Materials: 2004, 2020, and Beyond

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Materials are a critical element of any fabricated system, enabling opportunities not only to improve performance but also to increase system capabilities, reduce cost, and expand mission envelopes. As technology evolves, miniaturization, extreme environments, and multifunctionality will ensure that materials technology will continue to play a critical role. In fact, materials are the building blocks for theory put into practice and, with proper integration, can lead to the success or failure of a program or mission. In this article, we provide an overview of current technologically innovative materials and near-term challenges, and venture toward predicting important materials and their respective applications in the next few decades.

INTRODUCTION

Forecasting technology needs for critical future missions is challenging in today's ever-changing world. For example, recent world events have quickly reshaped the focus of most DoD organizations, consequently influencing the restructuring of APL business areas. NASA also has recently shifted focus. Thus the near-term implementation of new, innovative technologies with unique materials solutions is needed to address critical and timely issues associated with national defense, homeland protection, and related space exploration missions. Materials are an essential element in the advancement of technology, as they form the *building blocks* for all theory put into practice. Therefore, for APL and its customers, it is critical to understand how materials will impact a program.[1–3]

Take a moment and look around you. Everything you see is fabricated from a material. Historically, a typical materials development cycle runs 20 years. The first 5 years cover fundamental materials research at universities, government laboratories, and corporate research facilities. Issues addressed include material formulation, basic property characterization, and subscale fabrication processes. Over the next 5 years, materials development follows a more systematic process as critical implementation issues are investigated that include process scale-up, material and component modeling, and the identification and marketing of potential end uses. In the last 10 years of the cycle, materials are incorporated into components and integrated into system applications. This process requires extensive qualification testing that encompasses the statistical characterization of manufacturing processes and properties as well as component- and system-level functionality testing.

Developing time-critical solutions to our customers' problems often dictates the integration of an existing material. The challenge is to incorporate a material into an application very different from the original use for which it was developed. While APL cannot compete with industry in the costly development of new materials, it has developed a materials-related niche that is based on the implementation of existing and emerging materials to solve near-term problems. Material developers are typically unable to fill this role because of their limited knowledge of the overall system and component-level performance requirements. APL readily fills this gap through its extensive experience in hardware development coupled with a working knowledge of materials (including design and analysis methodologies, processing, and customized test and evaluation techniques).

Consider, for example, that simple and elegant initial APL development, the famous VT fuze. Materials were integral to its success, requiring the development of rubber cups to cushion the small vacuum tube that was then embedded into a wax mixture with the other electronic components to cushion them against the 20,000 *g* firing shock. The fuze also needed a new type of battery, a wet cell that started when a glass ampoule shattered with the launch load and the electrolyte was distributed by the spinning of the shell.[4] Although this example illustrates APL's classic role (and remains our primary role to our sponsors), the next challenge is to influence the materials development world so that we can reduce the development and fielding timeline of new materials.

MATERIALS FROM A SYSTEM PERSPECTIVE

APL is generally a rapid follower in materials technologies. We examine new materials and processes as they are developed with an eye toward either directly integrating them into our customers' programs or exploring new ways to combine materials to achieve solutions, both through design and processing innovations. Innovative materials solutions have been a forte of APL that originates through our intimate understanding of the interrelationships among materials and fabrication processes, analytical modeling of material-structure responses, proof-of-principle testing requirements, and procedures for deployment in fielded systems.

One of the driving requirements of research for structural materials has always been to find a lighter-weight substitute for existing engineering materials. This is particularly true for critical missions requiring the structure to move or be transported, travel farther, loiter longer, and carry more payload mass.[5] Consequently, the evolution of composite materials (i.e., polymeric, ceramic matrix composite, and intermetallic) provides reduced mass components while sustaining or improving performance. For APL, these materials form the building blocks of most missile and spacecraft structures.

Given the apparently endless list of materials, which ones are the most important for APL to focus on? Most new materials development is science-intensive and produces small evolutionary progress, so the likely place to begin is with the current front-edge materials that can impact our existing programs (Fig. 1). Focus on a near-term solution to a critical problem often yields a desirable blend of input from materials scientists, design and manufacturing engineers, and system engineers within APL. Existing and emerging materials have routinely been incorporated into DoD systems for air defense, biomedicine, civilian and military space, counterproliferation, precision engagement, strategic systems, and undersea warfare. The following section gives a brief overview of some critical contributions that materials have made to these APL business areas.

OUR CURRENT ROLE: MISSION-CRITICAL MATERIALS DEVELOPMENT

Air Defense

The need for a lightweight, noneroding nose cone is a mission-critical element of the Standard Missile Program. The joint U.S./Japan Cooperative Research Program aims to provide a high-performance alternative solution for missile defense applications through the integration of exotic intermetallic and ceramic matrix composite materials. This combination of materials was selected to yield improved aerothermal performance and rain erosion resistance without generating seeker-contaminating debris. APL's role has focused on developing integrated material and structural models, performing prototype aerothermal contamination testing in the Laboratory's wind tunnel, and providing oversight support at critical functionality testing.

Biomedicine

The need for lightweight, flexible, and soft armor jackets to defeat high-velocity rifle bullets, such as an AK-47, is evident by the number of cases where law enforcement officers and our armed forces face these weapons. Because current ballistic plates used to defeat rifle rounds limit mobility and lack sufficient protective coverage, particularly of extremities, APL is exploring a novel flexible armor system based on the arrangement of ceramic composite disks in energy-absorbing strain-rate–sensitive rubber layers. The composite disks comprise alumina, stabilized zirconia, and Fe_3Al, a strain-rate–sensitive intermetallic. Many strain-rate–sensitive polymers exhibit a very low modulus of elasticity (stiffness) at low strain rates but a very high modulus when the material is strained at a high rate. This means that

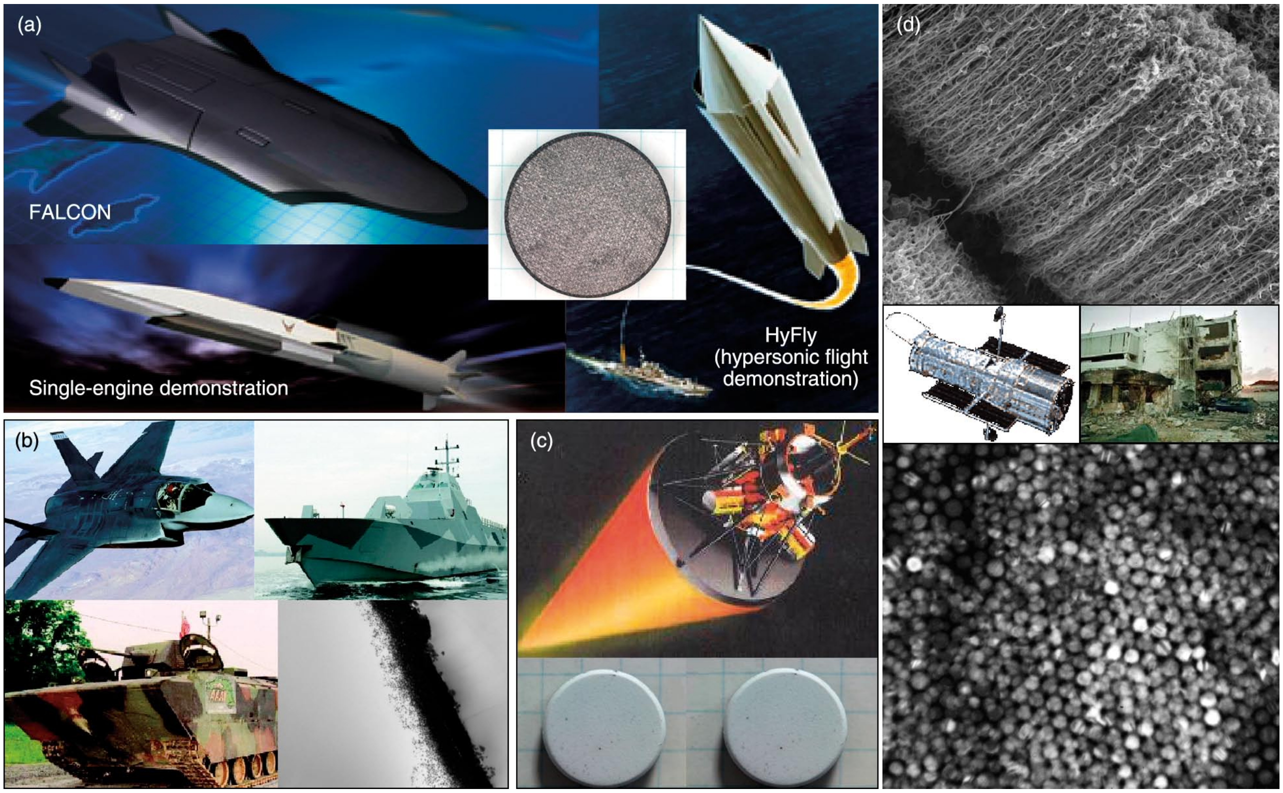

Figure 1. Materials that have served as enabling technology for past and current APL programs. (a) Refractory ceramic matrix composites for high-speed vehicles. (b) Engineered multifunctional films for paint replacement. (c) Ceramic coatings for extreme space environments. (d) Carbon nanotube interface for the Hubble Space Telescope (top and left inset) and nanoparticles (20 nm) for forensic identification of improvised explosive devices (bottom and right inset).

the material will remain flexible when a person walks or runs but under ballistic impact at high loading rates will stiffen to help dissipate the energy.[6]

Civilian and Military Space

Space is a highly demanding environment, with conditions unlike most encountered on Earth. Requirements on space-bound materials can range from radiation hardness to stability in extreme temperature environments to negligible outgassing in a vacuum. Because of these constraints, scientists and engineers are constantly seeking new materials that will provide advanced functionality.

For example, the requirements for the MESSENGER solar array substrate panels were far different from those for other spacecraft; not only did the panels have to be light and stiff, they also had to have extremely high thermal conductivity, near-zero thermal expansion, and metallized Kapton bonded to one side, and they had to survive temperatures up to 270°C (Fig. 2). These requirements were further complicated as the structure had to use conventional composite materials typically cured at 180°C (notionally their service limit). Early in the program, four vendors supplied qualification panels intended to meet these requirements, but the panels failed when tested at 270°C. The Laboratory then began to develop a robust substrate panel laminate with an innovative design and process. Using APL's process, the vendor was able to successfully pass qualification tests and deliver high-quality substrate panels that were populated with solar cells and mirrors, and then were integrated into the MESSENGER spacecraft, which is now on its way to Mercury.

Recently, a critical issue arose with the Thermal Interface Kit for the Space Telescope Imaging Spectrograph planned for the Hubble Space Telescope (HST) refurbishment mission. To attach a new spectrometer to the outside of the HST, good thermal contact needed to be ensured. The interface in question was not well suited for such contact, since the exterior of the HST was a rough surface not originally designed for this purpose. As thermal resistance at microscopic gaps can be very high in a vacuum, a suitable conformal thermal contact material had to be identified. To complicate matters, the astronaut applying the thermal contact material to this junction had to awkwardly maneuver upside down while sliding the material along a distance. Hence, conventional thermal interface materials were deemed unsuitable and a conformal, nonsticky thermal contact material was sought. APL proposed the use of a flexible array of carbon nanotubes, satisfying the high intrinsic thermal conductivity and high

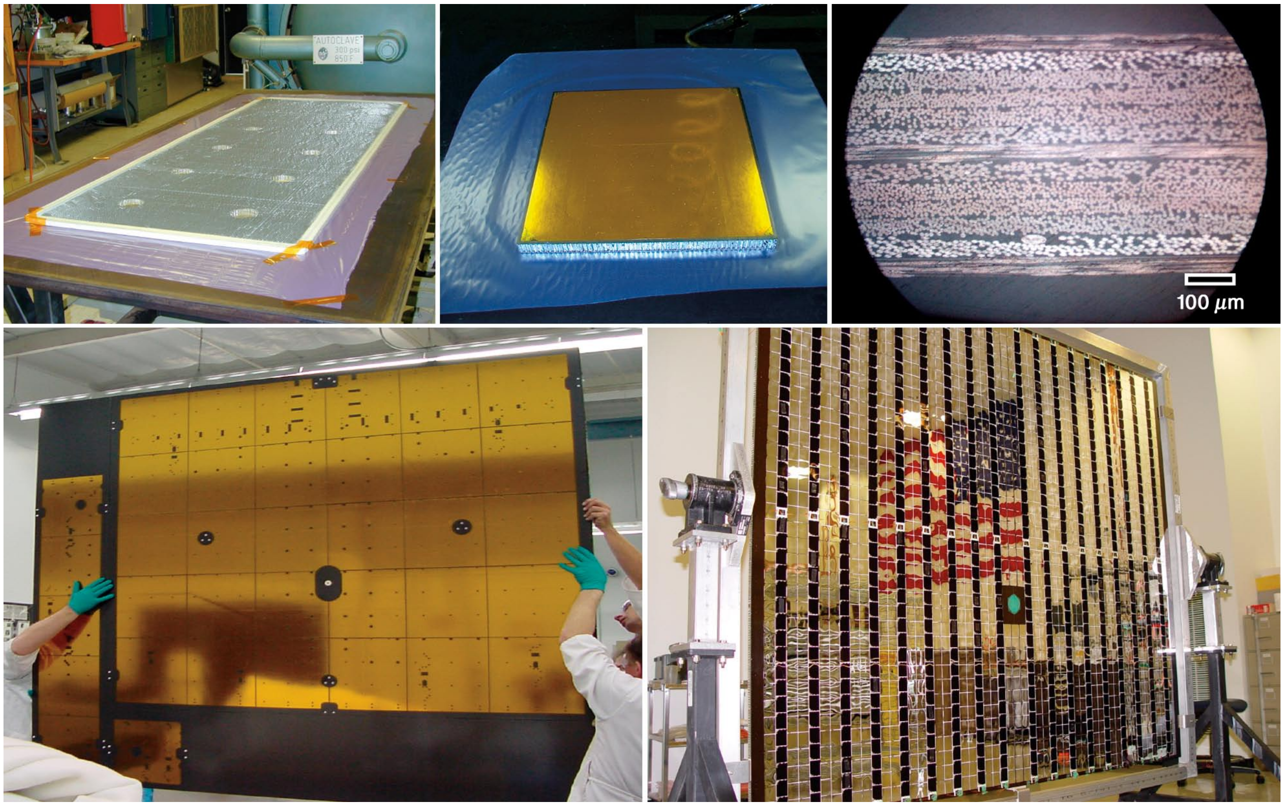

Figure 2. Advanced high-temperature composite solar array substrate fabrication for the MESSENGER spacecraft. Clockwise from top left: Panel process development and fabrication. Completed test panel. Micrograph cross section of the face sheet laminate. Populated solar array with solar cells and mirrors. Solar array substrate panel before solar cell application.

density requirements for the contact points. This concept was accepted and tested by NASA. The interface did in fact perform as well as conventional thermal contact materials, with the advantage of also being reversible.[7]

Homeland Protection

Energy management or dispersal is becoming a requirement for electronic systems and military sensors, shock absorption or mitigation on transportation platforms, personnel protection, and thinner, lighter, impact-resistant transparent materials for face shields and windows. APL is adapting and developing packaging materials that allow the use of more economical off-the-shelf electronics for these extreme conditions.

Precision Engagement

The HyFly program is jointly funded by the Defense Advanced Research Projects Agency and the Office of Naval Research and is structured to demonstrate technology associated with a hypersonic time-critical strike weapon. This missile features the dual combustion ramjet engine, developed in the 1970s by APL, and is designed to fly at speeds of Mach 6+ and to ranges exceeding 400 nmi. These system goals cannot be achieved without the development of refractory-based ceramic matrix composites (CMCs) tailored for engine and airframe components that can be operated for long durations without supplemental cooling.[8] APL has played a significant role in the development of materials formulation and process options and in conducting wind tunnel–based aerothermal testing and evaluation of components. As a result, a revolutionary CMC has been developed with demonstrated survivability in highly oxidative environments at temperatures greater than ≈2590 K for 10 min. or longer with negligible erosion.

Strategic Systems and Undersea Warfare

APL has also developed flexible syntactic foam that allows the fabrication of a floating GPS antenna for submarine deployment (unpublished results available from the authors). Commercial materials did not survive the deployment and retrieval mechanism.

OUR FUTURE ROLE: EMERGING MULTIFUNCTIONAL MATERIALS TECHNOLOGY

The use of existing materials coupled with emerging materials technology leads directly to the future of multifunctional materials and structures. This multifunctional thrust is uniform and unanimous across all organizations within the DoD. APL is uniquely positioned to influence the future direction of multifunctional materials as a result of its intimate involvement in current and emerging systems. A critical element that enables multifunctionality is manipulation of the physical microstructure of materials at the micro- and nanoscale levels. While our past materials-related activities have been at the macro level, a large portion of our future lies in the micro-nano world.

The prefix "nano" is particularly relevant to the topic of materials because many material properties change as certain physical dimensions approach the nanoscale. To illustrate the uniqueness of the nanoscale, consider that the hardness and strength in a polycrystalline material have a particular maximum value when grain size is on the nanoscale. Grain boundaries exist between grains in a polycrystalline material, and there are dislocations between lattice planes in each grain. Yield typically occurs as strain is applied when dislocations move in a grain. As grains become very small, the percentage of grain boundaries in the material increases. At some particular grain size, when strain is applied to the material, dislocations pile up at all of these grain boundaries and can no longer move. Therefore, the mechanism for yield is now essentially inactivated, and the material becomes very hard.

Ongoing and proposed research at APL incorporating these revolutionary nanoscale characteristics can be used for multiple purposes and thus inherently span several business areas. Other materials that do not rely on nanoscale phenomena and are still in their conceptual phase can also potentially impact future APL missions. These technologies need to be watched and experimented with by the Laboratory so that we can understand their strengths and limitations and make sound recommendations regarding their use in future applications. The following paragraphs describe specific new-start research activities at APL and identify interesting emerging materials technologies that appear to enhance our core technology capabilities.

Engineered Protective Coatings

Mission-dependent protective coatings that can be applied and easily removed to quickly alter the surface characteristics of vehicles or stationary platforms are currently being investigated within APL. These materials (commonly called "appliqué") are receiving increased attention within the DoD for applications requiring low-maintenance paint replacement, lightning strike protection, IR and laser defeat camouflage, and activated-on-demand self-decontaminating surfaces. These effects are obtained by doping thin Teflon-based films with a variety of nanoscale materials, thereby dramatically altering their chemical and physical characteristics. Envisioned impact areas at APL include unmanned aerial vehicle and Joint Strike Fighter camouflage and paint applications for precision engagement, self-decontaminating surfaces for counterproliferation, and low observable coatings for strategic systems and undersea warfare.

Optical Surfaces for Thermal Management

The ability to manipulate the optical properties of a surface to provide thermal management is an innovative approach to controlling equilibrium temperatures of future spacecraft structures. A potential application is NASA's Solar Probe mission, which uses a carbon/carbon heat shield to protect delicate instrumentation during the near-solar encounter. At the closest approach to the Sun, the blackbody equilibrium temperature is predicted to be 2100 K. At this temperature, the heat shield will outgas and compromise the collection of critical solar wind data. An alternate approach being investigated by APL is the development of a functionally graded material that would provide structural integrity and thermal management while ensuring protection to EUV, ionizing radiation, and high-speed particulate impact. The solution incorporates a white ceramic surface (e.g., PBN, Al_2O_3, and BaZP) that is integral to the carbon/carbon substrate. Preliminary test results indicate that the predicted equilibrium temperature for the heat shield will be on the order of 1300 to 1500 K, thus mitigating outgassing issues.

Structural Supercapacitors

Airborne vehicles (unmanned aerial vehicles, weapons, spacecraft, etc.) and ground-based platforms (e.g., unattended surveillance sensors and robotic explorers/observers) used for DoD missions have unique electrical power demands. Typical power scenarios range from long-duration, low-power operation to surge-power discharges. Long-duration, low-power scenarios result from basic system components such as onboard processors, sensors, actuators, and low-power endo-atmospheric communication devices. Surge-power requirements (typically short in duration) arise from satellite communications devices and load leveling for high-demand components such as electrical motors. Power demands are currently met using conventional energy storage devices (batteries) with poor power-density efficiencies, thus adding substantial parasitic mass.

A better method would be to fabricate the basic structures from a supercapacitor material. Such a "structural supercapacitor" would be capable of providing both primary and supplemental power to conventional power sources. A carbon-based composite material system that has tailorable structural and electrical properties is being investigated. The proposed system consists of a fiber-reinforced laminate containing both alternating high and low electrically conductive layers, impregnated with an electrolytic solution, to form a supercapacitor.

The microstructure of the material can be readily tailored to achieve supercapacitor characteristics compatible with power demands.

Rigidizing Ceramic Foams

Historically, large space-related structures such as antennas, positioning booms, and platforms have been manufactured on Earth and then transported to space. However, because of launch vehicle volumetric and mass restrictions, this approach is inherently limited and severely constrains the possible design and size of space structures. This has led to the development of inflatable structure concepts, which are very light, highly compact, and easily deployed. But inflatable structures require replacement gas to maintain their shape and may not have the required stiffness for some space applications.

APL is investigating a well-known material system that has physical properties and manufacturing characteristics well suited to the space environment. Sodium silicate or other similar inorganic compounds can be used as the precursor material for the formation of ceramic foams, glass matrix ceramic fiber composites, and glass thin films in space environments. These inorganic material systems are very stable liquids at room temperature and form low-density foams via dehydration (accomplished through the use of microwave, laser, or solar concentrator heat sources in conjunction with the vacuum of space). These materials can be engineered for in-space manufacturing and long-term use (e.g., maintaining the shape of inflatables).

The Future Soldier

Nanostructured materials promise future improvements in energy absorbing potential by providing increased numbers of energy absorbing surfaces and interfaces within a material. The Future Warrior 2020 system looks to adapt nanotechnologies into a complete head-to-toe suit that monitors, communicates with, and protects the soldier—all at reduced weight. The materials will consist of textiles impregnated with nanomachines, sensors, and a computer that turns impacted areas into hard armor as needed and enables medics to monitor the soldier's injuries.[9] The integrated communications will enable the commander to treat each soldier as an integrated weapon system, much like today's weapons platforms. Another potential development is inserting "nanomuscle fibers" into the textile that can actually augment the soldier's own strength.[10]

Next-Generation Electronics

Flexible electronics are devices deposited on flexible substrates (e.g., plastic), thus enabling the placement of electronics into nontraditional spaces. A highly desirable application of these materials is "electronic paper" on which circuits can be printed by inkjet or other printing. Work on flexible boards, including multilayered boards, is under way by many commercial companies and has the potential to revolutionize display technology. Improved plating processes that allow circuit formation on nonplanar/complex surfaces are great enablers toward this goal. Flexible substrates and conductors will allow circuit folding and routing through structural spaces, and even rolling into tubes.

Self-Healing Materials

The DoD and industry are exploring self-diagnosing and self-repairing materials to facilitate condition-based maintenance as a method of controlling costs and decreasing the probability of catastrophic failure. "Materials that are self-diagnosing, self-repairing, and are multifunctional would potentially be of great value in many applications."[11] Efforts are under way to develop composite structures that contain microspheres filled with an uncured polymer resin. When a structure built with this material is damaged, the resin will spread into cracks as they form and prevent the damage from propagating. Previous work on remotely queried embedded microsensors proved that wireless sensors could be embedded into structural materials.[12] The next step is the integration of sensors into the material that can trigger maintenance actions without degrading material performance. Nanoscale machines that bridge or rebuild localized areas of damage in a structure are also a possibility.

Environment-Friendly Materials

Biodegradable materials have typically been a compromise with trade-offs for other engineering properties. New efforts are focused on retaining material performance while adding biodegradability. Nontoxic, antifouling surface materials are being investigated for improved Navy hull coatings. Two approaches are under study: one to modify surfaces so that biomaterials will not adhere, and the other to develop coatings similar to the paints used today, but that do not leach into the water.

Nontoxic projectiles are also desirable for the military to simplify cleanup of the battlefield after a campaign. Traditional materials such as lead and depleted uranium are toxic and impose a cleanup cost on training and test facilities. "Green" munitions have been developed, but new material combinations and processing improvements are being investigated to minimize the impact of material substitutions on performance.

CONCLUSION

APL has historically provided and will continue to provide innovative solutions to mission-critical problems by applying existing or emerging materials technologies. Our unique role, made possible by our extensive hardware and systems engineering experience, enables timely, risk-managed solutions. The ability to integrate an extensive materials knowledge base developed through real-world experience, as well as one-of-a-kind design-analysis codes developed and calibrated over many decades that can perform high-fidelity testing of prototype hardware, enables a truly unique approach that is highly valued by our customers. While APL has not been heavily involved in fundamental materials development because of the prohibitive costs, we now see a strong trend toward the Laboratory providing sponsor-requested oversight during the early phases of development. This early involvement enables materials to be tailored to satisfy a broad range of performance requirements and potentially reduce the materials development cycle, as end use requirements are addressed from the onset.

Since the DoD continues to require more aggressive system performance, we see a strong trend toward multifunctional materials and structures. These solutions provide mass- and volume-managed designs that enable new mission capabilities to existing DoD systems. The key to multifunctionality resides in the ability to tailor the material system at the microscopic level. APL's role in this new technology thrust resides in our ability not only to affect the macro-level hardware results as we have previously done, but also to engineer the microstructure via macro- and nano-scale chemistry to produce materials with unique, previously unattainable physical properties. In the end, we envision not only added capabilities but also revolutionary solutions to entirely new classes of problems.

REFERENCES

[1]*The Defense Science Board 2001 Summer Study on Defense Science and Technology*, Defense Science Board, Washington, DC (May 2002); http//:www.ciaonet.org/wps/dod48/.

[2]*Materials Research to Meet 21st Century Defense Needs*, National Research Council, The National Academies Press (2003).

[3]*Assessment of Directions in Microgravity and Physical Research at NASA*, National Research Council, The National Academies Press (2003); http://nap.edu/books/0309086396/html/.

[4]Klingaman, W. K., *APL—Fifty Years of Service to the Nation*, JHU/APL, Laurel, MD (1993).

[5]*More Capable Warfighting Through Reduced Fuel Burden*, Defense Science Board Task Force on Improving Fuel Efficiency of Weapons Platforms, Washington, DC (Jan 2001); http//www.acq.osd.mil/dsb/reports/fuel.pdf.

[6]Biermann, P. J., Roberts, J. C., and Reidy, R., "Impact Resistant Flexible Body Armor," filed with the U.S. Patent and Trademark Office (27 Apr 2004).

[7]Sample, J. L., Rebello, K., Saffarian, H., and Osiander, R., "Carbon Nanotube Coatings for Thermal Control," in *Proc. Intersociety Conf. on Thermal and Thermomechanical Phenomena in Electronic Systems* **1**, pp. 207–301 (2004).

[8]*Defense Technology Area Plan*, DoD Director of Defense Research and Engineering, Washington, DC (Feb 2003).

[9]Kima, R., Koncara, V., Devauxa, E., Dufourb, C., and Viallierc, P., "Electrical and Morphological Properties of PP and PET Conductive Polymer Fibers," *Synthetic Metals* **146**, 167 (2004).

[10]Copeland, P., "Future Warrior Exhibits Super Powers," *American Forces Press Service* (27 Jul 2004).

[11]*Materials Science and Technology: Challenges for the Chemical Sciences in the 21st Century*, National Research Council, The National Academies Press (2004).

[12]Gause, L. W., Krantz, D., Biermann, P. J., and Belk, J., "Early Demonstration of Remotely Queried Microsensors," *SPIE* **3673**, 157–164 (Jul 1999).

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Paul J. Biermann is a Materials and Process Engineer in the Technical Services Department of APL. He came to the Laboratory in 1986 and has more than 24 years of experience with the manufacture and characterization of a variety of composite fiber/resin systems, from glass/epoxy to carbon/carbon. He has an extensive background in composite cure and assembly techniques, polymer molding and casting, rapid prototyping, tooling and mold fabrication, and adhesive bonding. His accomplishments include technical program management, design, and fabrication of composite components for spacecraft, biomedical, and underwater applications; materials test design; and primary technical responsibility for a series of independent research and development (IR&D) projects. Mr. Biermann has published 29 papers and a book chapter. He also holds 8 U.S. patents and has 7 U.S. patents pending and 28 other invention disclosures. He was awarded the APL Invention of the Year in Physical Science in 2003 for strain-rate–sensitive armor. **Jennifer L. Sample** received her B.S. in chemistry from Penn State University in 1997 and her Ph.D. in physical chemistry from the University of California, Los Angeles, in 2001. Since joining APL in 2001, Dr. Sample has worked extensively on bringing nanotechnology expertise and solutions to the critical challenges of APL sponsors and business areas. Her accomplishments include applying carbon nanotube arrays to thermal control applications, growth and synthesis of unique nanostructures, development of nanoscale patterning techniques based on self-assembly, and characterization of nanostructures. Her current projects include studying refractory materials for extreme environment applications, radiation effects on materials, advanced materials applied to aerospace applications, and chem/bio defense. Her primary focus is on solving challenging defense and aerospace problems using analytical and experimental methods, often involving nanoscale materials and phenomena. Her current responsibilities include providing materials and chemistry expertise on APL's High Temperature Materials and Chem/Bio Sensors IR&D project. **David Drewry** (not pictured) has more than 20 years of experience in the design and analysis, manufacture, and test and evaluation of developmental hardware and material systems designed for operation in highly stressing environments, including solid propulsion rocket motors, gun-launched munitions, guns, high-speed vehicles, and spacecraft. Hardware has ranged from prototype units featuring emerging technology to troubleshooting of fielded hardware. His material expertise includes polymeric composites, metallics, ceramic matrix composites, and highly energetic solid propellants. Currently at APL, Mr. Drewry supports the DARPA/ONR HyFly program, the Solar Probe program, and numerous research activities funded by DARPA, ONR, and AFOSR. Over the past 3 years, he has served as the Principal Investigator on an APL IR&D effort focused on next-generation high-temperature material systems tailored for spacecraft thermal management in the near solar environment. Mr. Drewry has a B.S. and an M.S. in mechanical engineering from West Virginia University. Further information can be obtained from Paul Biermann. His e-mail address is paul.biermann@jhuapl.edu.

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