteristics. The results of these measurements have been incorporated into the development of a noncontact probe of thermal stress at the surface of the sample. Current experiments performed at APL are calibrating the procedure so that an implementation of the technique can be developed for *in situ* wind tunnel testing.

Figure 5. Catastrophic failure of an IR dome results from aerothermal shock under high-speed conditions simulated in APL wind tunnel testing.

As a consequence of increased performance requirements for missiles and spacecraft, there is a clear need for affordable, high-temperature materials, what investigators call "unobtainium." Applications include hypersonic tactical missiles and thermal protection systems for reusable launch vehicles.

To significantly reduce costs, APL is developing flight hardware made from a class of new materials based on cellulose-derived carbon structures converted to silicon carbide by liquid metal infiltration. These materials do not require labor-intensive conventional composite lay-up or expensive diamond-tool machining, and they can be fabricated with a wide range of thermal and mechanical properties by varying the precursor material composition. These materials are applicable for engines, nozzles, and combustor liners in high-speed flight vehicles (e.g., the next generation of reusable launch vehicles). Efforts are under way to develop silicon carbide components even from carbonized wood to achieve high-temperature and erosion resistance.

Spacecraft Engineering

Survivable Solar Panels for Operations Near the Planet Mercury

The Laboratory is currently designing and fabricating the next mission to the planet Mercury, called MESSENGER: Mercury Surface, Space Environment, Geochemistry and Ranging. The MESSENGER spacecraft (Fig. 6) will have a solar array that must survive much higher temperatures than heretofore for most spacecraft, approaching 270°C. Conventional composite solar array substrates, however, operate at less than 130°C maximum. As a result, the solar panels must meet new and demanding technical and performance goals. System requirements have been developed for a variety of parameters including stiffness and

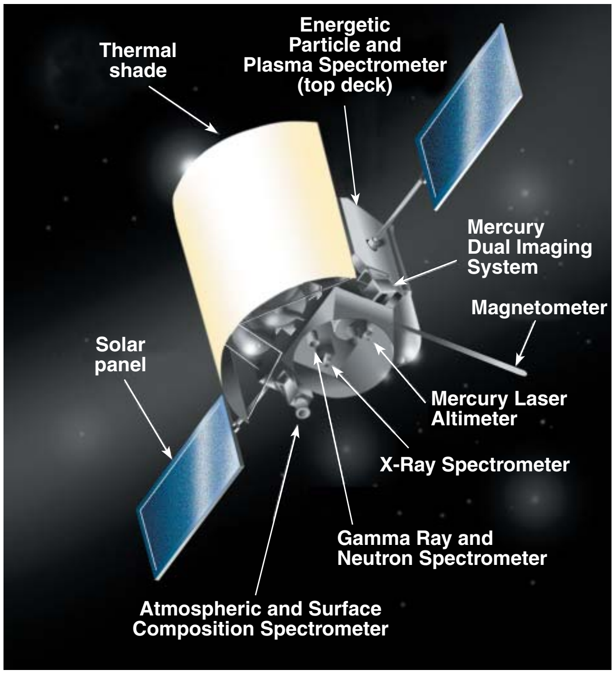

Figure 6. MESSENGER spacecraft (artist's rendering) showing critical portions that must be heat-shielded from radiation from the Sun and Mercury.

strength, thermal conductivity, temperature resistance, thermal shock resistance, flatness, hinge attachments, and low mass.

To reduce mass, MESSENGER's solar array was constructed with laminates tailored for the required mechanical and thermal loads using advanced composite materials with very high stiffness-to-weight ratios and lightweight aluminum honeycomb core material having an outer insulating layer of Kapton. The thermal shock environment requires the novel use of carbon fiber cyanate ester composite inserts at mounting locations to match the coefficient of thermal expansion of the panel skins. Standard materials and processes were chosen whenever possible to minimize schedule and cost risk. Extensive trials (including thermal vacuum) were conducted at APL to verify material selection and solve processing problems so that the flight panels would be free of defects. This technology will also be applicable to other spacecraft with missions near the Sun and may enable higher-temperature aero-braking missions into the orbits of Mars and Venus.

Composites and Advanced Materials for Thermal Control of New Spacecraft

APL is investigating new technologies based on advanced and composite materials for spacecraft thermal control. The goal is to remove the thermal management system as a significant user of spacecraft mass and power. At present, allocated heater power accounts for 10 to 30% of the spacecraft load. Separate radiator systems need to be thick for efficiency but thin for mass reduction. Technologies being investigated to drastically reduce thermal control resources include thermal switch technology, lightweight composite radiators, and improved thermal coatings.

APL is also developing and testing lightweight composite laminates using pitch-based fibers that produce a mass saving of three over conventional radiators. The combination of boron nitride powder plus a three-dimensional lay-up significantly increases the thermal efficiency of pitch fiber laminates. Laboratory investigators are also developing a new coating technique that will provide tailored optical properties to increase environmental stability and electrical conductivity.

Infrared Wireless Signal Harnesses for Small Spacecraft

One of the principal problems faced by spacecraft designers today, which is an impediment to reducing their size to microsatellites ("microsats") and nanosatellites ("nanosats"), is that the wiring harnesses are large, heavy, and custom-designed, and newer fiber-optic cables are labor-intensive. APL has begun investigating a new approach to communications in nanosats that replaces wired systems with an IR wireless link.

The Laboratory has also recently investigated materials and structures issues that affect the design of a wireless IR intrasatellite communications bus. We have considered a diffuse link that has required us to measure the bidirectional reflectance distribution function (BRDF) for various spacecraft materials. Measured BRDF data have been incorporated into a radiometric model that calculates the irradiance received throughout the plane of incidence. By varying emitter characteristics, reflector materials, and satellite geometries, this model can be used to optimize the overall communications system design. Since there are generally various obstacles in spacecraft, a diffuse link is less susceptible to shadowing than a line-of-sight link, although a diffuse link suffers greater losses. We have calculated and measured the irradiance received by IR detectors from light-emitting diodes modulated up to 4 MHz assuming an IEEE 1553 paradigm and have demonstrated operation with commercial off-the-shelf components.

Hybrid Inflatable Antennas for Spacecraft

In addition to composite materials being used in traditional rigid structures, they are being evaluated as part of large inflatable structures. By using inflatable antenna structures, spacecraft will be lighter, more reliably deployed, and less costly. They will, in addition, have smaller launch envelopes. APL's interest stems from the materials' potential for revolutionary reductions in mass, launch volume, and cost, and increased data rates on future space missions using very large antennas. The Hybrid Inflatable Antenna (Fig. 7), a concept developed by APL and ILC Dover, is an evolutionary step

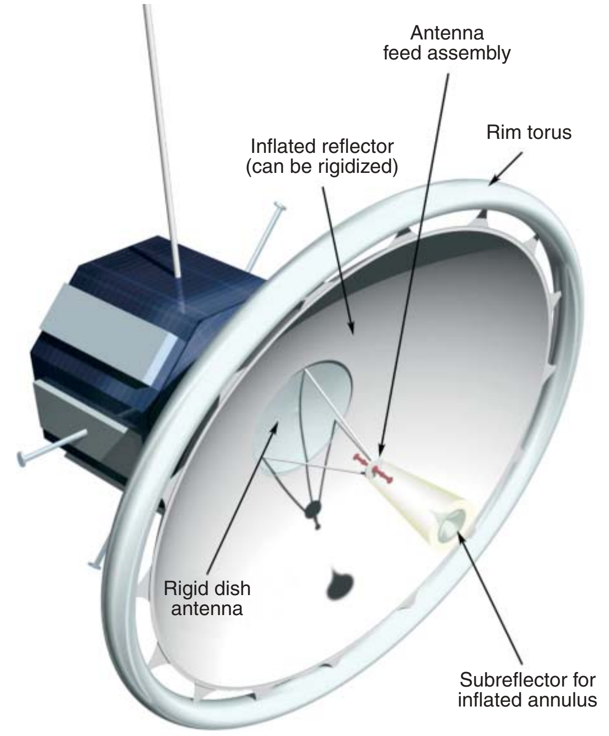

Figure 7. Hybrid Inflatable Antenna concept shown deployed on the next-generation spacecraft.

that reduces flight risk by providing a backup capability within the inflatable dish. This system combines a fixed parabolic dish with an inflatable reflector annulus that greatly increases antenna area. Current plans are geared toward developing a Ka-band (26–32 GHz) operating frequency. The rigid reflector provides a guaranteed high gain capability, and the inflated annulus provides "bonus" science return. For instance, a 1-m-diameter rigid dish acquires a 16 times greater data rate capability when the annulus is inflated to a 4-m diameter. In addition, an inflated reflector will not cover or impede the rigid dish if a deployment anomaly occurs.

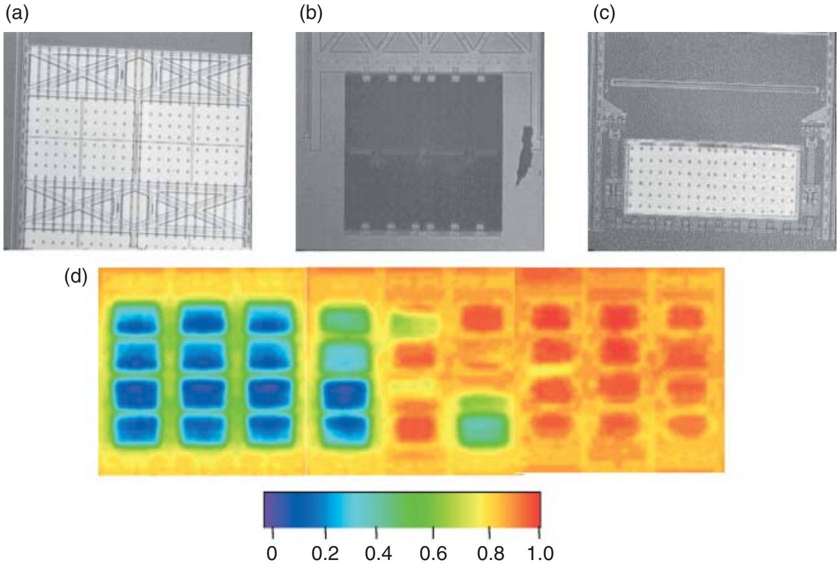

Figure 8. APL prototype MEMS louvers for thermal control: (a) slider-type shutter, (b) folder-type shutter, (c) detail of louver structure, and (d) IR image (in the 3- to 5-µm range) of a louver array in different states with an effective emissivity varying from 0.50 to 0.75 to 0.88 from left to right.

Micro- and Nanotechnology

Variable Emissivity Thermal Control of Spacecraft Using MEMS

Recent developments in microtechnology hold the promise of significant changes in the way we use materials, for instance, making them adaptable to the environment by changing emissivity to control microspacecraft temperatures (Fig. 8). The scale of these structures is also suited to small-scale systems and may serve to push APL in new directions like smart structures as well as microsats and nanosats.

Variable emissivity thermal control has been selected as a demonstration technology on the nanosat constellation concept for the New Millennium Program Space Technology 5 Project. The project will validate eight or more enabling technologies. One of the proposed technologies is the use of micromachined louvers or shutter arrays to demonstrate thermal control by varying the effective thermal emissivity of a radiator surface. At present, a number of louver and shutter prototypes have been designed and tested. The most promising design is microshutter arrays, actuated by small electrostatic comb drive motors. Prototypes are 2.5 × 5.0 mm and consist of nine independent shutter arrays. For the flight units, about 90 shutter arrays, each 10 × 10 mm in size, will be combined on a radiator and independently controlled. This is expected to allow linear control of the effective emissivity between approximately 0.1 and 0.5. The radiator can thus be adapted to a very broad range of thermal requirements during flight, which greatly increases a thermal engineer's design flexibility.

Flight and Stress Testing of MEMS Technology

APL is also involved in testing microtechnology in space environments. We will lead the team for the first long-term monitoring study of micrometer-scale devices in a high atomic oxygen, high solar ultraviolet, and solar max radiation environment as a member of the Materials on International Space Station Experiment. The micrometer-scale samples will be held in passive experiment carriers (PECs) on the exterior structure of the International Space Station for a 3-year period beginning in 2002. The APL lead PEC includes Sandia MEMS dies with photonic lattices, JHU dies for materials properties determination, APL dies with xylophone magnetometers, and a Jet Propulsion Laboratory sample of MEMS cantilevers.

In addition to space-based environmental testing, the Laboratory has also collaborated with the JHU Department of Mechanical Engineering in developing conventional ground-based mechanical stress test procedures using optical metrology techniques.

Fabrication of MEMS Magnetometers

The Laboratory has recently developed a vibrating bar magnetometer based on a xylophone resonating bar that uses the Lorentz force to measure magnetic fields. This technique is linear, has a wide dynamic range (from nanoteslas to teslas), and is ideally suited for miniaturization. Miniature magnetometers will enable the development of novel systems and subsystems, including magnetometer-assisted MEMS-based inertial measurement units capable of being used in smart munitions and mechanical mixing filters operating at microwave frequencies.

Nanostructured Materials

APL is also involved in nanostructured materials research. The Research and Technology Development Center is developing nanostructured surfaces for surface-sensitive and surface-selective optical spectroscopies for chemical and biological detection. Nanostructured substrates have become an important class of materials for sensor development, since extraordinarily high optical enhancement factors and single-molecule detection have been observed at various nanoparticle surfaces when using optical probes such as enhanced Raman scattering and visible fluorescence. The primary objective of this research program is the development of a methodology for the preparation or tailoring of chemically specific substrates for optical-based sensing. Initial investigations have focused on the use of chemically engineered nanometer-sized metal particles as the sensor substrate and surface-enhanced Raman scattering as the molecularly specific optical probe.

Other Activities

In other venues, APL is involved in a variety of diverse activities in materials and structures evaluation, including bridges and similar public structures for the Maryland State Highway Administration. These structures are subject to deterioration or corrosion of embedded metal bars in concrete. APL has developed a nondestructive measurement technique that determines the resonance (modal) properties of metal bars buried in such structures.

APL investigators are also involved in automobile safety tests sponsored by the National Highway Traffic Safety Administration. They are conducting rear impact sled tests to investigate the effects of seatback stiffness and energy absorption on occupant kinematics in rear impact collisions. This study will help determine the range of seatback properties that provides the best protection to vehicle occupants in these types of collisions.

Other large-scale structures are being redesigned by APL for improved sonar systems for the Navy. The Air-Deployable Active Receiver (ADAR) planar array sonobuoy is the Navy's primary air-deployed anti-submarine warfare acoustic sensor for detecting nuclear and diesel-electric submarines, but its size and effectiveness are limited. The Laboratory has proposed to increase ADAR capability by using stacers made from metallic memory tape helically wound to form a structural tube that can quickly deploy an array up to 40 times its compressed height with greater force and speed than possible with current technology.

OPPORTUNITIES AND CHALLENGES

Examining spacecraft engineering as an application area with respect to materials and structures, the technical challenges are those obviously associated with the stringent requirements of launch and spaceflight. Here, APL and its sponsors must respond with a generally conservative approach emphasizing minimal risk and tight quality control while timing the introduction of new high-risk materials and structures very carefully with respect to mission launch dates. The key operating principle is generally to maximize the data return at the lowest mass, cost, and technical risk while producing only one copy. This is a significant challenge.

Missile engineering offers a similar set of challenges: more difficult environments that stress the best and most expensive materials because of speed in the atmosphere. On the other hand, system requirements are now asking for multiwavelength materials or dual mode designs (i.e., RF and IR sensors looking through the same dome), as well as more sophisticated countermeasures and kinematic performance that drive us to better and better tolerances on dome parameters and composite materials for airframes and propulsion. Here, our key operating philosophy has been to make incremental changes to reduce risk and cost, especially in testing, which has taken a quantum leap in complexity and difficulty.

APL is facing several other challenges such as insertion of materials into existing or new systems and innovating new materials for the future—including guessing what they might be. We face challenges from outside the Laboratory and must determine what we can contribute. We observe that the simple notion of smaller, lighter, and stronger structures translates into novel and even exotic materials and more complex and odd-shaped form-factors requiring new fabrication capabilities, design methodologies, and diagnostics. Moreover, as budgets decline, many systems will have to stay in the inventory longer, necessitating more consideration for reliability and longevity and thus increasing infrastructure costs for materials inspection and repair.

Currently we use materials rather conservatively, that is, in their linear regimes. This practice is changing. As we attempt to push materials to their elastic limits, more accurate models, which exist, will require more accurate measurements for validation and actual use in design. In the future we can look to more exotic prospects such as smart materials and structures, or the synthesis of new capabilities by combining nanotechnology to make better composites or even enabling quantum computing, the stuff of science fiction.

Beyond APL, however, our sponsors will have an increasingly difficult time supporting new materials insertion and all the testing needed at the system and materials level. We may need to turn to the commercial world increasingly to tap into the economies of scale to reduce costs while adapting commercial materials and products (e.g., a growing reliance on plastics) to specialized needs. Recently, acquisition reform along with dual use has narrowed the “wiggle room” we have to achieve workable solutions while not losing touch with the metal.

For APL management, the challenge is a balancing act between providing a quality product (systems engineering, if you will) and keeping within tighter budgets and schedules. Our usual tried and true process of design, fabricate, test, and qualify still must be followed, albeit with the addition of concurrent engineering practices. APL has managed over the years to maintain a position of stable equilibrium, but in the future our efforts will continue to require bold vision and discipline.

CONCLUSIONS

Our strengths are in adapting and applying new materials to missile structures and in building and integrating spacecraft, where our “footprint” still remains large enough to keep our status as a world-class leader. By the same token, since we do systems engineering, we cannot afford to be too specialized in any one area, such as materials and structures, since that requires a more significant investment of resources to be competitive. We must necessarily work through our customer-facing departments to leverage the insertion and innovation of new materials and structures in systems. Materials are generally subordinate to structures in the overall hierarchy of systems and the level of attention the Laboratory is organized to give them.

We have a few options. Pooling resources from within the Laboratory to the maximum extent possible is one thing that we can more readily accomplish. This can achieve a critical mass of capability in an organizational sense, if it makes sense programmatically. Better matching people who like to innovate with those who like to apply technology, who also share an understanding of the application need, is also important. More effective and diverse interaction with institutions in government, academia, and industry that have a better concentration of resources in materials science and engineering is also warranted, perhaps in non-DoD communities. Another effective strategy is encouraging fellowships for APL staff members with outside institutions and establishing visiting scientist positions here at APL in materials science and engineering.

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