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Workshop on
INNOVATION IN MATERIALS PROCESSING AND MANUFACTURE:
EXPLORATORY CONCEPTS FOR ENERGY APPLICATIONS

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DIVISION OF ADVANCED ENERGY PROJECTS

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DIVISION OF ADVANCED ENERGY PROJECTS
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WORKSHOP SUMMARY

Introduction

On March 11 and 12, 1993, the Division of Advanced Energy Projects, Office of Basic Energy Sciences (BES), Department of Energy (DOE), sponsored a workshop in Oak Ridge, Tennessee, on "Innovation in Materials Processing and Manufacture: Exploratory Concepts for Energy Applications." The Division of Advanced Energy Projects provides support to explore the feasibility of novel, energy-related concepts that evolve from advances in basic research. These concepts are typically at an early stage following scientific discovery and, therefore, are beyond the scope of ongoing applied research or technology development programs.

The goal of the workshop was to bring together industrial, academic, and DOE Laboratory personnel to discuss and identify potential areas for which creative, innovative, and/or multidisciplinary solutions could result in major payoffs for the nation's energy economy, DOE, and industry. The topics emphasized in these discussions were: surfaces and interfacial processing technologies, biomolecular materials, powder/precursor technologies, magnetic materials, nanoscale materials, novel ceramics and composites, novel intermetallics and alloys, environmentally benign materials, and energy efficiency.

The workshop was built upon the foundation established by a number of studies on the future directions and importance of materials science and engineering. The National Academy of Sciences study, "Materials Science and Engineering for the 1990s: Maintaining Competitiveness in the Age of Materials" (National Research Council, Committee on Materials Science and Engineering, 1989) is an assessment of the progress and needed directions in the field in the face of increasing international competitiveness and energy/environmental concerns. One of the major recommendations of this assessment was to establish stronger programs focused on materials synthesis and processing that involve industry, government, and academia. A subsequent study by the National Science Foundation, "The Competitive Strength of U.S. Industrial Science and Technology: Strategic Issues" (National Science Board, August 1992), considered the specific issues related to U.S. industrial research and development (R&D). This study again concluded that there was a need for more extensive process-oriented research, including manufacturing and fundamental engineering, with industrial involvement as a key component. These, and other similar studies, have led to national initiatives focused on manufacturing technologies and advanced materials and processing.

One of the goals of the technology plan outlined by President Clinton and Vice-President Gore ("Technology for America's Economic Growth, A New Direction to Build Economic Strength," February 1993) is to promote advanced manufacturing technology. Related to this

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objective is enhancement of manufacturing R&D for the development of a new automobile, construction technologies, intelligent control and sensor technologies, rapid prototyping, and environmentally conscious manufacturing. The "green car" is one example of the potential programs related to this technology plan.

There currently are a wide range of federally supported R&D programs, including DOE programs, that are focused on materials synthesis, processing, and manufacturing. The scope of these programs is documented in, for example, the Advanced Materials and Processing Program report compiled by the Federal Coordinating Council for Science, Engineering, and Technology, Office of Science and Technology Policy (1992). Given these national planning guidelines, the purpose of this workshop was to identify specific, high-risk research topics that are not currently being addressed but, if proven, could make a major impact. This emphasis is novel, and, as a result, the findings of the workshop should provide unique input for program planning within DOE. Specifically, this type of information should be valuable for assessment of projects and directions for the Division of Advanced Energy Projects.

Workshop Structure: There were approximately 70 total participants (see Appendix A) for the workshop: 57 invited participants, plus 13 participants representing various DOE programs, and workshop organizers. To ensure industrial participation, over one-third of the invited participants were from industry with the balance from universities and federal laboratories.

The workshop had a 2-day format. The detailed program can be found in Appendix B. On the first day, there was an introductory session that summarized future directions within DOE's basic and materials technology programs, and the national studies on manufacturing and materials science and engineering. The balance of the workshop was devoted to brainstorming sessions by seven working groups. Each working group had two leaders, usually one industrial and one laboratory/academic partner. During the first working group session, the entire group was divided to discuss topics on:

1. Challenges for Hostile Environments,
2. Novel Materials in Transportation Technologies,
3. Novel Nanoscale Materials, and
4. Opportunities in Biomolecular Materials.

For the second session, the entire group (except for the working group on biomolecular materials) was reconfigured into new working groups on:

5. Alternate Pathways to Energy Efficiency,
6. Environmentally Benign Materials and Processes, and
7. Waste Treatment and Reduction: A Basic Sciences Approach.

The participants for each of the working groups are listed in Appendix C. The evening speaker, Dr. Lewis S. Edelheit, Senior Vice President for Corporate R&D of General Electric, provided additional focus on the industrial perspective on the interplay between R&D and technology. On the second day, all participants met to discuss the areas of innovation and opportunity that were defined by each working group. The working group leaders compiled white papers summarizing the conclusions of their groups. These papers make up the body of this report. The areas of opportunity that crossed multiple working groups and the major findings of each group are summarized below.

Areas of Opportunity: Cross-Cutting Themes

Several cross-cutting themes were identified by the working groups. These are categorized and summarized below.

Biomaterials and technology - In addition to the numerous topics identified by the group considering biomolecular materials, potential applications for biomaterials and technologies were identified by many of the other working groups. This field is gaining new understanding at a rapid rate. Potential opportunity areas include low environmental impact polymers and ceramics, catalytic antibodies, applications of multi-functional arrays of biomolecules, biolubricants, biosurfactants, photo-bio-electric cells, in situ biological treatment of contaminated ground water, and novel soil washing techniques.

"Green Car" - Many of the areas addressed by the workshop apply to the development of the "green car." Improvements in battery recyclability and removal of toxic elements, more recyclable aluminum alloys and polymers, functionally gradient materials, improved materials processing technologies, better catalysts, smart materials, etc., are all needed in order to attain this goal.

Smart materials - The parallel to sensors during manufacture is "smart materials" to be used in the field—materials that can recognize and respond to their environment in controlled ways. Again, virtually all working groups identified a host of applications for which smart materials could make a real impact, ranging from materials that could transform from insulating to conducting to ceramics with sensory feedback.

Process technologies - A major area emphasized was the minimization and/or elimination of toxic and other chemicals and materials that represent a threat to the environment. Areas that need innovative solutions include development of technologies for direct fabrication of components (e.g., near-net-shape processing); development of chromium-free coatings for corrosion protection; technologies that use benign chemicals in polymer processing; water-based lubricants; techniques to remove mercury from coal; novel lighting fixtures (no toxic materials); separation technologies (waste and recycle); new degreasing solvents; low-temperature processing technologies; field joining techniques for composite materials; joining of dissimilar materials; biological process for simultaneous detoxification and regeneration of activated carbon filters; biomolecular delivery of active agents to defined locations; technologies to eliminate lead and cadmium from batteries; and replacement materials for lead-containing, free-machining brasses; lead-oxides in paints; and chromium oxide in refractory bricks.

Lubricants - There were several suggestions for improvements in lubricants that could be of significant benefit to the environment. These included biolubricants, water-based lubricants, and development of dry-surface processing of metals.

Catalysts - Improved catalytic materials are needed to improve energy efficiency and reduce environmental impact. Areas for opportunity included biocatalysts; improved size-and-shape selective inorganic catalysts; modeling; and catalytic polymers.

New materials - Beyond those outlined above, a general area for opportunity was the development of new materials and alloy compositions that are amenable to recycling.

Examples included polymers with resins that can better tolerate recycling and aluminum alloys that can better tolerate compositional variations. New technologies that could provide major lifetime extensions were also discussed, including the development of wear-resistant polymers. Fully evolved functionally graded materials could have a wide range of applications. Similarly, nanophase materials need further development in order to be viable for a variety of applications. Improved insulation materials also could result in major payoffs and energy savings.

Modeling - Process and fabrication modeling were identified as areas of opportunity in virtually every technology addressed by the workshop. Participants bemoaned the lack of scientifically up-to-date models in several areas, as well as the lack of the needed properties data to use in the models. Innovative, multiscale modeling techniques, representing a radical departure from traditional, established approaches, have the potential to make a real difference in efforts to make manufacturing more efficient, economical, and environmentally sound. The introduction of parallel computers to process modeling presents a real opportunity for major advances in the field.

Sensors - For more effective manufacture and processing, the engineers and operators have to know "what is going on." Novel sensor and characterization technologies are needed for on-line, real-time applications; for use in hostile environments; bio-sensors; sensors for sorting technologies (recycle); and in-line particulate sensors (fine particle buildup).

Summary of Working Group Results

Challenges for Hostile Environments -

Surfaces: New surface characterization tools [e.g., in situ atomic force microscopy, Low Energy Electron Diffraction (LEEDS)]; improved technologies for surface finish specification; improved coatings.

Shape Forming: Lower temperature processes; novel approaches to processing; better equipment (e.g., powder processing).

Joining: Field joining/repair of composite materials (e.g., clad tubing).

Sensors: In-process and field applications; miniature; more robust; rapid response.

Modeling: Algorithms based on current scientific foundation; multiscale models, new constitutive equations; expanded properties data bases (ceramics, polymers); new, reliable thermodynamic data (e.g., silicon nitride, microwave processing); process models.

Novel Materials in Transportation Technologies -

Materials for Vehicles: Self-reinforcing materials (e.g., liquid crystal polymers, ceramics that develop in situ toughening microstructures); thermal

management materials (e.g., solar control coatings that can be either reflective or transparent); smart materials (e.g., materials that transform between insulating and conducting, shape-memory alloys, electro-rheological fluids); materials with high damping capacity (to reduce noise, vibration, and harshness); analytical models (to predict relationships among material properties, components, system design); functionally gradient materials; materials with increased life and more effective repair for highways.

Materials for Alternate Power/Fuel Systems: Materials for on-board storage of hydrogen and compressed gas (e.g., metal-lined polymer matrix composites, novel materials that chemically bind with fuels); materials for energy storage (batteries, capacitors, and fly wheels); catalysts for emission control (e.g., biomimetic coatings).

Manufacturing Processes: Joining of dissimilar materials, direct fabrication of components (e.g., physical vapor deposition); coating research (chromium-free coatings for corrosion protection, wear-resistant polymers); innovative metal-forming processes (e.g., superplastic forming).

Modeling: Process modeling, introduction of parallel computational methodologies; design of polymer composites and ceramics; near-net-shape fabrication.

Recycling: Wrought aluminum alloys that are more tolerant of compositional variations; complete removal of impurities during recycle of aluminum and magnesium alloys; polymers (e.g., recycle-tolerant resin formulations).

Novel Nanoscale Materials -

Process Technology: Innovative synthesis methods; process scaleup; structural integrity and flaw-size control through understanding of consolidation and sintering processes at nanoscale; stability at high temperatures; nanophase composites (e.g., functionally graded); synthesis routes for coating technology; economic processing and manufacturing.

Characterization: Theory and modeling; increased instrument resolution for structure and chemistry characterization; new methods.

Properties: Broad spectrum of measurements, including optical, electronic, magnetic, mechanical, and chemical properties; technologies to control properties; interface control; size-property relationships used as fundamental design tools; engineering properties and life prediction.

Opportunities in Biomolecular Materials -

Biopolymers: Modified silks and related structural proteins (longer fibers, controlled pore sizes, large-scale inexpensive production); catalytic polymers (e.g.,

specificity, no side products); noncatalytic proteins (e.g., adaptation of chlorophyll, bacteriorhodopsin, etc., for energy conversion, opto-electronic application, and modification of surface properties).

Mineralized Biomolecular Materials: Controlled mineralization on defined polymer or thin-film structures, biopolymers dispersed in ceramics and other matrices for enhanced toughness and improved sintering and other properties.

Self-Assembled Materials: Control of growth of layers of semiconductor, magnetic, and ceramic materials; application in sensors and surface modification.

New Materials: Supramolecular assemblies (e.g., large assemblies with defined shape and function, springs); hybrid structures (e.g., molecular reinforced composites); new polymers; smart materials.

Alternate Pathways to Energy Efficiency -

Energy Generation: Ceramics [e.g., increased fracture toughness, sensory feedback ("smart" ceramics)]; improved electrode materials; improved catalytic materials (e.g., biomimetics to catalyze at ambient temperature and pressure; improved size-and-shape-selective inorganic catalysts; development of self-assembling macro-molecular structures; models to predict catalytic activity for parallel computers); solar materials [e.g., organic materials for in situ photoelectrolysis of water to produce hydrogen; automated, modular self-replicating solar collection (inorganic analog to "forests")].

Energy Storage: Hydrogen storage materials (e.g., improved materials to reversibly adsorb and release hydrogen); battery and capacitor materials (e.g., improved primary and secondary batteries, and capacitors with enhanced efficiencies; elimination of lead and cadmium).

Energy End Use: Electrical uses (e.g., improved rapid solidification processes for magnets, high-T_c superconductors); insulation [e.g., lower thermal conductivities (aerogels, high-temperature polymers); environmentally conscious manufacturing processes (no CFCs); models to predict thermal conductivity]; process waste heat [e.g., improved heat exchangers (design, ceramics); thermoelectrics (e.g., multilayers)]; combustion uses [e.g., reticulated ceramics, burner design, effluent treatment (catalysts on ceramics, plasma processing)].

Recycling: Materials that do not degrade during recycling (e.g., aluminum alloys tolerant of compositional variations).

Environmentally Benign Materials and Processes -

Ceramics: New process techniques using aqueous media, removal of chromium oxides from refractory brick, low-temperature processing techniques, elimination of toxins during processing (e.g., biogenic materials to replace polymer binders and processing aids, replacements for lead-oxide additives in paints and enamel glazes, standard handling processes for whiskers).

Metals: Elimination of environmental hazards for the metal surface industries (e.g., dry surface processes and self-cleaning coatings); economic alternatives for chemicals used in chemical vapor deposition (CVD) and physical vapor deposition (PVD) processes; laser-cutting techniques; substitutes for lead in free-machining brasses; water-based lubricants; materials for alternate refrigeration systems.

Composites: Fiber recycling processes, environmentally friendly polymer-matrix composites.

Polymers: Mineralizable polymers; environmentally benign additives for polymer processing; stronger, thinner papers; better quality polymers.

Energy: Storage materials for hydrogen, compressed natural gas; fuel cells from solid oxides; techniques for removal of mercury from coal; elimination of toxic substances from lighting fixtures (e.g., tritium, thorium oxide, mercury, etc.).

Environmental Technologies: Sensors (e.g., in-line particulate sensors); materials to encapsulate toxic substances; risk assessment tools.

Waste Treatment and Reduction: A Basic Sciences Approach -

Waste Minimization: Longer life tire materials; biolubricants, biosurfactants (to replace petroleum-based chemicals); plastic development from biomaterials; 100% degradable plastics; ultrafine particle processing technologies; development of advanced ion exchange materials (e.g., temperature- or pressure-dependent exchange reactions); safer dry-cleaning solvents; new degreasing solvents (e.g., supercritical carbon dioxide).

Recycle/Reuse: Improved filter technology (oil filters); materials and processes to enhance recycle of plastic and metal; recyclable batteries; separation technologies (removal of hazardous materials from ash); recycle and regeneration of organic adsorbents (new materials and methodology); biological processes for simultaneous deoxygenation and regeneration of activated carbon.

Treatment, Storage and Disposal: Better waste destruction technologies (e.g., bio-detoxification processes); landfill recycle; nuclear waste form design; improved models and data bases (e.g., thermodynamic, ion activity coefficients).

Remediation: Better treatments of contaminated ground water (e.g., in situ biological treatment); soil stabilization (e.g., organic immobilization); soil washing (e.g., biological processes for detoxification of organics, separation processes for treatment of ultrafine particles).

WORKING GROUP REPORTS

"CHALLENGES FOR HOSTILE ENVIRONMENTS"

Arvid E. Pasto and William Rhodes

The goal of this working group was to identify critical areas in need of innovation related to application of materials in hostile environments. The workshop focussed on areas relating to DOE's needs and thus was heavily energy oriented. The participants decided not to specifically define "hostile environments" and not to focus on specific materials. Rather, the major economic sectors with which DOE is involved were listed, and the major materials technology areas, as they relate to these sectors, were considered. From this matrix, the technologies that were involved in many or most of the sectors were evaluated with respect to the "gaps" in the technology, and these gaps were ranked in importance.

The sectors considered included: (1) health/medical/biosystems, (2) transportation energy, (3) energy conversion, (4) communications/information systems, (5) chemical processes, (6) manufacturing processes, (7) infrastructure, and (8) the environment. The technologies assessed were: (1) design, (2) modeling/simulation/testing, (3) field engineering, (4) new materials, (5) shape forming, (6) process and application-specific sensors, and (7) surface treatments.

The three most critical needs areas that would benefit from innovation were voted to be the following:

1. **modeling/simulation,**
2. **sensors, and**
3. **surfaces.**

These areas are more completely specified in the following paragraphs, and then several areas of lesser overall importance are described.

Modeling/simulation is now becoming widely used for material, component, and system design. The software and hardware for performing these design models and simulations have become more available with the rapid rise in capability of the personal computer. However, the workshop participants felt that many of the algorithms utilized in current software are lacking in several areas, particularly in that they were devised many years ago and haven't been brought up to date vis-a-vis current knowledge. The finite element software used has become more user friendly, but a critical need exists for better auto-meshing routines and for programs that will allow multi-scale modeling. That is, in areas of a component or system where there is little stress gradient, or no interfaces, the mesh can be widely spaced, but where there exist high-stress gradients, and particularly at interfaces, the mesh must be smaller. This multi-scale meshing must be optimized with respect to computational power required. Also, in dynamic modeling, the time scale of the interval steps must be made to vary automatically with the mesh size so as to minimize required computational power. The participants also felt that, in many cases, better constitutive equations are required. Of

course, to feed appropriate data into these models or simulations, a much better, especially more useful, data base of properties is required. This latter requirement is made all the more critical by the rapidity of emergence of new materials, especially polymers and ceramics. The modeling of processes, such as densification of ceramic powder compacts, puts a premium on the need for knowledge of materials properties as a function of density during densification. Another need in this area is for better "solid free-form" modeling software.

In the area of ~~sensors~~, participants felt that sensors are critically required in numerous areas. These included new or better sensors both for in-process application, and for use in materials or systems in field application, to provide for retirement of components for cause. In-process sensors are required for better characterization, for instance, of the phenomena occurring during the preparation of a green ceramic body, or during the casting of a metal component. There exists a specific need for miniature sensors, especially in the medical arena, and for inclusion into small components. Sensors, in many cases, also need to be made extremely robust to handle their environment.

The final, major generic technology area in need of innovative thinking is that of surface phenomena. Specifically, many processes in the sectors considered are limited by erosion, corrosion, or bio-incompatibility. If there were better understanding of the fundamentals of these phenomena, especially through the advent of better surface characterization tools and models, the participants felt that new materials could be devised. Also, this would bring better understanding of how to modify these surfaces. In situ dynamic atomic force microscopy and LEED were singled out for special attention. Another area of surface analysis that would benefit from better equipment and software was that of surface finish specification, to include some measure of surface perfection, or freedom from defects. Surface physical form characterization requires finer probes capable of detecting physical defects such as very tightly closed cracks and small, deep cavities.

A topic somewhat related to the last was that of joining of materials, which a majority of the participants felt was an area ripe for innovation, yet was not now being sufficiently funded by federal agencies. This is especially true for field joining or repair of composite materials such as clad tubing.

Participants bemoaned the lack of research groups or support in the United States for such apparently unrewarding work as the development of thermodynamic data. An example cited was that the currently published free energy data for such an industrially important ceramic material as silicon nitride was of doubtful accuracy. The same situation occurs for data collection in other fields; so-called "stamp-collecting" work is unexciting and thus not performed by high-quality researchers. For instance, microwave processing is currently receiving much attention, yet there are few groups measuring the dielectric properties of materials at gigahertz frequencies as a function of frequency, temperature, pressure, etc. Finally, as mentioned earlier, another lack cited is that of good data bases, in general, for corrosion, mechanical properties, sintering, etc. Many data bases that do exist are not truly useful because they are incomplete or poorly constructed.

The final topic considered relevant to many of the sectors was that of shape forming, especially in regard to the ability to net-shape form, or better, "custom-shape" form materials. Much material and effort is wasted in secondary processing activities such as machining and

grinding of ceramics and rolling or drawing of metals. This research area might include development of lower temperature processes, better materials of construction for fabrication equipment, and new processes for shape forming. Modeling can play a major role in developing a better understanding of such currently utilized shape-forming processes as injection molding and pressure slip casting by allowing better visualization of fluid flow under pressure into the often complex shaped molds. Rheology of powders and powder/binder mixtures is another specific area in need of better measuring equipment and theories.

"NOVEL MATERIALS IN TRANSPORTATION TECHNOLOGIES"

Ron Bradley and Andrew M. Sherman

The Transportation Working Group was made up of representatives from manufacturing companies, materials suppliers, and a broad cross section of researchers from national laboratories and universities representing the metals, ceramics, and polymers areas. With such a diverse group, there was no lack of good ideas. The challenge for our group was to select those ideas that should be given highest priority and that are the most suitable for funding by the Advanced Energy Projects Division.

Materials for Vehicle Systems: There is a vigorous competition among materials for applications in automobiles. The past two decades have seen the evolution and implementation of high-strength steel alloys, dramatic increases in the use of plastics and aluminum, and the development of many specialized materials, such as in catalytic converters. Significant R&D efforts are currently directed at the use of aluminum and polymer composites to replace stamped steel in vehicle structures and at the use of advanced materials, such as metal matrix composites, titanium alloys, and ceramics, in powertrains and other demanding components. As in all materials and processes used in the ground transportation industry, cost-effectiveness considerations are a dominating criterion in the selection decision. However, in addition to these areas, the following materials concepts, if successfully developed, would be of value in the longer range:

Self-reinforcing materials, e.g., liquid crystal polymers or ceramics that develop in situ toughening microstructural components during synthesis, could prove to be desirable structural materials. A key requirement would be that these materials be made from low-cost feed stocks by economical processes.

New thermal management materials present a wide range of unique possibilities. Solar Control Coatings, which can be either reflective or transparent depending on conditions, could help to save energy expended on air conditioning. If employed as a paint, this could also offer opportunities for customer appeal in terms of appearance. The operation of such coatings might be either passive or active. Even if not embodied in a coating, a "smart" material with these properties might be employed in a thin panel which would insulate or conduct as necessary.

Smart materials, such as shape-memory alloys and electro-rheological fluids, have been investigated for various applications. In order to exploit the potential of these interesting materials, there needs to be a better linkage between specific applications and the direction of further materials development.

Improved noise, vibration, and harshness (NVH) performance will be a major customer-driven requirement in future automobiles. The ways in which materials innovations can contribute need to be much more fully explored. Some examples of possible topics include the development of structural materials with very high damping capacities. These could be in selected locations to absorb noises near the source, e.g., the valvetrain, water pump, etc. There is a need to develop analytical methodologies

that predict the relationships between material properties, component and system design, and NVH. This capability would be applicable to current materials and would be essential to achieving the optimum benefit from new materials developed for damping applications.

Although there are numerous examples of "functionally gradient" materials (e.g., carburized steels) in current use, it is widely recognized that there is potential to engineer and exploit gradients in structure and properties into almost any type of material. Research efforts should be guided by the needs and potential of specific applications.

The development of new and unique materials for highway infrastructure is an area frequently overlooked. Among the areas our workshop group identified as promising for research are materials for construction that offer increased life or more effective repair (e.g., of pot holes). It is also worth asking if improved road materials might contribute to increased safety and/or fuel economy.

Materials for Alternative Power/Fuel Systems: The move toward alternative powered vehicles, such as electric/hybrid, and toward alternative fuels, including those made from renewable energy sources such as alcohol from biomass, presents new requirements for materials and materials processing technologies. The following are some possible areas for research:

Materials for on-board storage of hydrogen and compressed natural gas (CNG) are needed. These might include materials for tank storage, such as metal-lined polymer matrix composites, or materials in which hydrogen or CNG are chemically bound.

Materials for energy storage, including batteries, capacitors, and fly wheels, are needed.

Catalysts for emission control with alternative fuels are needed. Biomimetic coatings were suggested as one possible research approach.

Manufacturing Processes: Manufacturing-related technologies that would benefit the transportation industry include the following:

Research on joining dissimilar materials, including metal to metal, polymer to metal, polymer to polymer, and ceramic to metal, is needed.

Research on direct fabrication of components such as physical vapor deposition to produce turbine blades in one step instead of the multi-step process now employed. This is an area where innovative approaches to processing could result in very high payoffs.

There is a need for a broad spectrum of coating research. Some of those identified by the working group include chromium-free coatings for corrosion protection and wear-resistant coatings for plastics. Surface modification of polymers by ion implantation to improve wear and corrosion resistance was suggested as one avenue of research.

Innovative metal-forming processes, such as superplastic forming, are needed. Research on these processes or on alloys to modify the alloys microstructure or properties to make them more amenable to advanced forming techniques would be useful.

Modeling and Computational Analysis: With the introduction of massively parallel computers, there is an opportunity to reduce the time required for design and development of materials and materials processing by use of computational analysis and mathematical modeling. The working group suggested that the materials development and process development described in previous sections should be accompanied by mathematical modeling of the materials system or process. This was particularly suggested for the design of polymer composites and for the processing of ceramics.

Recycling: Technologies for the recycling of automotive materials, both scrap produced during manufacturing and vehicles at the end of their useful life, is a high-priority need. A high percentage of currently used materials is effectively recycled. However, as the materials mix changes, for example, in response to the need for weight reduction, newly developed or improved technologies will be necessary. Aluminum and magnesium alloys and polymer composites are the materials most likely to be used in substantially greater amounts; the following are some possible areas for longer range research efforts:

Wrought aluminum alloys, which are more tolerant of compositional variations, so that impurities introduced during recycling, e.g., by mixing various alloys, will have minimal effect on the alloy's properties and manufacturability.

Cost-efficient methods for controlling the composition of aluminum and magnesium alloys during recycling, such that undesired impurities can be completely removed. This would facilitate the recycling of high-purity magnesium alloys and would enhance the economics of aluminum alloys.

The development of resin formulations for polymer composites, which more readily lend themselves to recycling.

"NOVEL NANOSCALE MATERIALS"

Richard W. Siegel and Egon Wolff

The workshop group on nanoscale materials initially focused on the considerable progress made in the past few years in national laboratories, universities, industrial laboratories, and most recently in spin-off pilot manufacturing companies across a broad front in nanostructured materials. Significant aspects of this work have been funded by DOE/BES programs. These efforts have led to the creation of new nanostructured materials by a variety of methods including gas-phase synthesis, chemical processes, and mechanical methods. Demonstration of unique technological opportunities has resulted from the preliminary data that have been produced on the novel properties and processing behavior of these materials. Their unique properties, and the ability to engineer these properties during synthesis and processing, have clearly resulted in significant industrial interest in using nanostructured materials, as evidenced by the workshop discussions.

Background: Increasing interest in recent years has focused on a variety of novel synthetic nanostructured materials, with average grain or other structural domain sizes below 100 nm, with the anticipation that their properties will be superior to those of conventional materials that have phase or grain structures on a coarser size scale [Kear et al., "Research Opportunities for Materials with Ultrafine Microstructures" (National Academy, Washington, D.C., 1989), Vol. NMAB-454]. This interest has been stimulated not only by the recent efforts and notable successes in synthesizing a variety of fascinating isolated atom clusters, such as the fullerenes, zero-dimensionality quantum-well structures and one-dimensionally modulated multilayered materials with nanometer scale modulations, but also by the rapidly developing potential for synthesizing three-dimensionally modulated, bulk nanophase materials via assembly of atom clusters [Andres et al., *J. Mater. Res.* 4, 704 (1989)], chemical synthesis, or mechanical attrition.

The various types of nanostructured materials share three features: atomic domains (grains or phases) spatially confined to less than 100 nm, significant atom fractions associated with interfacial environments, and interactions between their constituent domains. Nanostructured materials include zero-dimensionality atom clusters and cluster assemblies, one- and two-dimensionally modulated multilayers and overlayers, respectively, and their three-dimensional analogues [Siegel, "Mechanical Properties and Deformation Behavior of Materials Having Ultra-Fine Microstructures" (Proc. NATO Advanced Study Institute, Vimeiro, 1992), M. Nastasi et al., eds., p. 509 (Kluwer Acad. Publ., Dordrecht, 1993)]. Interest in the possibilities for nanostructuring materials has resulted in a variety of new methodologies for manufacturing novel materials with ultrafine structural or phase domains by means of which creation of new levels of property engineering become possible through the sophisticated control of scale, morphology, interaction, and architecture.

For example, atom clusters in the nanometer size regime, containing hundreds to tens of thousands of atoms, can now be produced in commercial quantities by means of either physical or chemical processes. These materials can take advantage of and incorporate a number of size-related effects in condensed matter ranging from electronic effects (so-called "quantum size effect") caused by spatial confinement of delocalized valence electrons and

altered cooperative ("many body") atom phenomena, such as lattice vibrations or melting, to the suppression of such lattice-defect mechanisms as dislocation generation and migration in confined grain sizes. The possibility to assemble size-selected atom clusters into new materials with unique or improved properties may thus impact our ability to engineer a wide variety of controlled optical, electronic, magnetic, mechanical, and chemical properties needed for a variety of technological applications.

Generally, in synthesizing nanostructured materials from atomic or molecular precursors, one wants to be able to control a variety of microscopic aspects of the condensed ensemble [Siegel, "Mechanical Properties and Deformation Behavior of Materials Having Ultra-Fine Microstructures" (Proc. NATO Advanced Study Institute, Vemeiro, 1992), M. Nastasi et al., eds., in press (Kluwer Acad. Publ., Dordrecht, 1993)]. First and foremost is the size and size distribution of the constituent phases or structures. The desirable sizes are generally below 100 nm, since it is in this size range that various properties begin to change significantly, owing to a variety of confinement effects. A property will be altered when the entity or mechanism (or combination thereof) responsible for that property is confined within a space smaller than some critical length associated with that entity or mechanism.

Second, the compositions of the constituent phases in a nanostructured material are of crucial importance. This can simply mean maintaining phase purity during synthesis in a single-phase nanostructured material, such as an oxide or a metal, or it can mean controlling the impurity doping levels, the stoichiometries, the solute gradients, the phase mixtures, or combinations of these in more complex nanostructured materials. In this case, however, the length scales over which such composition control must be maintained can frequently push the limits of our present technical capabilities.

The third aspect of nanostructured materials that one would like to be able to control in synthesis is the nature of the interfaces created between constituent phases and, hence, the nature of the interactions across the interfaces. These interfaces can, of course, be grain boundaries between the same phase with differing orientations, heterophase interfaces, or free surfaces. Since the number of interfaces present in nanostructured materials is very large compared with conventional materials [Gleiter, *Prog. Mater. Sci.* 33, 223 (1989)], this control takes on a much greater importance. Nevertheless, it is most often rather difficult to create a nanostructured (or any other) material with prescribed interfaces. The greatest success, to date, in this area has been achieved with one-dimensionally modulated nanoscale multilayers.

The properties of nanostructured materials are determined by the interplay among these three features (domain size, composition, and interfaces). In some cases, one or more of these features may dominate. Thus, one wants to be able to build nanostructured materials under controlled conditions but with an eye to the particular property or properties needed. The degree of control available depends upon the particular manufacturing method used to create the nanostructured material. Nevertheless, it is becoming clear that we are on the verge of a major revolution in materials synthesis and processing for significant technological applications.

National Industrial Needs: The usefulness of a new technology is measured by the benefits it can provide to society. Economic, environmental, and energy-related issues are of critical national importance and have been clearly articulated by the U.S. population and representatives from the various government agencies.

Industrial participants in the workshop identified the component areas that require breakthroughs in materials technology in order to meet market and regulatory expectations. Representatives from universities and national laboratories, presenting areas of research, have shown promise for synthesis and processing technologies that can provide nanoscale materials useful to industries' needs. Industrial application needs and areas described by the private sector participants that can be significantly impacted by nanostructured materials are shown as follows:

<u>Industrial Competitiveness</u>	<u>Environment/Emissions</u>	<u>Energy Reduction</u>
structural components	solid lubricants	insulation
sensors	catalytic converters	solar panels
wear-, erosion-resistant	nanoporous filters	high-temperature
coatings	refrigeration devices	components
thermal-barrier coatings	solar panels	high-energy capacitors
		magnets

Components contributing to industrial competitiveness do so through enhancements in strength and reliability by a reduction of flaw size inherent in the overall (nano) grain size materials and higher density of grain boundaries. Coatings made from nanoscale materials have better insulative properties and lower conductivity; improved strength due to reduction in flaw size is applicable here as well. In the environment and emissions area, these nanoscale materials offer significantly larger surface areas for rapid catalysis. However, meeting these national needs requires a serious commitment from the federal funding agencies, industry, and the research community.

Research Needs: The workshop participants elucidated a number of research needs in the areas of process technology, material characterization and properties that must be effectively dealt with if the national industrial needs for nanostructured materials are to be satisfied.

In the area of process technology, the following topics were highlighted: Understanding basics, scaleup, parts fabrication, structural integrity and flaw-size control, stability at high temperatures, nanophase composites, and new synthesis routes including those applicable to coating technology.

Characterization needs were noted in the areas of theory and modeling, increased resolution capabilities in currently available instrumentation for observing both structure and chemistry, and new research tools amenable to nanoscale materials.

The properties of nanostructured materials need to be investigated over a broad range, and the ability to engineer and control them through synthesis must be elucidated.

The mechanisms for the unique properties of nanostructured materials need to be explained and then used as fundamental design tools. Engineering performance and durability must also be investigated.

In addition, it is deemed imperative that the economics of these materials and the clear possibilities for reducing integrated manufacturing costs by using them must be taken into account. If a serious national effort to meet these research needs is mounted, the workshop participants concluded that revolutionary materials performance could result from the nanostructuring of a wide variety of materials for industrial applications. A national consortium on nanostructured materials was considered by many of the nanoscale workshop participants to be necessary to accelerate, in an internationally competitive manner, the development and commercial implementation of nanostructured materials and devices.

Conclusions: The research accomplished, to date, indicates that there are tremendous opportunities for synthesizing nanostructured materials with new architectures at nanometer-length scales from atomic or molecular precursors via the assembly of atom clusters and by a myriad of other techniques now becoming available. The keys to the future of nanostructured materials, however, will be both in our ability to significantly improve the properties of materials by artificially structuring them on these nanometer-length scales and in developing the methods for producing these materials in commercially viable quantities.

The future appears to hold great promise for nanostructured materials, based upon the limited knowledge that has already been demonstrated, that even in our crude initial attempts to change and control the properties of materials via nanostructuring, it is possible to dramatically alter a variety of technologically important properties of materials in this manner.

It has been shown, for example, that the strength of normally very ductile pure metals can be significantly increased simply by reducing their grain sizes into the range where dislocation generation and migration become confined and difficult. On the other hand, normally very brittle oxide ceramics and intermetallics can be rendered more ductile and formable by reducing their grain sizes into the range where grain boundary sliding becomes facilitated by the high number density of internal interfaces and the rapid atomic diffusion therein. Since cluster "building blocks" can already be assembled with some modicum of control over the retained porosity and composition in the nanophase compact, it has also been demonstrated that significant positive effects on the chemical reactivity of a self-supported nanophase "catalyst" and the optical transparency of a nanophase ceramic "window" can result.

The possibilities for engineering the catalytic, optical, and also electrical properties of nanostructured materials will be further enhanced by the ability to control the compositions and defect structures in these materials. Such examples suggest that even more exciting opportunities may be available as we learn in the future to synthesize more sophisticated multifunctional and functionally graded composite nanostructured materials.

Combining the various aspects of nanometer scale and composition and interface control in nanostructured materials to create a variety of new technological materials with atomically engineered properties will be a great challenge. Fortunately, we are beginning to learn something about the relationships between nanostructure and material properties and how these might be changed through a variety of synthesis and processing methodologies to

control material performance. It seems quite possible that by developing the means for creating new materials engineered from atomic or molecular precursors, we may indeed be on the threshold of a new era in materials technology. It is a challenge, therefore, that appears to be well worth the effort.

"OPPORTUNITIES IN BIOMOLECULAR MATERIALS"

Mark D. Alper and David Fink

Introduction: It has been recognized for millennia that living organisms synthesize and process an extraordinary range of materials that can be used for other applications. While cave dwellers focused on skins for clothing and bone for tools, we now see lubricants in joints, adhesives in marine mollusks, optical materials in the eye, semi-permeable membranes in all cells, and molecules that can pump ions convert photon energy into chemical energy or recognize and respond to events in the environment. These sorts of materials hold especially great promise for applications today because of their inherent energy efficiency and environmental compatibility. They are usually biodegradable and lightweight, and their synthesis and processing have low energy demands, produce far less toxic and nontoxic waste, involve water rather than hazardous solvent media, do not require petroleum feedstocks, and often involve far fewer steps than are required for corresponding nonbiological materials.

While materials produced by living organisms have been known for their useful properties and, in fact, are used widely outside the organism, it has been recognized that for many nonbiological applications, the properties of these materials would need to be altered or enhanced before they could perform at the required level. In many cases, the forces of evolution have been focused on allowing living things to craft materials that are just "good enough" for any given criterion, the result of a compromise to allow satisfaction of other criteria not necessarily relevant to a nonbiological materials application. In other cases, the properties for which the materials have been evolved are simply different from those needed for the new, nonbiological application. It has, for example, been shown repeatedly that enzymes are not designed for maximum stability but simply for sufficient stability to function under the conditions of the cell. In plants, the light harvesting system of chlorophyll has been designed to capture photons in low light. As a result, it is poorly designed for use in commercial systems designed to take full advantage of the photons available under high-brightness conditions.

Until recently, the redesign and optimization of biological materials was not more than a wish, and there was no organized field devoted to the pursuit of these opportunities. Less than a generation ago, the concepts of specifically modifying a single nucleotide monomer among the thousands in a particular gene, of selecting individual antibody molecules from a population of 10^{10} , or of improving upon natural silk, were as unimaginable as the idea of electronics without vacuum tubes had been a generation before that. The recent revolution in biochemistry, molecular biology, and bio-organic chemistry has changed that: a new field of materials research, "biomolecular materials," has arisen in which researchers specifically modify or simply create bio-molecules with desirable properties for specific applications. It is a new field; a great deal of fundamental research remains to be done. However, some groundwork has been laid, and judiciously chosen research directions are very likely to result in significant new achievements in the coming years, both in the basic research and also in the more applied aspects of the field.

Biomolecular Material Categories - The panel on Biomolecular Materials first sought to define the boundaries of the discussion and identify those materials that were and those that were not to be included in the study. It was agreed that appropriate targets of investigation should include those materials that are:

- made by living organisms,
- made by living organisms and then modified in the laboratory,
- made by living organisms that had themselves been modified,
- made *in vitro* by a process that is unique to a living organism, and
- made *in vitro* by a process patterned after that of a living organism.

The last category includes materials not necessarily thought of as having a biological origin. It was included in the discussion because the research involved in developing these materials involves the study and adaptation of the same biological processes involved in the synthesis of the materials in the preceding category.

It was also noted that the end use of a biomolecular material need not involve a living organism—the nature of the material and its synthesis is the primary defining factor.

Finally, it was agreed that not all materials with an end use in a living organism would be included. Some (for example, alloys, ceramics, silicones, or many synthetic polymers designed for implants but not resembling biomolecular materials either in structure or in mode of synthesis) would be more appropriately labeled biomaterials.

Focus Areas - The panel outlined four major areas in the field that could serve to organize the discussion for identification of research directions:

1. **biopolymers materials,**
2. **mineralized materials,**
3. **self-assembling materials, and**
4. **new materials.**

Crosscutting all these areas is the study of techniques for synthesis and processing.

Biopolymers: In the broad field of biopolymers, the panel identified several major areas for research:

Structural polymers include, for example, the proteins silk and collagen, the carbohydrates cellulose and chitin, polyesters including the polyhydroxyalkanoates (PHAs), and the nucleic acids including DNA and RNA. The synthesis of these polymers could proceed either *in vivo* or *in vitro* and, depending on the polymer involved, could proceed through the use of naturally occurring, modified, or synthesized genes (DNA sequences) with naturally occurring or modified monomers.

Basic research issues here involve the development of an understanding of the relationship between the monomer sequence of the polymer and the structure and properties of the

polymer. More specific, technical issues involve, for instance, the stability of synthetic DNA sequences (especially those that are repetitive), scale-up to industrial levels, and solubility of novel polymers.

Advanced Energy Program projects focused on specific properties could have a major impact in a relatively short time. One example mentioned was the modification of the gene for silk, possibly by inserting a new DNA sequence coding for a recognition site that would lead to longer silk fibers capable of forming networks or materials with controlled pore sizes. Alternatively, even though PHAs are already commercially available as plastic films, they are still the subject of active research, especially with regard to the control of properties through the substitution of novel monomers in the polymer. Success in transferring genes into organisms, such as plants for large-scale inexpensive production, would have a major impact.

Catalytic polymers include naturally occurring enzymes, those which have been modified through the techniques of genetic engineering and catalytic antibodies, which might be referred to as "created" enzymes. Their great value is based primarily on their specificity, that is, their ability to select a single starting reactant from a mix and then selectively convert it to a single product with no side products to leave problems of toxicity or waste. Their ability to catalyze reactions at room temperature and pressure and to produce products that are likely biodegradable makes them particularly useful for research aimed at issues concerning energy and environment.

Basic research in this area involves the development of an increased understanding of the relationship between the amino acid sequence of the enzyme and its function, both substrate specificity and catalytic activity. Questions of enzyme stability and activity in harsh environments are also to be pursued.

Shorter term goals with great potential impact involve the designed alteration of the enzyme to permit catalysis of a novel reaction or the development of catalytic antibodies to give new enzymes that accept novel substrates and make novel products or have increased stability in industrial reactors.

Functional noncatalytic proteins include, for example, the proton pump bacteriorhodopsin (which has been shown to function in holography and pattern recognition); the plant photosynthetic protein chlorophyll, which plays a major role in the conversion of light into chemical energy or water to hydrogen for coal gasification; and other proteins which can function, for example, in the efficient transfer of electrons or as lubricants or adhesives.

Basic research here is dedicated to increasing our understanding of the mechanism by which these functions are performed and how small changes in the proteins can lead to significantly altered function.

Examples of potentially exciting focused research for AEP include, for instance, increasing the efficiency with which chlorophyll uses light energy to produce hydrogen gas (for coal gasification) or electrical currents ("photo-bio-electric cells"), modifications of bacteriorhodopsin to control its functioning in holography, or redesign of protein lubricants or adhesives. Of particular interest with both the functional and structural proteins would be manipulation of portions of the genes (domains) to create a single protein with multiple

functions. One such product, a fibronectin derivative, is already on the market. A final area of great potential importance and impact, as mentioned above for structural proteins, is the development of techniques to move the genes for desired proteins into organisms such as plants that can serve as low-cost, high-efficiency "factories" for their production.

Mineralized Biomolecular Materials have, as their traditional model, tissues such as bone, teeth, and shell. More recently discovered natural systems include magnetic or semiconducting particles in microorganisms. In all cases, the nature of the crystallization of the inorganic phase and, therefore, the mechanical and other properties of the material is controlled by underlying organic material. For example, the egg shell is believed to have as many as ten distinct mineralized regions, each controlled by a different organization and structure of the underlying matrix polymers.

Fundamental research in this field focuses on the understanding of the nucleation and crystallization processes and their regulation by specific macromolecular mediators. Other important issues include the mechanisms by which ionic constituents are transported to the growing ceramic zone and the nature of the layer-by-layer construction principles, which are the biological equivalent of Free Form Manufacturing, and which lead to net-shape, fully-densified, organic-ceramic composite structures.

Focused, shorter term research could involve mineralization on defined polymer or thin film structures, or the construction of molecular dispersions of biopolymers in ceramics that could provide increased control of the microstructure, perhaps increasing toughness and decreasing sintering temperatures. The control of the growth of the layers of semiconductor, magnetic, and ceramic materials on functionalized thin self-assembled (see below) films is also an attractive target, decreasing both the health hazard of the processing and the temperature required for it, while increasing accessible complexity by introducing, for example, pores in the films.

Self Assembled Materials: The term "self-assembly" can be applied to the processing of a wide variety of biomolecular materials, including both proteins and carbohydrates. The panel focused on lipid-like monomers that can self-assemble into mono- or bilayer films, or vesicles, and liposomes for discussion in this section of the report. Supramolecular structures are discussed below.

Manipulation of the structure of the lipid-like monomeric units has great potential for allowing control of the properties of these structures or, in fact, creating more complex structures of defined function. Control of thin film structures for mineralization research or of membrane structures to act as matrices for functionally active proteins, as described above, would be major contributions. Control of the surface of the films, through synthetic, bioorganic, and surface chemistry would allow the development of sensors, surface modification agents, or structures for separating materials. The partition of hydrophobic and hydrophilic regions in these materials also holds great potential for their use in delivery of active agents to defined locations.

New Materials: The recent emergence of the field of biomolecular materials, based primarily in the development of techniques for their synthesis and processing, fuels expectations for the

development of novel materials that are based on, but bear increasingly little resemblance to, their biological model. Examples of such structures include those with or based on:

- novel microarchitectures and supramolecular assemblies,
- hybrid structures,
- new polymers, and
- "smart" materials.

Supramolecular Assemblies - The very fact that the nature of the synthesis of biomolecular materials is simplified through processes such as self-assembly or enzymatic synthesis allows us to reason that more complex structures can be constructed through these means than would otherwise be attainable. Biological examples abound, including functioning protein complexes of over 100 subunits or molecular weights in excess of 1 million. The exquisite complexity of a cell membrane, with lipids, proteins, and carbohydrates as components of transport, signaling, recognition, and electronic systems, is another excellent example of the potential for complex multifunctional, designed materials. The concept of producing large assemblies with defined shape or function (e.g., springs) from synthetic and naturally occurring materials is not beyond imagination.

Hybrid Structures - The living organism has set a clear example of the value of combining different types of polymers in a single molecule. Glycolipids, glycoproteins, and lipoproteins involve carbohydrates, proteins, and lipids covalently linked in single molecules as components of multifunctional arrays. Simple models have already been studied in which block copolymers have been shown to fold spontaneously into highly ordered multiphasic structures. Alteration of polymer properties to allow blending holds great promise for novel properties. Molecular reinforced composites, using biomolecular materials of different shapes and mechanical properties, show promise.

New Polymers - Biological polymers usually involve the use of monomers with a common combining group for polymerization and a small number of variations at other parts of the molecule. This limited number of variants (4 in nucleic acids, 20 in proteins) is already far in excess of the number presently available to traditional polymer chemists. The development of an increased range of variants or the development of an increased array of combining groups opens the way toward novel polymers with unexpected properties and structures.

Smart Materials - Proteins are the ultimate "smart" materials. Many can sense the presence of multiple environmental factors and perform a complex, weighted summation of the influence of these factors. These proteins can then alter their shape and function in response. Development of simpler models of these structures would be an important advance.

Conclusion: In general, the panel agreed that recent research breakthroughs in a variety of fields have created a wealth of new opportunities for the development of new biomolecular and organic materials. There is now enormous potential for the atomic-level design, synthesis, processing, characterization, and use of these materials in a wide range of material applications. Some applications are reasonable targets now, others will come soon, still others after more extensive fundamental research. It is also likely that additional areas, for example, those based on biological motors, thought processes, or self regeneration, will also be fruitful at some time in the future.

"ALTERNATE PATHWAYS TO ENERGY EFFICIENCY"

Jeff Richardson and Richard R. Petrich

As organized today, the energy industry (whether derived from natural gas, coal, petroleum, electricity, or some other source) is composed of a complex network of generation (supply), transmission, storage, and end use. The efficiency of this network determines, in part, the effectiveness of any particular energy source. Improving energy efficiency is a policy, as well as a technical issue, requiring an integrated, third-generation R&D approach. Consequently, any proposed innovations would need to be evaluated in the context of national goals motivated by enhancement of energy security, environmental considerations, and, ultimately, improved economic competitiveness. These national goals tend to be long term but need to be balanced against and partnered with industrial goals, which tend to be more short term and profit/cost driven.

From our working group, it became apparent that although a number of changes and innovations leading to improved energy efficiency could be implemented, perhaps the most effective strategy would be a program containing a balance of short- and long-term goals. Each industrial/national goal would be associated with corresponding technical goals in materials and manufacturing processes and include an overall systems evaluation to relate and evaluate the technical innovation to the overall industrial/national goal. Finally, wherever possible, international cooperation should be sought, as global benefits resulting from improved energy efficiency cannot be fully achieved based solely on national advances in materials and manufacturing processes.

The working group, which consisted of many representatives from various industries, felt that many improvements in energy efficiency could result from application of systems engineering motivated by national policy using existing materials and manufacturing processes. Examples of such energy efficiency improvements would result from increased mass transit, introduction of smaller cars for local travel, and use of proven alternate energy sources such as wind power (e.g., although ranking 12th in the nation in terms of wind energy, California produces 98% of the nation's wind-generated electricity). Other alternate energy sources (geothermal, oil shale, underground coal gasification, waves and tides, biomass and biofuels) were briefly discussed and have obvious potential advantages for improving energy efficiency with corresponding materials and manufacturing issues (e.g., lightweight structures for wind turbines, corrosion-resistant materials for geothermal). However, these energy sources were not further discussed because they have been and/or are being actively pursued and appeared less susceptible to unsuspected breakthroughs in appropriate innovations in materials and manufacturing processes.

Each of the four phases of the energy life cycle (generation, storage, transmission, and end use) was examined for specific examples where innovations in materials and manufacturing processes would have high leverage in improving energy efficiency.

Energy Generation: In a broad sense, the generation of energy can be classified as those fuels obtained from renewable and non-renewable sources. For example, fossil fuels represent non-renewable energy whereas solar energy is a renewable source. Because of

recent public and private environmental concern (motivated in part by national goals), it is anticipated that natural gas will play an increasing role as a non-renewable fossil fuel, particularly in non-utility power generation, transportation propulsion, and co-generation power applications (i.e., where useful heat in addition to electricity is generated).

Ceramic Materials - Improved ceramic materials in turbine components would result in higher operating temperatures ($\geq 1200^{\circ}\text{C}$) with corresponding higher thermodynamic efficiencies and reduced atmospheric emissions. In addition, the reduced cooling requirements would also result in higher gas throughput and, hence, higher efficiency; it is estimated that a 1 to 2% increase in efficiency would result in a \$1 million/year savings for a 200-MW gas turbine. Material property improvements in ceramics and ceramic matrix composites focus mainly on increases in fracture toughness (e.g., fiber reinforcement, crack bridging, and nanostructured ceramics in nanolayered form). In addition, development of sensory feedback systems, perhaps through smart ceramic materials, would provide information relating to *in situ* materials degradation and incipient subcritical flaw formation and hence permit graceful, instead of catastrophic, failure. Successful implementation of such a system would hasten the insertion of ceramic components into initially stationary (shroud and/or nozzle) and subsequently dynamic (bucket) components. Improved ceramic materials and corresponding manufacturing processes for ceramic components may also hasten the use of natural gas in co-generation power facilities, using either gas turbines or fuel cells. An additional materials requirement for ultimate insertion of fuel cells into the energy community is for improved electrode materials (lower resistance, longer cycle life, improvement chemical, and electrical efficiency).

Catalyst Materials - The field of catalysts materials is certainly suitable for improvements in performance and manufacturing processes. While catalysts find application in a wide variety of energy-intensive chemical processing (e.g., petroleum refining, bulk chemical synthesis), the specific application of improved catalysis for natural gas conversion to liquid fuels would improve energy efficiency. Such conversion would not only provide alternate fuels for transportation but would also potentially simplify transport of natural gas to processing plants and reduce energy requirements in the processing plant. Specific examples include the following: (1) the use of biomimetics to catalyze under ambient temperature and pressure the homogeneous and/or heterogeneous conversion of natural gas to liquid fuels; (2) the use of improved size- and shape-selective inorganic heterogeneous catalysts, which might include further advances in molecular sieves or low density, submicrocellular materials; (3) the use of improved computational chemistry techniques employing massively parallel processing machines to predict catalytic activity as a function of molecular composition and nanoscale structure; (4) the development of self-assembling macro-molecular structures that contain a range of specific catalytic sites, much like a microbiological factory, to perform a series of chemical transformations.

Solar Energy Materials - The most promising renewable energy source continues to be solar energy. While substantial effort in semiconductor photovoltaics have and continue to be pursued, the development of organic solar conversion materials offers the opportunity for a new approach to higher solar conversion efficiencies using potentially more environmentally benign materials. Such materials may be used directly as photovoltaics to generate electricity for the utility grid, for local applications, or for electrolysis of water to produce H_2 . Alternatively, organic solar conversion materials could be used for *in situ* photoelectrolysis of

water with the resulting direct production of H_2 (which is environmentally preferable to H_2 produced from natural gas or coal). Finally, solar energy could be used as the energy source in an automated, modular, self-replicating solar collection facility. Once again, this would be an inorganic analog to a biological process (e.g., forests) and would exhibit exponential growth and hence, depending on the level to which it could be implemented, result in significant energy savings.

Energy Storage: Natural Gas Storage Materials - Any improvements in energy efficiency must include improvements in energy storage, particularly for alternately fueled vehicles. The need for improved pressure vessels (currently using a mix of metal containers and fiber composite wrap) for storage of natural gas was discussed, but it was not viewed as a high-leverage issue. Similarly, the need for improvements in the natural gas distribution system was not considered as a high-leverage issue.

Hydrogen Storage Materials - Similarly, improvements in materials used for room-temperature storage of hydrogen were discussed but not viewed as a high-leverage issue. However, improvements in alternate storage methods for H_2 , particularly in improved materials and systems for cryogenic storage and improved materials to reversibly adsorb and release H_2 , were specific suggestions where innovation in materials and corresponding manufacturing processes would exert high leverage on making efficient introduction of H_2 into the nation's energy economy.

Battery and Capacitor Materials - Finally, improvements in materials and manufacturing processes associated with electrical energy storage were singled out as suitable for innovation with high leverage. Such materials would result in improved primary batteries (irreversible chemical conversion), secondary batteries (rechargeable, reversible electrical storage), and capacitors (infinitely rechargeable). Differences in batteries and capacitors relate to cycle life, voltage, specific energy density, and specific power density, so improvements in both are required to permit significant improvements in efficiency of electrical energy storage. Environmental considerations drive the need for new battery and capacitor materials in addition to performance and lifetime requirements (e.g., avoidance of Pb and Cd in future battery systems).

Energy Transmission: Significant energy losses occur in transmission and distribution of electrical energy, amounting to some \$7 billion annually nationwide. Replacement of conventional, iron-core transformers with amorphous steel, a metallic glass with low electrical losses, results in a 70% decrease in losses. These materials are just beginning to be inserted into the market. The obvious further, next generation materials and manufacturing breakthrough is the ultimate insertion of high- T_C superconducting materials into electrical energy transmission and distribution. While this is not immediately realizable, improved continuous processing manufacturing development is needed in order to eventually be able to realize this goal. Real-time dynamic characterization of materials under high-temperature/pressure synthesis/processing conditions would accelerate the development of feasible manufacturing processes.

Energy End Use: The final phase of the energy life cycle that we discussed was the end use of energy and innovations in materials and manufacturing processes that result in improved energy efficiencies.

Electrical Uses - Electric motors represent a significant energy load within the industrial sector (e.g., approximately 3% of the nation's energy usage is expended just by the textile industry in electric motors; two-thirds of the nation's total electric power is used in some sort of electric motor, from which 5 to 10% of the energy is typically lost). Incremental improvements in motor efficiency, which require significant innovation in materials and manufacturing processes, can translate into substantial energy savings. The fabrication of Nd-Fe-B magnets has been produced via rapid solidification technology since the late 1980's. However, due to the high cost of production, limited applications have been developed. Additional improvements in manufacturing processes to reduce the cost of rapid solidification would result in improved magnets and electric motors. High- T_c superconducting materials (theory, synthesis, and processing elements) would impact electric motors to a significant extent. The working group also briefly discussed new materials for lighting; although significant, improved materials and processes are currently available to make substantial reductions in present electrical usage represented by lighting.

Insulation - Improved insulation would result in considerable energy savings worldwide. Technical requirements are improved materials with significantly lower thermal conductivities over a wide temperature range (e.g., aerogels, high-temperature polymers made into foams and fibers) and the corresponding environmentally conscious manufacturing processes [e.g., no chlorofluorocarbons (CFCs)] to make them in a cost-competitive fashion. The ability to computationally predict thermal conductivity as a function of temperature, composition, and nanostructure would expedite the discovery and development of improved insulating materials.

Process Waste Heat - Significant energy loss is represented by low-grade process waste heat (e.g., cooling water at 40 to 50°C); this energy is either wasted or augmented to achieve a sufficient temperature for current processes. Improved heat exchangers (i.e., design, ceramic materials) and thermoelectrics (e.g., using multilayers, where theory predicts considerable improvement in the figure of merit, and new processing innovations to make significantly high-precision multilayers in commercial quantities) to utilize low waste heat more effectively would have considerable industrial impact. In many cases, a total systems analysis is required because new environmental regulations and concerns will force the insertion of new materials and processes that require further research, development, and maturation (e.g., banning of freons will not only effect the manufacture of insulation foams but also the design and use of air-conditioning and refrigeration systems, to where new materials and manufacturing processes with environmental advantages, such as aerogels and emulsion foams for insulation and thermoelectrics for cooling, will have to be developed for insertion into the market).

Improved Materials for Combustion - Combustion will continue to drive the energy sector for some time, particularly as natural gas becomes even more important. Natural gas has long been the preferred fuel for a variety of applications for the industrial sector due to its convenient gaseous form, competitive price, and low emissions relative to other fossil fuels. In order to meet ever tighter emissions standards (e.g., low NO_x) while improving efficiency, additional R&D is needed in the areas of natural gas combustion and heat transfer. Improved burner materials, such as reticulated ceramics, have been under development to improve radiant and convective heat transfer. Further system design work is required in the area of flame stability. Finally, because of increasing environmental concerns, additional

R&D for effluent treatment of combustion products (e.g., catalysts on ceramic materials in turbines, catalysts, and plasma processing for diesel engines/power plant effluents) is also required.

Recycling: Finally, recycling needs to be considered as an alternate pathway to energy efficiency. A prime example of the implementation of such a technology is the recycling of aluminum cans (where approximately 90% of the energy is saved during the manufacture of recycled cans). Other areas of recycling of end-use products include automobile components and appliances. In each case, materials need to be developed (e.g., compositionally forgiving Al alloys) that do not degrade during the recycling process. As with many technologies, although they exist, many are not adopted because of poor return on investment or prohibitively high initial costs. Consequently the energy pathway and the economic issues must be considered in parallel, rather than in series.

"ENVIRONMENTALLY-BENIGN MATERIALS AND PROCESSES"

Carl C. Nesbitt and Charles H. Byers

Given the broad topic of "Environmentally Benign Materials and Processes" and a working group of nearly 30 individuals representing industry, academe, and national laboratory interests in metals, ceramics, composites, and polymers, the following "ground rules" were presented to coordinate the effort at the onset:

1. Do not attempt to define "benign" or "hazardous" as each would have a very different definition for every person.
2. Describe specific areas of concern within your own body of interest (by class of material, processes, toxins, etc.).

Removal of lead from free-machining brasses and elimination of gallium and arsenic in semiconducting materials were presented as examples of current research areas to initiate discussions. An additional framework to help focus the discussions was presented and adopted by the group to facilitate the brainstorming of ideas. The framework for discussion was derived based on the general assumptions that environmentally hazardous materials may be used during the manufacture of products, that products used for years may be toxic in their own right, and that past processes may result in areas that need restoration and remediation technologies. Therefore, the general topics to guide our discussions were as follows:

1. **pollution generated during the synthesis and processing of materials,**
2. **elimination of toxic materials** currently used, and
3. **environmental technologies** (cleanup, monitoring, etc.).

The three areas outlined above were further divided into subsets of the classes of materials or processes as the discussions progressed. The various areas of research suggested by the group to be pursued by a consortium of industry, university, and government laboratories are summarized below.

Pollution generated during the synthesis and processing of materials: Ceramics - One important area of potential research stems from the fact that much of today's ceramic materials are produced from organic solvents. New techniques in production from aqueous media are needed in this area. In addition, development of processes to remove chromium oxides from refractory brick was discussed. To avoid thermal discharge into the environment, low-temperature processing techniques were also discussed as well.

Several ideas were put forth to eliminate toxins produced during ceramic processing. Biogenic materials must be developed to replace the polymer binders and processing aids currently used. Replacements are needed for the lead oxide additives in paints and enamel glazes. In addition, it was recommended that some effort be given to standardize handling processes for whiskers.

Metals - Of primary concern to the metallurgists in the group were the environmental hazards posed by the metal surface industries. Dry surface processes and self-cleaning metal coatings were defined as potential areas for research. A significant area for research would be to find economical alternatives to the agents used in CVD and PVD processes. Laser-cutting techniques are also expected to be an increasing area for research.

Substitutes for lead in free-machining brasses are needed. Basic research in this area is limited. In addition, development of indirect firing techniques for metals processing was recommended. Research into water-based lubricants could lead to better recyclability of metal wastes and lower environmentally hazardous discharge from metal-producing plants. Developing materials for alternate refrigeration systems was also added.

Composites - Fiber recycling processes were considered to be a major topic for research. As well, environmentally friendly polymer-matrix materials were discussed.

Polymers - One area for research could focus on developing mineralizable polymers for specific applications. Further research would investigate environmentally benign additives used in making polymers. As well, development of stronger, thinner paper materials would lower the need for wood pulp paper products.

General Materials Discussion - A major concern to the participants was in the lack of concerted efforts to recycle materials. Automobiles, polymers, etc., all could use standardization to allow for easier recycle. Some suggestions were to use relatively pure components in an automobile to facilitate the separation of parts into various recycle streams. Changes in the operation and design criteria could be developed as part of a research effort in manufacturing practices in the various classes of materials.

Energy - A need was perceived in the area of materials development for alternate fuel sources. Storage facilities for hydrogen, compressed natural gas, etc., require specific physical properties which may be engineered by the material scientists and engineers. In addition development of fuel cells from solid oxides should be studied. Processes for removing mercury from coal prior to burning would lower the operating costs of the coal-fired, power-generating plants by reducing toxic emissions.

Elimination of Currently Used Toxic Materials: Several specific areas of potential research were discussed. The elimination of toxic substances (such as tritium, thorium oxide, mercury, etc.) from various lighting fixtures was a top priority. Advancing new battery technologies away from toxic substances was an area felt to warrant a significant research effort. Polymer development to improve the quality and reduce the dangers from the reactants in consumer products made from polyacrylate gels was another key area of research potential.

Environmental Technologies: The primary focus of the group in this area dealt with better process control and modifications to wastes to render them inert. Sensors for various applications are in great demand. One example would be an in-line particulate sensor that will alert the operators when dust emissions exceed a certain setpoint value. Combustion emission control could be facilitated through developing new techniques and materials.

Materials are needed to encapsulate toxic substances to render them inert in landfills. As well, development of risk assessment tools for industries to use in their own setting was deemed to be an important area.

Conclusions and Observations: A broad range of research needs were brought to the table and discussed. Process development, material development, manufacturing alternatives, and environmental policy were all general areas put forth as holes in the current body of knowledge in the area of benign materials and processes. The primary change to the group was, however, to discuss "high-risk/high-return" projects. This was not accomplished to the desired degree, simply because few members of the group had similar areas of concern.

It was put forth by one member and appeared to be the consensus of the group that funds from the DOE could best be served if applied to areas of research in industries with limited production with high-risk problems. Industries of this type include metals finishing, surface coating and painting, and dry cleaning, to name but a few. These industries are common in that they often are users and dischargers of some of the most hazardous substances known; they are dependant on much larger suppliers of materials to process, which dictate processes and reagents; and have little resources of their own to pursue the necessary avenues of research for alternative processes.

"WASTE TREATMENT AND REDUCTION: A BASIC SCIENCE APPROACH"

David Chaiko and Alfred Galli

The focus of this working group was to identify potential areas of research that represent opportunities for innovation with high payoff to the nation's energy economy in the area of waste treatment and reduction. The discussion emphasized areas where innovative technology development could help to significantly reduce the import and use of fossil fuels, minimize the environmental impact of industrial activity, and, at the same time, enhance the worldwide competitiveness of U.S. industry.

A number of the technologies discussed in the context of waste treatment and minimization overlap with the discussions generated in the working group session on environmentally benign materials and processes. These overlapping issues include the reduction of waste products during processing and manufacturing by extending the life cycle of materials through indefinite recycle. This could be described as closed-loop manufacturing in which there are no environmentally harmful waste products produced. Another overlapping issue is the expanded use of materials derived from renewable resources.

The development of innovative technologies often requires the linkage of knowledge from several different areas of science or engineering. This can make it difficult to find a programmatic home for these types of research initiatives. The basic science approach to finding technological solutions to waste treatment and reduction begins with high-risk, exploratory concepts that show potential for significantly impacting the nation's energy economy.

During the discussion of the working group, a wide range of areas that could benefit from innovative technological solutions were suggested. In an effort to organize the results of the working group, their suggestions were grouped into four main categories:

1. **minimization;**
2. **recycle/re-use;**
3. **treatment, storage, and disposal; and**
4. **remediation.**

The details from the discussion of each of these categories are presented below.

Minimization: The easiest way to minimize the costs of waste treatment is to reduce pollution at its source. This means that chemical and manufacturing processes will have to be redesigned with a focus on the closed-loop utilization of materials and energy. The ideal closed-loop process would achieve waste reduction through endless recycle of materials and utilization of byproducts. The traditional material balance equation for processing and manufacturing includes a materials input with output streams of products and wastes. As scientists and engineers, we are being challenged by society to modify that materials equation and totally eliminate the production of wastes.

The automobile plays a very significant role in modern society and, therefore, improvements in design, manufacture, and performance necessarily have a large impact. One area of automobile technology that the group felt would have significant impact on waste reduction would be the development of improved tire compounds, which would extend tire life to 80,000 miles or more.

It was also felt that biotechnology could make significant impacts on waste reduction through the development of biolubricants and biosurfactants as substitutes for petroleum-based chemicals. These materials would be less toxic and environmentally hazardous, and, at the same time, their use would reduce our reliance on nonrenewable resources. The development of new plastics from biomaterials should also be encouraged. Plastics that are 100% degradable would be very useful for consumer packaging applications.

The group felt that the DOE should continue the development of clean-coal technologies to reduce emissions of sulfur and nitrogen oxides. A technology area that would probably fit into the AEP mission is the development of ultrafine particle processing technologies. Fine particles are difficult and expensive to process, and quite often this material is set aside as waste because of a lack of technologies that can profitably process particles that are 20 to 50 μm or less in diameter. The industrial use of high-gradient magnetic separation for processing clay is an example of successful ultrafine particle processing. Ultrafine particle processing was a theme that also came up during discussions on waste treatment and remediation.

An example of a specific technology in which innovative developments could significantly reduce waste production is the development of advanced ion-exchange materials. Ion exchangers, in which the exchange reaction is temperature or pressure dependent, would reduce the amount of process chemicals used in purification procedures. With current exchange materials, ions are stripped from the exchanger by passing either acidic or basic solutions or neutral, high ionic strength solutions over the exchanger. The use of salts, acids, and bases in this way only increases the burden of waste treatment facilities. For example, the use of conventional ion exchangers for home water softeners results in the disposal of large amounts of salt into municipal water treatment systems.

The development of safer dry cleaning solvents is an area that does not have direct impact on the energy economy but which might benefit from the transfer of technology developed by DOE. A considerable amount of research is being conducted by DOE for the development of new degreasing solvents such as supercritical carbon dioxide. In essence, dry cleaning solvents are sophisticated degreasing solvents. Tens of millions of gallons of solvents are released to the environment each year. The impact of these releases on the air quality in large metropolitan areas is of the same scale as auto emissions and emissions from the petrochemical industry.

Recycle/Reuse: The emphasis on waste reduction has commonly been linked to industry, but it may also be useful to begin thinking about applying closed-loop concepts to domestic activities. This can be illustrated by the following example. With current automobile technology, the engine oil needs to be changed three to four times a year in order to

maximize engine life. Some of this oil is reprocessed and used again, but with improved filter technology, it may be possible to operate the vehicle through its normal life time without ever having to change the oil. This would reduce the handling and exposure of service personnel to this hazardous material.

The development of new materials and processes to permit increased recycle of plastic and metal automotive parts was considered a high priority. It was also felt that considerable effort needs to be devoted to ensuring that the various components of batteries from electric vehicles could be recycled or disposed of safely.

Another problem area with direct energy impact is the disposal of fly and bottom ash from coal-fired power plants. New separation technologies need to be developed for the removal of hazardous materials from ash and new, and expanded uses for the ash need to be found.

Research should also be directed toward the recycle and regeneration of organic adsorbents. Activated carbon is often used for organic removal from gas and liquid streams. If the organics cannot be steam-stripped from the carbon, then it is disposed as waste or sent to a processing plant where the carbon is regenerated by combusting the outer surface of the particles. This process is expensive: it consumes 10 to 20% of the carbon through each regeneration cycle and produces secondary wastes that must be dealt with. New types of organic adsorbents and new methods of regeneration need to be found. Perhaps biological processes could be developed for simultaneous detoxification and regeneration of activated carbon.

Treatment, Storage, and Disposal: The recommendations of the group in this category are very broad based. There is and always will be a need for improved separation technologies that have higher selectivities and produce fewer secondary wastes.

Better waste destruction technologies need to be developed. This is all the more important in light of the current administration's stance on incineration. Biotechnology is viewed as a major player in this effort. For example, new bio-detoxification processes are needed and, in fact, may be of use in ensuring that off-gases from incineration processes can be safely released to the environment.

A lot of effort has been directed toward increased recycling as a way of extending the life of landfills. Perhaps we need to apply these concepts to achieve the recycle of municipal landfill space itself. We need to rethink the way we design landfills so that enhanced rates of degradation of materials put into the landfill are achieved. We also need to be careful about what materials we do or do not put into our landfills. For example, the disposal of yard waste in landfills is being banned by some states; however, these materials may be necessary to support biological activity and improve the quality of decay products.

New technologies for nuclear waste storage and disposal need to be developed. This is a problem of major proportions, and extensive amounts of resources are already being devoted to these problems by the DOE. Innovative solutions to the problems of waste form design could have a very big impact on the cost of disposal. Nuclear waste destruction through

transmutation of the long-lived actinide elements is an area of great interest. Innovative technologies that can "burn" these elements at high throughput and low cost are needed.

One area of research that is of fundamental importance to the development of waste treatment technologies and whose support has fallen through the cracks is that of thermodynamic data collection. Ionic activity coefficient data are needed to develop more accurate models of aqueous processes. These data are also needed to improve our ability to model the interactions and the movement of pollutants in the environment. There is currently an appalling lack of this kind of data. Work devoted to improving the accuracy of thermodynamic models of Pitzer, Bromley, and others under high ionic strength conditions needs to be carried out. The modeling of activity coefficients of trace components in high ionic strength multi-component systems needs to be developed further.

Remediation: Very serious difficulties are faced when attempting to remediate contaminated groundwater. It is becoming apparent that "pump and treat" technologies are too expensive and too inefficient. For remediating organic contamination, in situ biological treatment offers the hope of becoming a low-cost and effective approach. The incorporation of microbial or even semi-purified, and immobilized enzyme systems into active subsurface barriers may be an effective approach.

Considerable amounts of work have been done of the development of soil stabilization technologies for immobilizing inorganic contaminants. More research should be directed toward the development of technologies for organic immobilization in subsurface environments.

In discussing remediation, the topic of soil washing needs to be addressed. The group felt that new biological processes for the detoxification of organics needed to receive more attention. Also, the development of separation processes for treating ultrafine particles should be a high priority. The treatment of micron- and submicron-sized particles is an area that needs a considerable amount of work. Conventional soil washing approaches involve the separation of fine particles (i.e., clay portion of the soil) with subsequent disposal. With fine-particle processing technologies, this soil fraction could be processed further and thereby concentrate the contaminants in an even smaller volume. This would also allow more of the soil to be cleaned and returned to the environment.

APPENDIX A
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WORKSHOP ON

INNOVATION IN MATERIALS PROCESSING AND MANUFACTURE:

EXPLORATORY CONCEPTS FOR ENERGY APPLICATIONS

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APPENDIX B
WORKSHOP PROGRAM

APPENDIX B WORKSHOP PROGRAM

Innovation in Materials Processing and Manufacture: Exploratory Concepts for Energy Applications

Wednesday Evening, March 10

7:00 Registration and reception (cash bar)

Thursday, March 11

7:30 Registration; Coffee and rolls available

8:40 Welcome (Bill R. Appleton, ORNL)

8:55 Basic Energy Sciences - Directions for the 1990s (Louis C. Ianniello, BES)

9:15 DOE's Materials Technology Research and Development Programs (Peter H. Salmon-Cox, CE)

9:45 Future Directions for Materials Science and Engineering: Summaries of National Studies
(Alfred Galli, EPA)

10:15 Future Directions for Manufacturing (F. Stan Settles, OSTP)

10:45 Coffee Break

11:10 The Value of Innovation in Materials Evolution (Douglas F. Craig, ORNL)

11:30 Perspectives from the Advanced Energy Projects Division (Walter M. Polansky, AEP)

11:40 Charge to Workshop, Logistics of Working Group Sessions (Linda L. Horton, ORNL)

11:50 Lunch

1:00 Working Group Sessions

Challenges for Hostile Environments

Arvid E. Pasto, ORNL and William Rhodes, Osram Sylvania

Novel Materials in Transportation Technologies

Ron A. Bradley, ORNL and Andrew M. Sherman, Ford

Novel Nanoscale Materials

Richard W. Siegel, ANL and Egon Wolff, Caterpillar

Opportunities in Biomolecular Materials

Mark D. Alper, LBL, and David Fink, Bio-Integration

3:00 Coffee

3:30 Working Group Sessions - 2

Alternate Pathways to Energy Efficiency

Jeff Richardson, LLNL, and Richard R. Petrich, Gas Research Institute

Environmentally-Benign Materials and Processes

Carl Nesbitt, Michigan Technological University and Charles H. Byers, ORNL

Waste Treatment and Reduction: A Basic Science Approach

David J. Chaiko, ANL and Alfred Galli, EPA

5:30 Adjourn

6:30 Reception, Dinner

"Winning with Technology", Lewis S. Edelheit, Senior Vice President,
Corporate R&D, General Electric

Friday, March 12

7:30 Coffee and rolls available

8:30 Summaries and Discussion of Working Groups
(about 20 mins per Group)

9:50 Coffee Break

10:00 Summaries and Discussions, continued

11:20 Coffee Break

11:30 Overall Summary of Workshop, Recommended areas of Opportunity (Linda L. Horton, ORNL)

11:45 Closing Remarks (Walter M. Polansky, AEP)

12:00 Lunch

1:00 Post-Workshop Session

Working Group Leaders prepare draft summaries

4:00 End Post-Workshop session

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