

NEW WORLD VISTAS
AIR AND SPACE POWER FOR THE
21ST CENTURY

MATERIALS VOLUME

This report is a forecast of a potential future for the Air Force. This forecast does not necessarily imply future officially sanctioned programs, planning or policy.

Abstract

In this publication, important materials issues identified by the *New World Vistas* (NWV) Materials Panel are reported. The charter of this panel is provided in Appendix A. During this study, one or more members of the panel visited the organizations shown in Appendix C. From detailed discussions with technical leaders in these organizations, panel members attained an in-depth understanding of technology needs and potential technology developments relevant to the U.S. Air Force. In addition, several policy issues concerning how technology development is carried out within the Air Force (and within U.S. industry) were discussed and considered in detail by the panel.

The findings and recommendations of the NWV Materials Panel are provided in this report. Major recommendations, in both policy and technology opportunities (near-term and far-term), are compiled at the beginning of the Executive Summary. The next two sections of the Executive Summary describe the importance of materials and suggest policy and infrastructure changes to foster materials development. The remainder of the Executive Summary consists of short sections covering the most important materials applications in the Air Force. The full report consists of chapters corresponding to each section of the Executive Summary; these chapters are intended to provide more comprehensive detail on key issues of interest to technical experts and managers of research and technology development.

Advanced materials are crucial to the Air Force mission. This was a common theme borne out in discussions with each of the organizations visited by the panel. It is essential that this be recognized by Air Force policy makers, and indeed, by those who control the allocation of resources.

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Executive Summary

Overview

There is little question that the Air Force faces an exciting future in advanced materials. This is because materials can provide the technological edge that will maintain the U. S. Air Force (USAF) as the world's preeminent aerospace fighting force. One only has to examine the impact of materials in the past on Air Force systems (e.g., stealth materials in the F-117A and B-2) coupled with the fact that we are just entering the designed materials age, to appreciate the quantum leaps in performance and mission effectiveness that may be realized by the judicious use of advanced materials. We see this trend continuing and probably accelerating into the future. While it is difficult and perhaps even dangerous to predict technological developments many decades into the future, we outline below six scenarios as examples of materials development that would have a major impact on the USAF in the first half of the twenty-first century.

- Imagine an aircraft that is tailored made from materials that were computationally designed at the atomic/molecular level to allow the platform to accomplish a specific mission. The materials would be designed to be multifunctional via the specification of specific properties. In one case, these properties might include low observability and high strength/stiffness to render the aircraft technologically superior in a ground attack mode. In another case, the materials might be chosen to yield a low IR signature and yet be capable of sustained, high Mach number flight. Both aircraft would be designed by computer from “dialed-up” materials to accomplish specific missions. Indeed, it may be possible to change the properties of materials on a single airframe, as the mission demands, thereby yielding a vehicle of incredible multi-role capability.
- Imagine a precision weapon system in which the yield of the conventional warhead could be selected in flight so as to destroy a target and yet minimize collateral damage. Indeed, the yield might be selected automatically via sensors in the missile that would interrogate the target prior to impact to determine the minimum yield that is required to accomplish the mission.
- Imagine an aircraft that has been fabricated from self-healing materials and structures, such that battle damage is healed or the effects are minimized before the airplane returns to base. In the converse, imagine an aircraft that might consume, as fuel, unneeded appendages and systems after delivery of its weapons on target. Both ideas would greatly enhance survivability and mission effectiveness, and their gains would be achieved through the development of advanced materials.
- Fire has always been the Achilles' heel of high-performance aircraft from the earliest days of aviation. This is because the fuel is flammable and the higher the energy density (and hence potential for destruction of the airframe) the better the fuel. But does it have to be that way? Imagine then a fuel that is synthesized on board, as needed, from nonflammable components, thereby maintaining the inventory of flammable materials within the airframe to an absolute minimum. The impact on survivability would be enormous.

- Imagine a technology that would allow a maintenance depot to predict the development of damage due to fatigue, corrosion, or corrosion fatigue on a tail-number basis with sufficient temporal and spatial accuracy that maintenance could be scheduled on the basis of condition and condition alone. The savings would be enormous.
- Finally, imagine a technology whereby parts could be manufactured on an as-needed basis by using lasers to polymerize monomers in three dimensions, i.e., free-form manufacturing. Parts of many different shapes could be “dialed-up” from a single monomer system, thereby eliminating tooling time and expenses and greatly simplifying the manufacturing process. The need to maintain large inventories would be eliminated and changes in design would be as simple as reprogramming the computer.

The above are but a few of the opportunities that await the Air Force in advanced materials over the next fifty years. While these materials-based technologies are not with us today, except in very rudimentary form in some cases, they are not “pie in the sky.” They all stem from the incredible advances that are now being made in materials science and technology at the fundamental level. These advances, in turn, are the payoff for past investments in the future, in terms of basic research and education. Such payoffs are long-term, frequently requiring more than three decades to come to fruition. For the large part, they cannot be predicted, nor can one rely upon them happening, particularly in the absence of the appropriate prior investment. That some (perhaps even many) will become realities in the future is ordained by the nature of scientific discovery. It goes without saying that if we are to maintain the technological edge over potential adversaries, it must be we who harvest the crops.

We envision a future Air Force that is materially innovative and astute, one that has a robust R&D capability that proactively influences the development of advanced materials and advanced materials technologies. We see an Air Force that is not averse to reasonable risk in introducing new materials into aerospace systems and one whose metrics are enhanced performance and greater efficiency at a reasonable cost. Finally, we envision new materials as key enabling factors in allowing the Air Force to accomplish its mission of global reach and global power.

Policy Recommendations

During the next fifty years, the Air Force’s battlefield superiority will be threatened by today’s drastic and continuing reduction in U.S. long term industrial R&D in materials. To counter these effects, the Air Force needs to develop new mechanisms to ensure that the U.S. industrial base for advanced materials capabilities and infrastructure does not erode beyond the point of being responsive to Air Force materials needs. Thus, we recommend the Air Force commit to:

- Maintaining robust R&D programs and capabilities in innovation and development of materials for long range critical Air Force needs and not relying solely on commercial sources. Our national policy with regards to advanced materials should ensure technological advantage. Because the Air Force is a small customer for

advanced materials, commercial entities will not become reliable sources for R&D in materials unless large commercial markets exist for those same materials.

- Ensuring new funding and programs which integrate advanced materials into current and future systems, in order to help counter the downturn in military aerospace R&D.
- Demonstrating and incorporating new materials, which offer significant payoffs, in flight systems and rocket technology.
- Ensuring continued performance of aging aircraft and missiles. In order to reduce costs, the Air Force should move from programmed depot maintenance to condition based maintenance. This fundamental change in maintenance will require support for the development of new technologies in nondestructive evaluation/inspection (NDE/I), situational sensors, and life prediction techniques.
- Increasing resources for materials and processes R&D to alleviate the increasing cost of operating and maintaining the aging fleet.
- Aggressively pursuing new technologies for affordability that lessen the impact of advanced materials and Air Force operations on the environment. Environmental issues must be supported at the highest levels in the Air Force command structure.
- Adopting life cycle costing (LCC), which recognizes that early investments in materials and processes can dramatically lower life cycle costs of both new and upgraded systems. In addition, the Air Force must consider the potential cost of disposal of materials and systems and make the appropriate investments that can minimize those costs.

Opportunities in Materials and Process Technology

Some key factors driving future developments in materials and processes include: the need to lower costs and improve affordability of both new and upgraded military systems, providing the best performance systems to ensure military superiority by assuring longer life and reliability of systems and components, and addressing strategically important issues such as better stealth materials and non-polluting fluids and propellants. Finally, the Air Force needs to be the leader in novel materials R&D, such as computationally synthesized functional materials and computational materials processing, that will dramatically reduce the time and cost of development through elimination of extensive testing and current practices of creating expensive data bases for design and manufacture. Among the many opportunities in these and other areas, the paragraphs below list some premier candidates for both near term and far term applications.

Near term opportunities (less than 20 years)

- Structures: Continued focus on implementation of enhanced fiber-reinforced composites with emphasis on combined multifunctional structural and electromagnetic characteristics. Explore opportunities for unexplored structural applications like hypersonic weapon systems. Continue evolution of revolutionary new process methods that guarantee reliability and durability while reducing component costs.

- **Aircraft Engine Materials:** Successful development of the advanced materials for the Integrated High Performance Turbine Engine Technology (IHPTET) initiative will enable turbine engines with improvements such as a 100 percent increase in the thrust-to-weight ratio and up to a 50 percent decrease in fuel consumption. These engine improvements will result in dramatic operational capabilities, such as fighters with a 45 percent increase in take off gross weight and increased range. Key materials and processes for IHPTET are in the classes of intermetallics, metal matrix composites, and ceramic matrix composites. Other classes of unique new engine materials will be developed for emerging non-manrated hypersonic systems.
- **Fuels and Lubricants:** Endothermic fuels are the enabling technology for turbines in the future. An endothermic fuel uses the engine's waste heat to create a more energy-dense fuel. Advances in lubricants and seals are absolutely critical to meet mission requirements of aircraft and space vehicles of the future.
- **Optical and Electronic Materials:** The commercial technology in silicon electronics is on an evolutionary path without historical equal. While the Air Force has a significant challenge to apply this technology, it must also recognize that many of its force multiplying technologies are derivatives from niche (non-silicon) materials: IR sensors, radars, lasers, and high-temperature, adverse-environment electronics. Investment in these areas remains a critical need for the Air Force in order to maintain technology superiority.
- **Aging Systems:** Develop new methods for reducing the cost of maintaining the aging fleet. Promising approaches include: 1) Inspection without coating removal. Advanced, high resolution automated inspection methods will enable structural crack and corrosion inspection directly through paint. This will obviate the need to remove paint for inspection. 2) Direct fabrication of replacement components. New materials and processes will enable direct fabrication of finished components, allowing a dramatic reduction of inventories. This will be crucial to the required reduction in the infrastructure needed to maintain the fleet. These technologies will also enable life-cycle engineering modification of functional replacements for components that are causing problems. 3) Remote inspection of aging systems. Combined active optical inspection methods, such as laser-generated ultrasound with flexible fiber optics and MEMS, will enable assessment of internal structures without requiring disassembly.
- **Pollution Prevention:** Remediation is a very large expenditure for the Air Force. To prevent recurrence in the future, investments are required today for alternative green processes to replace existing hazardous material processes, many of which are unique for military systems.
- **Space:** Develop advanced high performance composites, both carbon-carbon and organics for thermally managed, lightweight, multifunctional structures and components. These can provide a highly desired order of magnitude improvement in thermoradiators for space applications via the use of ultrahigh conductivity carbon

fibers and conducting resins. Other significant opportunities include materials for sensors and new materials for systems to ensure access to space.

- **Transitioning Advanced Materials into Flight Systems:** The Air Force needs a program for the rapid introduction of advanced materials into flight test systems. We recommend the establishment of an Advance Materials Plane program (using existing vehicles as test beds) at the Air Force Flight Test Center.
- **Rocket Propellants:** 1) Implement major improvements in solid fuel motors by incorporating advances in binders and oxidizers (5-20 percent improvement in mass-to-orbit or a 5-15 percent increase in specific impulse). Similar improvements in liquid systems are possible. 2) Develop advanced hybrid systems with improved performance (goal of 350 sec for a strap-on) by using new oxidizers, TPE binders, gel binders, and new fuels like aluminum hydride 3) Use cryogenic high energy density materials and materials like metallic hydrogen (specific impulse greater than 1500 sec) to revolutionize access to space (performance several times greater than LOX/H₂).
- **Energy Generation and Storage:** Develop advanced secondary batteries and supercapacitors having energy densities and power densities in excess of 500 W·hr/kg and 10 kW/kg respectively, for use in advanced spacecraft. Advanced fuel cells that directly use (i.e. without reforming) liquid fuels or that employ biofuels need to be developed as LO, ground-based power sources.
- **Pyrotechnics:** Develop advanced flares for aircraft protection to defeat state-of-the-art missile seeker heads. Develop metastable interstitial composites to create extremely high temperatures for destroying chemical biological warfare agents.
- **Explosives:** 1) Exploit an opportunity for the Air Force to bring to the field advanced explosives and directed energy charges based on recently invented energetic materials. Emerging materials and technologies could result in a doubling of the explosive power of warheads. 2) Develop technologies to allow tuning of explosive charges (to fill the gap between conventional and nuclear weapons), implement advanced thermites, and exploit nanoformulated explosives to improve yield and control.

Far term opportunities (greater than 20 years)

- Prediction-based computational methods that can be used to design and synthesize of high temperature materials that will be tailored for specific applications/components. These materials will tend to have microstructures on the nano-scale and be synthesized atom by atom, obviating all of the current methods of fabrication, such as casting and metal working, with the result that these materials will be defect-free and manufactured “right the first time”. Performance, weight savings, and cost reductions will each be optimized.
- Nanophased organic materials and nanostructured composite materials, which integrate sensing, energy conversion, and structural functions. Develop new mechanisms for the systematic creation of new material structures and properties.

- Micro electromechanical systems to exploit revolutionary multifunctionality for systems at small scale approaching molecular dimensions.
- Aircraft Engine Materials: 1) Devise solutions to problems limiting the application of existing attractive materials (e.g. refractory alloys that will provide a 200°C increase in use temperature for high-pressure turbine (HPT) airfoils). 2) Synthesize new materials making use of innovative schemes for materials processing, such as laminating nano-scale composites (e.g., thermal barrier coatings that may lead to an increase of 260°C for HPT airfoils). 3) Evolve new systems applications such as hypersonic vehicles where improved or alternative materials will be used, possibly in conjunction with changes in design. These will lead to marked improvements in performance, including thrust/weight (e.g. single fluids for fuel and lubrication), resulting in savings in operational costs.
- Dynamic Stealth Materials: These materials would allow the pilot/system to change the signature characteristics of multifunctional materials at will to meet real time requirements, thereby providing the Air Force with a significant tactical advantage in the projected battle space.
- Field a family of new generation, environmentally friendly launch vehicles that are capable of inserting payloads ranging from 1000 to 100,000 pounds into LEO to meet increased demand for space access. The propulsion system should consist of entirely recyclable materials and components. Single-stage-to-orbit could become routine.
- Self-monitoring and self-healing materials to permit in-flight battle damage repair.
- Sprayable structural composite materials to cover surfaces with coatings that have one or several of the following functions: switchable antennas, tunable transmittance (e.g. for radomes), energy storage (e.g. batteries), energy production (e.g. solar cells), and sensing.
- Recyclable airframe materials that can be reversibly sintered. Organic and composite nanoparticles are particularly promising and are unexplored.
- Materials to enable enhanced optoelectronic and all-optical information gathering, transmission, processing, and storage. Processability, switching speed, and tunability give molecular and polymeric materials the greatest potential, and these materials should be further explored.
- Computer development of new materials and processes with experimental validation (e.g. complex compositional scanning for new materials and atomic-to-structural level understanding). This must also include the ability to model and assess flaws and damage in materials under realistic service conditions, especially in regions of high stress gradients, such as joints and interfaces.
- Functionally designed and fabricated material structures using localized placement of material, similar to methods employed in the semiconductor chip industry.

This could also lead to highly-unitized structures exploiting composite anisotropy with fully modeled and optimized three-dimensional (3-D) architectures.

- Path-dependent prediction of structure lifetime using real time sensor input of environmental parameters (temperature, stress, corrosion) coupled with deterministic damage models.
- Hybrid propellant systems having ultrahigh energy densities to replace liquid propellant systems.
- Novel component/materials design philosophy that provides for refurbishment of fatigue damaged areas of structural components with new materials to restore original functionality. This technology will be enabled through new computational predictive technology, coupled to materials processing, assembly, and manufacture.

Why Materials are Important to the Air Force

Air Force systems are an extremely complex integration of numerous materials and materials systems from high temperature turbine engine blades to airframe structural composites. Thus, the selection of key design materials impacts the life-cycle cost of a weapon system, including acquisition (materials and fabrication), operation, assurance, maintenance, and disposal costs. New materials offer improved performance and capabilities, such as stealth, non-chlorine-containing propellants, super-emitters, and composites that allow missions to be performed with minimum detection and loss of aircraft and personnel. In aeropropulsion systems, higher operating temperatures translate to lower specific fuel consumption and higher thrust to weight ratios.

Affordability is also a key criterion for assessing the value of new technology and its potential incorporation into military applications. Although enhanced performance continues to be a high priority, improvements must be achieved with affordable technologies. However, affordability must be considered in terms of the life cycle cost of the system. This means that revolutionary materials and processes, which in some cases are more expensive than those currently in use, may have a favorable overall impact on a system's life cycle cost (and may also provide performance advantages).

New Materials Policy and Infrastructure

The 20th century has seen the emergence of many materials that have enabled new technologies and have impacted directly our defense systems. The large scale refining of aluminum and synthesis of other airframe materials, (e.g. synthetic rubber for tires and silicon single crystals for computers), have all been key discoveries over the past century. The latent technology-enabling power of new materials is obvious if one considers a hypothetical 1995 world in which these three materials, or the processes for their large scale synthesis were not known, but remained to be discovered over the next 50 years. Our capabilities in chemical synthesis, materials characterization, and computation of properties are rising exponentially at the present time. Thus, statistically we have an excellent chance of discovering over the next 50 years comparable success stories in the realm of new materials that will enable new and important Air Force technologies. U.S. human resources alone in synthesis, characterization, and computation will

not lead easily to these critical discoveries. The key in raising the probability of success is for the interested parties, the Air Force being one, to develop a well thought-out new materials policy.

On the experimental side, the future mechanisms of materials discovery will have to include rapid property screening methodologies with very small laboratory scale quantities (milligrams to grams), and these efforts will have to be coupled closely to scale up processes when a promising new material is identified. On the theoretical side, there is no question that the search for new materials using computers will aid the exploration, thus raising the probability of critical discoveries. With regard to rapid screening, the use of the combinatorial libraries approach, as used in drug development, should be explored for new materials development, coupled with computational efforts that predict properties of new materials. Experimentally, the approach will require major hardware development for the rapid screening of micro-samples of new materials.

The full potential of a new material for technological implementation cannot be assessed without scale up of mass by at least three orders of magnitude relative to the amounts typically produced by the original discoverers. The infrastructure to pursue scale up of what appears to be a promising material as defined by the original target is, in most cases, nonexistent. This particular situation is very common in both academic and government laboratories, and presently even in industrial laboratories. Currently, the U.S. faces a major problem with regard to the exploration of new materials, since R&D efforts in this area are being rapidly downsized. The general U.S. picture for discovery of new materials that would impact directly on the Air Force over the next 50 years does not appear to be encouraging as of 1995. A new materials policy by the scientific establishment of the Air Force is therefore of critical importance. The model proposed is to fund new materials research at Air Force laboratories, and at industrial and academic institutions as well, searching carefully for in-house or external network capabilities to close the "new materials exploration loop". The new elements in the policy should include requirements for synthetic projects that demonstrate real, budget-committed connections to a structure-property screening capability and, most importantly, a second connection to a scaleup capability. The scaleup effort should probably be funded with 6.2 funds, but the basic premise in the proposed loop is to establish an early coupling of 6.1 and 6.2 funding, which seems to be critical for the successful development and implementation of new materials. This aspect of the new materials policy should also be facilitated through the creation of scaleup stations for new materials at either Air Force or academic laboratories. A final requirement before the 6.1 investment is made should be a vision by the investigators of what industrial establishments in the U.S. could implement the large scale production of proposed concepts.

The next 50 years might be totally infertile worldwide with respect to technological implementation of new materials or might give rise to dramatic developments that are beyond our current comprehension. This is the nature of discovery in the field of advanced materials; is frequently revolutionary in concept but slow in implementation. However, the real policy question to address is whether or not U.S. government institutions, the Air Force in particular, can afford to take the risk of not investing in the exploration for new materials. The risk is to be assessed in the context that other important countries are investing in new materials exploration, especially Japan, Germany, France, Korea, and China, as well as several emerging countries in the Third World. The lack of an aggressive U.S. government-supported campaign in new

materials in the future could cause us to lose the technological lead, since U.S. industry is only weakly involved in this exploration at the present time and most likely will remain so in the foreseeable future. Furthermore, government involvement in the area of new materials discovery has great potential for commercial payoff, since materials often have multiple applications. Examples that demonstrate this principle are the use of aerospace metals in orthopedic surgery and advanced composites in sporting and consumer goods. Therefore we have the following recommendations:

- Special funding of a 6.1/6.2 hybrid nature should be offered to establish “scaleup stations” to support development of new materials concepts at academic, commercial research, and Air Force laboratories.
- Establishment of a strong program of hybrid 6.1/6.2 funding for the exploration of relevant new materials. This program should be established under the guidelines of a new materials exploration loop with the objective of inducing some regeneration of the U.S. materials infrastructure.

An Air Force of Aging Systems

Reduced procurement of new aircraft is forcing the AF to extend the operational life of its current weapons systems. For the foreseeable future, this process will continue. This unanticipated extension is placing ever greater emphasis on the ability to find, characterize, and ameliorate the deleterious effects of age and use. Changes in mission requirements, to account for the lack of new aircraft for specific missions, are also accelerating the rate at which modifications must be made to existing aircraft in the fleet. In addition, many aircraft are now expected to operate with expanded mission requirements that were not envisioned originally. The health of the aging fleet is dependent on the ability to identify and characterize changes in materials and structures throughout their lifetimes. To meet these challenges, we need to:

- Develop life prediction methodologies: Integration of sensor outputs with deterministic materials behavior models will allow path-dependent lifetime predictions at the subsystem and component level, thereby leading to more cost effective maintenance decision-making.
- Validate corrosion prediction: Advanced, quantitative corrosion assessment methods will lead to validation of both corrosion and corrosion fatigue prediction methodologies, allowing much more effective control and reduction of fleet airframe and engine operation and maintenance costs. The assessment methods would include advanced sensors and multifunctional materials that would accurately track both environmental conditions and quantitative materials response.
- Refurbish materials and processes: As a corollary to condition-based maintenance (CBM) and turbine engine disk retirement for cause (RFC), a new materials/structures design philosophy will design key components to allow removal of corroded and fatigued areas with ready replacement via novel deposition/insertion/formation of new materials in place, thus eliminating 90 percent of the cost of current component replacement.

On a total system basis, retrofits, replacements, and upgrades are critical elements in all efforts to extend the life of the aging fleet. This is a particularly effective strategy for onboard electrical, electronic, and electro-optical systems, since these tend to be replaceable on a unit or modular basis; electronic, optical, and magnetic materials technologies are the enablers for this concept of life extension. As an example, the F-15 is expected to have two complete avionics suite upgrades before the airframe is finally retired.

Environment and Life Cycle Considerations

There is clearly a relationship between the environment and national security. Environmental considerations can affect national security in three fundamental ways—they pose a direct threat to the health or well-being of the public, they contribute to regional instability, or they threaten social stability.

We have probably entered the first phase of a major shift in national security thinking, involving planning to operate in a “green” future. Sherri Wasserman Goodman, Undersecretary for Environmental Security, supports this contention as revealed in her testimony to Congress in 1994—“At first the notion of a ‘green’ weapon system may seem absurd, but in reality it is not. These systems spend most of their lives in a peacetime role and often remain in the inventory for thirty years or more. During that time maintenance and refurbishment performed by contract and at our industrial depots use large quantities of hazardous materials and generate large quantities of waste.”

The Department of Defense (DoD) and the Air Force have been at the forefront of developing remediation technologies and pollution prevention processes that can contribute significantly to U.S. competitiveness. The Air Force can play a role in enhancing U.S. international competitiveness, while developing methods to control emissions, prevent pollution, and remediate past problems. At the same time, we must ensure that technologies vital to air and space supremacy can be utilized by requiring that the Air Force itself addresses the associated environmental concerns. One method to achieve this objective is to establish within the Air Force laboratories a group focused on developing the database and methodologies for performing life cycle analysis (LCA) for all current and future materials and systems.

Computationally-Driven Materials Development

Since materials are pervasive, significant changes in how materials are developed impact the AF acquisition of materials technologies. A revolution is on the horizon — a change to computationally-driven materials development. Though computers have reinvented other fields, applications in materials development have been more limited. A wholesale change in materials development practice has not yet occurred because of the complexities involved.

Computational development of new materials and processes with experimental validation is the wave of the future. Complex multicomponent systems can be studied systematically, which could not effectively be done by a purely experimental approach because of the large number of variables. The mechanical behavior of materials will be understood from atomic to structural levels. From this understanding, new materials will be developed which may have, for example, enhanced toughness. Significantly higher strength materials and higher temperature materials are also likely to result.

Recently, several examples of true materials design from atomistic simulations have emerged. To illustrate, the Air Force needs new, solid state materials such as IR detectors. Traditionally, such materials were developed by synthesizing candidate materials, growing suitable crystalline specimens, and evaluating their properties. A large number of iterations were necessary to generate enough candidate materials to explore all variables, and only a few of these materials were selected for further development. The first-principle techniques have now been used to design a series of new small band-gap compounds. Based on the calculated electronic properties, it was possible to down-select candidates for synthesis. Clearly, adoption of similar techniques to guide selection of materials for development, and to avoid unproductive research avenues, will dramatically shorten development times and enhance success rates.

Materials modeling is complex. Indeed, the task spans much of physics, chemistry, polymer science, materials science, chemical engineering, mechanical engineering, and electrical engineering. Integration of modeling with experiments will change the way the fields are practiced. The Air Force should support development of new materials modeling methods to increase the number and type of materials problems which can be economically and reliably modeled.

Structural Materials

Structural materials have been largely responsible for the major performance improvements in current Air Force systems, and will be enabling for any significant performance gains in current and future systems.

A second emerging development is multifunctional structural materials. In addition to supporting mechanical loads, the material may incorporate sensors to detect and evaluate loads or failure, and to interact with the surrounding electromagnetic environment. Intrinsically multifunctional materials have the potential of doing this without incorporating parasitic sensors. Multifunctionality may be homogeneously distributed throughout the material, as in a heat sink, but is more likely to be locally applied, such as a graded coating for oxidation resistance or as a thermal barrier. This approach is similar to semiconductor chip fabrication with localized placement of desired materials. The development of processes that can transport large quantities of material, such as plasma spray coating to build up a wing skin, are desirable. This is a continuation of the development of building up a material rather than machining it away. Direct spraying of parts will lead to significant cost reduction, compared to production and consolidation of a powder.

Limited production runs makes freeform manufacturing attractive, as well as providing the capability for easily building-in multifunctionality. Replacement of failed parts could be easily accomplished by using x-ray computed tomography to scan the part, adjusting for wear, and then freeform manufacturing from developed CAD/CAM data.

Longer range goals are the development of self-healing materials, recovery to the undeformed shape, and smart repair of cracks. These goals all try to restore a material to its original capabilities. There are approaches to each of these areas.

We recommend that the AF initiate the equivalent of an in-house X-plane program to enhance technology transition of new materials (composition or processing) to aircraft. New

systems are being built with old materials technology. Currently, the transition cycle for new materials is inordinately long, and hence the opportunities for introducing new materials in Air Force systems are severely limited. This engineering development effort would allow the accumulation of flight hours on new materials to provide the necessary systems application confidence.

Engine Materials

Research and development of materials suitable for use in turbine jet engines and other types of advanced propulsion systems may be considered over two time frames, one of 10-15 years and the other beyond 20 years. The importance of new engine materials to the Air Force can be translated into increased thrust-to-weight ratio, improved reliability and reduced maintenance, lower engine emissions, lower noise, and lower signatures. Goals include reducing engine weight by 50 percent and increasing thrust-to-weight by 100 percent. New materials and designs play a vital role in meeting these objectives.

In the shorter term, new materials for the following components are being developed as part of the IHPTET Materials Program: light weight fan blades — organic matrix composites and Ti alloys; T_3 compressor disks — Ti matrix composites; compressor blades — γ -TiAl; 816°C (1500°F) HPT disks — dual alloy superalloys; HPT airfoils — NiAl compounds and new superalloy processes; static components (cases, ducts, etc.) — γ -TiAl; and combustor and exhaust nozzles — ceramic matrix composites. Successful implementation of these developments will increase thrust/weight between 60 to 100 percent, and decrease fuel consumption by 30 to 40 percent.

In the longer term, progress in these areas will be curtailed by the markedly reduced long-range research investment by the engine producing companies. It is essential that new schemes be developed involving cooperative research between industrial technologists and others from universities and government laboratories to ensure that the long-range research on materials, which are clearly of interest to engine builders, is done. The responsibility for this lies fairly and squarely on the Air Force laboratories.

New research concepts for materials in engines to be developed beyond a 20 year period must consider not only advanced turbine engines but also hypersonic systor scramjets. It is possible to consider recommendations regarding these systems in three different categories. These are:

- Research on existing materials which have remarkable properties in one sense, but have undesirable properties in another sense, have limited their application. Research should be aimed at applying innovative concepts, including processing, and compositional and microstructural modifications, to overcome these limitations.

Example—oxidation resistant refractory alloys: high strength, good ductility and toughness leading to a 200°C increase for blades, while using innovative techniques to provide oxidation resistance.

- Developing and synthesizing new materials, making use of innovative schemes for materials processing. This represents a very exciting possibility for advances in engine technology business, with the possibility of truly revolutionary advances in performance factors.

Example—nanoscale laminated materials: enhanced thermal barrier coatings (260°C increase for HPT blades); erosion and wear resistant coatings; tunable coatings for signature control; metallic multilayers with improved properties in the areas of fatigue, fracture, and creep (similar temperature advantage over Ni super-alloys), and multilayer processing of entire components from new alloys.

- Development of new systems applications, where improved or alternative materials will be used, possibly in conjunction with changes in design, which will lead to marked improvements in performance (e.g. thrust to weight).

Example—magnetic bearings: high temperature capabilities of new magnetic materials give rise to radical changes in design of disk systems. It will be possible to dynamically position disks during operation, eliminating contact of components in high-g turns. Ultimately, some classes of engines may be able to run with no liquid lubricant, dramatically reducing cost and maintenance.

Nonlinear Optical And Electronic Materials

Electronic and optical materials are key contributors to the present and future technology superiority enjoyed by the Air Force. They are all required for information gathering, transmission, processing, storage, and display, for the control of weapons systems, and for energy generation and directed energy concepts. Force multipliers, such as IR sensors, RADAR, GPS navigation, smart seekers, and lasers for rangefinders, and target designators are all part of this technology superiority. Certainly, the weapons systems central computer and its silicon microprocessors and circuits are also key. Currently, the electronics and photonics industries are built on only a handful of materials, principally semiconductors, such as silicon and gallium arsenide, and a few other solid state inorganic compounds. Silicon technology will be advanced by the commercial marketplace and the Air Force and DoD will struggle to keep systems up-to-date. The other technologies are all dependent on non-silicon materials—GaAs in digital radar, HgCdTe of IR sensors, unique laser materials, and custom sensor windows for both IR and microwave. These are often referred to as niche materials. The AF has had, and must continue to have, an aggressive R&D program to support emerging materials to maintain superiority of electronic and optical sensor systems.

We expect these materials to continue to play a major role in industry. However, for even higher performance systems, these materials are intrinsically limited, and new materials must be found and developed. In the future, a much wider array of materials, from novel multilayered semiconductors to new polymeric materials, will be available for advanced optical and electronic applications. These new materials will be designed and processed at the atomic scale to provide optimized electrical and optical properties to meet specific Air Force requirements. As our capability to custom design and grow new materials expands, electronics foundries will change to a flexible manufacturing format, where the same growth and processing equipment will be used to create a wide variety of optical and electronic devices on demand.

These improved materials will make possible sensors with high sensitivity across the entire electromagnetic spectrum, data transmission links with greater than 200 gigabits/second, parallel processing of data at breathtaking speeds, three-dimensional data storage with almost instantaneous access, and holographic cockpit displays. They will make possible the next generations of control systems, such as the mounting of sensors and processors directly on aircraft engines. These materials will lead to new weapon concepts, such as directed energy weapons, as well as to the systems which counter them.

Electrically conductive polymers have been evaluated for some time. Polyaniline is well on its way to being the first widely commercially available, processable conductive polymer. Yet more conductive polymers will be needed since polyaniline will not meet all requirements for conducting polymers. New conductive materials, still laboratory curiosities, need to be developed into viable materials, and still others need to be synthesized.

The applications of conductive polymers are myriad. Light emitting diodes, photovoltaics, and corrosion inhibitors based on conductive polymers have all been demonstrated. The AF has interest in these and should support their research and development, as engineering polymers. The Air Force needs these materials as gap sealants, conductive matrix resins, and conductive wires. For example, the F-15 contains approximately 500 pounds of thin-gage signal wire. This could be reduced to less than 100 pounds by conductive polymers. These are niche applications not likely to be addressed by non-DoD efforts.

Weapon systems present difficult materials challenges not often encountered in the civilian sector. The Air Force needs high temperature inorganic semiconductors, especially for applications in engines and other hot environments. While several candidate materials have been identified (e.g. doped diamond), development work should continue in order to bring these materials into the Air Force inventory.

Energetic Materials - Propulsion

Our platforms are vulnerable to longer range, higher performance weapons that are available from the former Soviet Union. Our current propellant systems utilize old technology and cost more and more as incremental patches are applied to bring out-of-date systems into compliance with current operational requirements. The current inventory of propellants and other energetic materials were identified 20 to 40 years ago as having the optimum fit to the cost and performance trade-offs of the time. We are currently flying or using systems that use storable propellants selected in the 1950s and 1960s to meet prevailing cold war performance, cost, availability, toxicity, and environmental needs. Our society, industrial base, and particularly environmental and health laws continue to evolve and redefine our operability restraints without evoking a concomitant change in the energetic materials we employ. Yet ingredients have been discovered and are available that are capable of providing revolutionary payoffs for the armed forces. Other new materials are under investigation. Thus, we can correct the situation by employing our best technology in a cost and time effective manner.

The Air Force needs an aggressive program of research and development to create a new generation of boosters, air-to-air interceptors, air-to-ground missiles, and spacecraft rocket motors based on new technologies. We have fallen behind our adversaries in important areas. High payoff items identified in rocket propulsion are as follows:

- *Near term:* Major improvements for solid fuel motors due to incorporation of advanced binders and oxidizer (5 to 20 percent improvement in mass to orbit or 5 to 15 percent improvement in specific impulse) with a concomitant improvement in liquid systems. Thermoplastic elastomers and gel binders will give environmental and processing advantages.
- *Middle term:* Development of advanced hybrid systems with improved performance (goal of 350 seconds for a strap-on), investigate the use of hybrid concepts, new oxidizers, and new fuels like aluminum hydride.
- *Long term:* Development of cryogenic high energy density materials and propellants like metallic hydrogen (specific impulse greater than 1500 sec, i.e. 4 times greater than LOX/H₂) to revolutionize access to space.

Energetic Materials - Explosives

New higher energy explosives are available, but only minimal usage has been made of these materials. These energetic materials all have the ability to dramatically increase the explosive potential of warheads and bombs. These new materials can be especially effective in direct energy explosive warheads, such as those proposed for use in the next generation of air-to-air missiles. We foresee, in the long term, explosive concepts being developed to allow for “tunability” of explosive charges, as a way to vary the energy output to match the mission requirements. We also need to rethink the design requirements for explosives to match the new needs of moving metal and momentum transfer in smaller warheads. Advanced thermites are available that provide the ability to attack chemical and biological warfare sites with improved probability of destroying the target without release of the agents. High payoff items in this area are:

- *Near term:* Major improvements in the capability and/or size reductions of specialized warheads due to implementation of new materials, such as CL-20, trinitroazetadine (TNAZ), and energetic binders. New explosives are valuable for reducing the size of precision weapons.
- *Middle term:* Enabling technologies to allow tuning of explosive charges, implementation of advanced thermites, nano-formulated explosives to improve yield and control.
- *Long term:* More esoteric concepts include using theoretically possible molecules, such as polymeric nitrogen (3 times the energy density of HMX), fuels such as metal hydrides, and cryogenic explosives.

Fuels

Fuels have two basic functions; as a dense energy source and as a coolant. The energy density of hydrocarbon fuels combusted with air is unsurpassed. As a cooling fluid, state-of-the-art fuels (JP-8) have only limited capacity. Current and next generation turbine engines are exceeding the capacity of the fuel to handle the heat load. This results in coking of the fuel and subsequent clogging of fuel passages and ignitors.

Endothermic fuels are the enabling technology for turbines in the future. An endothermic fuel uses the engine’s waste heat to create a more energy dense fuel. Endothermic fuels are

simply fuels that decompose under a thermal stress to absorb heat (thereby providing a heat sink) and give hydrogen and an olefin. The engine is cooled by heat absorption caused by a chemical process, and more energy is available for the combustion process. Over the much longer term, it may be possible to synthesize fuels on-board from, for example, low flammability components in order to reduce the risk of battle damage. The synthetic route may be endothermic, thereby allowing the fuel to also act as an efficient coolant. High payoff items are:

- *Near term:* Implement improved thermal stability fuels and improved cleaning agents.
- *Middle term:* Endothermic fuels.
- *Long term:* Chemically reacting and in situ synthesized fuels.

Lubricants

Advancements in lubricants and seals, as well as sealants and other nonstructural materials, are absolutely critical for the Air Force to meet mission requirements of aircraft and space vehicles of the future. Increasing the thrust-to-weight ratios of future turbine engines will require the development of efficient lubricants that can withstand these higher temperatures. New lubricants must be developed to reduce the propensity for coking of current engines and when new, more efficient engines are fitted to aging aircraft. Turbine engine temperature requirements are exceeding the capacity of state-of-the-art lubricants. Current synthetic polyol esters have an upper temperature limit of 400°F, while perfluoropolyalkylethers, which are under development for future advanced turbine engines, will have upper temperature maximums of 630°F to 700°F. Compatible sealing technology must also be developed hand-in-hand with advanced lubricants. Both liquid and solid lubricant technology developments, including technology for hard coats and wear resistant coatings, will be necessary to meet the requirements of both expendable and man-rated engines of the future. Greatly improved liquid and solid lubricants must be developed to increase the lifetimes of spacecraft moving mechanical assemblies, such as control moment gyros and reaction wheels.

Thermal breakdown of lubricants is not currently a major maintenance problem for the Air Force. However, future systems may be severely compromised due to lack of adequate lubricants or adequate development of new concepts. High payoff items are:

- *Near term:* Increase the thermal stability of polyol ester lubricants to 450°F and increase the stability and capabilities of the perfluoropolyalkylethers and sealing systems to 700°F.
- *Middle term:* Investigate solid lubricant technology to provide lubrication to 1500°F-1800°F. Eliminate lubricant completely by use of single fluid concept (100 pound weight savings per engine), couple with endothermic fuel for additional gains or use vapor phase lubricant (Note: Single fluid concept is a very high risk approach).
- *Long term:* Magnetic levitation of motor parts and bearings. (Note: Solid or liquid lubricant may still be required for startup and shutdown).

Materials For Low Observability

Low observability (LO) is the application of technology to reduce aircraft signatures in selected regions of the electromagnetic spectrum in order to evade detection. LO is required in the radio-frequency (RF) and infrared (IR) regions, and it is highly desirable in the visible. These requirements are based on current sensing technologies: operating in the RF and IR ranges and on the ready availability of optical sensors.

The major gains in survivability achieved to date have come from the combination of improved designs and advanced materials. Future improvements in this area are not likely to be realized without advanced materials.

Materials interact with RF radiation in many ways, from bulk conductivity to molecular rotation modes and nuclear magnetic resonances, so there is a wide variety of possibilities in addressing LO. Many present and future trends in materials research can be expected to have LO/RF applicability. RF-absorbent materials and structures employing either conductivity or energy-coupling properties of the materials are bound to be the primary means of providing LO. Adding LO to fielded aircraft will continue to be a need. Additionally, to the extent that LO/RF is addressed with geometric solutions, materials that can change shape could enhance LO. Other “smart” materials may also be relevant, such as those with tunable dielectric and electronic properties. The scope of LO research should not be limited to IR and RF due to the possibility of future improvements in sensor technology.

Interactions with IR and visible radiation are more limited, with surface reflectivity and the photochemical realm carrying the current technologies. Innovative LO techniques in these regions will therefore require basic research, and the necessity for matches to background IR characteristics make solutions to this problem expensive.

A more extensive discussion of LO technologies is beyond the classification level of this document.

Materials for Missile, Space, and Launch Systems

Affordable, reliable, maneuverable, and smaller space systems are the key to the future of space systems. Of the many materials and materials processing technologies being pursued, two areas stand out as offering significant payoffs for missile and space systems: molecular self-assembly/nanotechnology and miniaturization/microelectronic machines (MEMS). Both fields have developed rapidly, and both offer potential for lowering the cost and improving the performance of space and missile systems.

Nanostructured materials have significant promise for a number of applications, both military and commercial. For aerospace uses, nanometer-based processing could provide advanced electro-optic materials, sensors, and specialized structural materials. Nanoassembly offers the possibility for creating multilayer structures specifically designed on a molecular level. For example, work is being conducted on multispectral windows, which consist of nanostructured silicon with specially designed dielectric properties imbedded in diamond or other high-temperature substrates.

Because of the high cost of inserting payloads into space, (\$10,000 - \$20,000/16) miniaturization of space components is a high-payoff investment. For missiles, cost impacts are less certain, but miniaturization clearly offers the advantage of improved performance. The reduced size will increase the need for effective thermal management. Continuing advances in miniaturization of electronics and sensors will reduce both the weight and volume of satellite and missile components. Micromachines enable extensive miniaturization of components and can provide devices with unique capabilities. Such devices include ultrasensitive acceleration sensors, microactuators, pumps, reflectors, and even gearboxes. High power density advanced IR sensor materials and nonlinear optical materials for high speed on board data processing and transmission will make major contributions to both weight and volume reduction and increased mission capability. Recent developments, such as microtubes, offer possibilities for micromachine applications as well as potential uses in processing unique components, such as self-cooled nozzles or self-monitoring “smart” devices and structures.

The achievement of micrometer precision in fabricating new devices revolutionized the electronics industry during the 1960s and 1970s, which in turn enabled development of a new generation of advanced weapons systems. Similar revolutionary advancements may be realized over the next few decades through nanometer processing. A consistent long-term investment in the fields of nanotechnology and miniaturization is strongly recommended. These fields offer great potential for enabling the development of new components and devices for aerospace systems and also have potentially broad commercial significance.

In addition to light weight, high temperature materials for launch systems, another key area in which improvements to rocket propulsion are needed are bearings in turbopump engines. Traditionally, vibrations experienced when the pump is cooled for liquid oxygen operation cause heat generation, leading to thermal runaway (LOX to GOX). In an attempt to solve this problem, these motor bearings are made of silicon nitride machined to a very fine finish with a low coefficient of friction to assist in maintaining low temperatures during operation. There are two problems with this approach. First, these bearings require high quality silicon nitride produced only in Japan. Second, the precision production and machining required for the necessary surface finish are done in Germany due to the absence of U.S. capability. Thus, there is no domestic source for these materials or components. Clearly, it is essential that our ceramics capabilities be markedly improved, not only for the production of high performance materials but also in the high level machining required to render these materials suitable for component application.

Another important area is developing approaches to combine high thermal conductivity, high modulus, and low coefficient of expansion with improved strength in carbon fiber composites. Thermal management and dimensionally stable structures are often limitations in space. Simultaneously achieving the thermal, electrical, and optical properties as well as the structural loads and displacement requirements will lead to decreased weight.

Function-Integrated Materials

The technological selection of materials commonly targets a given collection of properties, which define the material’s primary function in a system. For example, in an Air Force context, carbon-epoxy composites of an aircraft serve a structural function and are selected

because they offer a good compromise on low density, high stiffness, and high strength. Piezoelectric materials, on the other hand, are not usually selected for a structural function but for their ability to perform mechanical-electrical energy transduction with high efficiency. The materials of optical fibers are selected, of course, because of their light transmission properties, but they do not have, in fact, ideal mechanical flexibility and repair processability. Materials as we know them and use them at the present time are largely “monofunctional.” Many materials-enabled technologies can be envisioned through synthesis of structures in which multiple functions are integrated by molecular design in one material. The best examples of function-integrated materials by design are, in fact, found in biology and remain generally an unachieved goal in technology.

The vision for function-integrated materials would be materials in which sensing functions using photons, mechanical forces, and/or magnetic or electric fields are built into the molecular structure within the boundary conditions of a secondary or even tertiary function related to structure, or the ability to interconvert energy. Such binary and ternary combinations of functions by structural design has not really occurred technologically. An example of the application of such materials in Air Force systems would be sprayable and adhesive batteries or solar cells for the wings of aircraft to convert solar energy at high altitudes to electrical power. These sprayable batteries would be ideally composite structures that have the processability of currently known materials and even have load bearing capacity. Another relevant technology would be sprayable, structural composites that have a switchable antenna function to receive and process information or be stealthy on demand. The concept can be extended to sprayable materials for tunable radomes and special sensors. To close the loop on function integration, the new materials that should be explored must have potential to be recyclable. This is important not only for environmental purposes but also because function integration in materials will enable technologies at a cost.

An extremely promising and unexplored group of materials for function integration are nanophased organic materials and nanophased composites. The materials concepts proposed include the following:

- Nanoparticle polymers, that are polymeric materials made up of single molecule, nanosized particles with defined shape.
- Nanostructured composites containing organic materials and semiconductors.
- Self-assembling superlattices of discrete inorganic, organic, and/or composite nanostructures.

Energy Generation and Storage

As more advanced spacecraft are fielded in the next century, a need will develop for ultra-high energy density and high power density secondary batteries and/or supercapacitors to act as electrical buffers and power sources. These power sources should be capable of delivering in excess of 100 kW for periods of minutes (a demand that would be met by supercapacitors) and 30 kW more-or-less continuously (to be met by secondary batteries). Current battery and supercapacitor technology cannot cost-effectively meet these needs. A concerted effort is required to develop advanced power sources. Promising approaches include solid polymer electrolyte batteries based on lithium, which are now being developed, and advanced “all polymer” batteries,

still to be developed, that involve the movement of protons through the lattice on charge and discharge. We need secondary batteries with specific energies of greater than 500 W·hr/kg, and supercapacitors with power densities greater than 10 kW/kg. Based on previous battery development cycle times, the required technology is unlikely to be available before 2020.

Significant gains in solar cell technology can still be accomplished. One approach is more extensive use of compound semiconductors with high conversion efficiencies. Another is to enhance the performance of solar cells by tuning the semiconductor band gap to match the solar spectrum. Record breaking conversion efficiency of 27 percent has been demonstrated using these strategies. Another exciting possibility for higher efficiency is the “discovery” of semiconductor materials that generate more than one electron per photon, through hot electron or Auger generation processes. These types of materials are predicted to have conversion efficiencies approaching 50 percent.

The Air Force should also consider developing advanced “ambient temperature” fuel cells as LO alternatives to diesel generators for ground support functions. The most promising systems are advanced proton exchange membrane fuel cells like those that flew on Apollo and Gemini, but fueled by methanol without reforming. The technical challenge is to develop electrocatalysts that will permit the direct oxidation of methanol at the anode. Even more advanced systems might use jet fuel as the fuel, but this will require enormous advances in electrocatalysis. Other more far reaching fuel cells include those that burn biofuels using enzymes as electrocatalysts.

There are opportunities for impressive advances in airborne power generation based on advances in magnetic materials. These include the development of superior soft magnetic materials, possessing simultaneously high strength, high temperature, high magnetic strength, and low electrical loss, for advanced motor/generators directly integrated with small and large turbine engines for airborne power and self-starting aircraft. Advanced hard magnetic materials are also required for bearing applications on these same systems.

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