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A FEDERAL LOOK AT THE NEEDS FOR ENERGY-RELATED MATERIALS RESEARCH AND DEVELOPMENT

PART I: NEAR-TERM PROGRAM

APPENDIX 5: MULTI-IMPACT BASIC RESEARCH AND EXPLORATORY DEVELOPMENT PANEL REPORT

Prepared at the Request of
Committee on Materials (COMAT)
Federal Council for Science and Technology

FOREWORD

The objective of Part I of the National Plan for Energy-Related Materials Research and Development is to specify materials requirements and provide guidance for government-sponsored materials work in support of the near-term national energy program. The report is based on a study by the Committtee on Materials (COMAT) of the Federal Council for Science and Technology. The working group, called the COMAT Energy Task Group, is divided into seven panels, each of which is responsible for specific technology areas. Twelve federal agencies and departments are contributing, and several of their participants have assumed panel leadership positions. The Energy Research and Development Administration is responsible for overall coordination.

This document contains supplemental information to the Multi-Impact Basic Research and Exploratory Development Panel Report.

5A - METALS FOR ENERGY

I. Bulk Metals and Alloys

A common theme running through many of the energy programs is the need for materials, usually metals, that will work at higher temperatures and pressures and be more resistant to corrosion and erosion than are the materials currently in use.

In many cases we lack a knowledge of the behavior of the mechanical properties of metals at high temperature. The nature of deformation and creep and the responsible mechanisms are not very clear. Even elastic constant measurements may not be available at high temperatures. A similar situation occurs at the other end of the temperature scale where little is known of the detailed mechanical properties of metals used as structural materials in superconducting machinery.

The question of erosion seems to have received rather minor attention and the mechanisms involved may be different depending on whether the impact rate is high or low. An understanding leading to a predictive capability is badly needed here.

Similarly, there has not yet evolved a basic understanding of corrosion mechanisms for metals especially in a sulfide atmosphere which frequently is of interest.

All of these problems point toward the necessity of strong continuing programs relating the kinetics of vacancies, interstitials, and dislocations to the macroscopic properties of metals.

In addition, there is a large need for alloy development that arises in several ways. Shortages of specific materials, such as Ni, Cr, and Co, will push for a larger program to find substitutes. A shortage of steel-making capability itself may encourage the substitution of other materials where possible. The increased future use of reclaimed scrap as raw material will introduce new classes of "poisons" that need to be evaluated and understood. At present, alloy development appears to be aimed at a few specific problems; the science of alloys should increase so that analytic and predictive capabilities are available for many classes of use.

Finally, the appearance of whole new classes of organic and inorganic "metals," such as $(SN)_x$, suggests that there may be many surprises ahead and that a broad research program should be supported.

II. Surface Problems

In many cases it will not be possible to develop a single material with all the required properties such as corrosion resistance in high strength materials. The developments of claddings and coatings and practical means of applying them then becomes an important task.

A relatively new class of surface treatment is the use of ion implantation to alter the physical and chemical properties of surfaces. While this is a relatively young technique, and therefore far from industrial production, except in the semiconductor industry, its potential for metals should be carefully explored.

Also, the role of metal surfaces in catalysis and in corrosion should be understood in detail at the atomic level. This will involve the continuation of strong programs to measure and understand the motions and reactions of atoms and ions near the surface of metals. This area of science has grown greatly in the last few years and should have a productive future.

III. Fabrication

There are two principal problems related to fabrication of metals. One is to find better ways to fabricate the refractory metals which are required in many applicatons. The other problem is to devise processes for making large tonnage metals, such as steel and aluminum, that require substantially less investment of energy.

IV. Testing and Surveillance

Nondestructive methods for testing materials is a long standing need. Radiography and acoustic methods are often used; more esoteric methods such as neutron scattering and positron annihilation are under study. However, many needs remain. In addition to evaluating the perfection of material as produced by a manufacturer, there is a whole class of needs involving surveillance and in-service monitoring coupled with the equally pressing problem of making remote repairs without dismantling a complex piece of apparatus.

V. Information Transfer

There are a variety of ways in which the engineering community learns of the properties of materials. Handbooks are basic tools. Some societies maintain information centers and some agencies have established information centers in areas where the agency feels a special need. However, there is no national program that plans these information centers or makes their output broadly available. Financial constraints frequently force the center to charge for its services and this need for transferring funds may make the service so slow that the information is useless because a decision has had to be made earlier by the user. Also the information centers often do not have information critical for a designer: how the material has performed in service.

If it were possible, the development of a good national materials information system would be a tremendous asset. Barring such a national endeavor, ERDA should look carefully to see to what extent its needs are met by existing information centers. The creation of additional centers may be necessary to fully capitalize on the development of improved materials.

5B - THE IMPACT OF POLYMER SCIENCE AND TECHNOLOGY OF THE ENERGY PROBLEM

The purpose of this report is to map out those areas in which polymer science and technology can contribute to the solution of the energy problem. Such a mapping must, of course, be incomplete; it requires imagination and no man (few men) should expect to place bounds on the limits of imagination of the scientific community. Nevertheless, this report will, at the very least, provide a listing of some subjects, a statement of some important problems, and it will provide a framework into which new imaginative ideas can be attached.

I. Solar Heating

The use of plastic rather than glass windows in solar flat plate collectors must be investigated to see if there are advantages to the plastic. Possible advantages are lightness of weight, lower index of refraction resulting in less reflection and the possibility of better tailoring of the light adsorption characteristics.

Investigation into the use of polymers for thermal insulation seems appropriate. Foamed polymers superior to glass wool in thermal conductivity already exist. Methods of making them cost competitive in all situations should be investigated. Development of on-the-spot foaming techniques would eliminate the transportation cost for bulky insulating materials. The development of structural foams suggests that load bearing and insulation characteristics could be incorporated into the same structural member.

The replacement of the aluminum in aluminum storm windows appears to be a viable option both because of the reduced energy necessary to make plastic compared to aluminum, and because of the fact that plastics are better insulators than aluminum.

(1) Solar Ponds

Solar ponds rely, for their efficacy, on the maintaining of the density gradient of a variable compositon of salt water. The density gradient must be sufficiently large in order that the hearing of bottom layers does not cause an inversion due to thermal expansion. In this way the major cause of heat transfer, which is convection, is removed. One alternative to brime solutions is the use of a polymer gel. To be a viable alternative one must have a low cost gel with proper visible and infrared absorption properties. Also, it must be stable to ultraviolet radiation and not be biodegradable. Another use of plastics would be in a film to lie over the pond. Its purpose would be to prevent wind-caused waves from destroying the gradients in the brime solution.

(2) Photochemical Conversion

Photochemical conversion can result in the dissociation of molecules into energetic components or it can result in the creation of larger energy storing molecules. An example of the first is photodissociation of water into H_2 and O_2. An example of the second is photosynthesis of H_2O and CO_2

into starch. Either process can result in energy storage. The biological laboratory of evolution has spent several hundred million years perfecting photosynthesis as a method of converting H_2O and CO_2 into starch. There are in fact suggestions to the effect that the use of plants as an energy source is competitive with any other process. Certainly it has the extreme virtue of being renewable indefinitely whereas anything we do with coal and oil results in permanent depletion. One question of importance is whether we can mimic the photosynthesis effect. Another is whether we can understand it so that we can use the same ideas, but perhaps with different materials more suited to the needs of synthetic conversion. It is apparent that research into organic semiconductors is a relevant field. Membrane research is also required.

Biological research into other biological conversion schemes that perhaps antedate the present method may give us an insight into the mechanism of photosynthesis. Another area of biological research is the attempt to maximize yield. This would involve both the choice of the right plant and attempts to genetically improve what is now available.

Photodissociation will, in all probability, require the use of polymeric semipermeable membranes as a method to separate the products.

II. Fossil Fuels

Both crude oil and coal can be viewed as polymeric materials. As such, Polymer Science and Technology are highly relevant. In fact, the past and present needs for solving the problems of refining of oil have had an impact on the process of creating the very science of polymers. The optimizing of refinement of crude oil that has proceeded under the influence of the profit motive probably cannot be significantly improved upon. However, coal and oil shale present some interesting opportunities.

(1) Oil Shale

Oil can be taken from oil shale by heating or by supercritical solvent extraction. Both of these methods use large amounts of fuel due to the high temperature required. Also, they result in a larger volume of waste than the original volume of material. This presents a waste disposal problem. One area of future work is the possibility of (in situ) depolymerization of the high molecular weight oil in the shale. The polymer organic chemist has much to contribute in this area.

(2) Depolymerization of Coal

Coal, because of its abundance relative to oil, should become a source of gasoline. Since the Germans actually made gasoline from coal during the last war we know it is possible. One wonders whether improvements on the old method are feasible. One wonders whether the highly crosslinked, highly conjugated system called coal cannot be cracked into a linear low molecular weight hydrocarbons by adding hydrogen and the ingenuity of some, as yet unknown, polymer chemist.

III. Transporation

(1) Flywheels

Rotating flywheels have been shown to hold potential as a primary source of energy in automobiles. They are already being used to store energy in a regenerative braking system in certain subway cars. There is also the possibility that they can be used to provide the surges of power needed in auto transportation--passing, climbing hills, accelerating into super highway traffic, etc. This would allow a smaller, lighter gasoline engine. In addition to savings in size and weight, an engine without the demands for a wide range of acceleration and power option can be made more efficient.

Investigators have discovered the surprizing fact that the material most suitable to the manufacture of flywheels is a light, high strength material rather than a heavy, high strength material. Kevlar, a high strength polymer, is, for example, mentioned as a material of choice. This suggests that research into high strength and ultimate strength polymer fibers is an important area of study. Carbon fibers also should be investigated.

(2) Rubber Band Energy Storage

It has long been known that pound for pound natural rubber can store two orders of magnitude more elastic energy than the best spring steel. It has been suggested that a rubber band of one hundred pounds can be used to power a small car. More probably, rubber would be used to store the energy lost when a car is braked to a stop. It would then be used to help accelerate the car when needed. Obviously, more research into the failure of rubber under repeated elongation is needed.

Another use of rubber is in the engines presently being fabricated in the form of bicycle wheels whose spokes are made of rubber. They work off a temperature difference between two reservoirs just like any other heat engine, but they do not require a large temperature difference to operate. Again, what is needed is a rubber that will break only after millions of stretch-strain cycles.

(3) Plastics in Automobiles

The reduction of automobile weight by substitution of plastics for metals is presently an ongoing process. Each pound saved in this way saves gasoline. It also reduces the strength needed in the structural members and the weight needed in the engine. Replacement of some of the structural members by a light weight composite plastic-metal load supporting member is a possibility. Structural foams are a leading candidate.

Tires are a source of energy dissipation in moving vehicles, on the order of 10 percent. The objection to making them more elastic and less dissi pative is that the ride deteriorates. One can achieve a comfortable ride by allowing the shock absorbers to take over more of the ride-smoothing qualities. On very smooth roads there should be no rolling friction due to tires. The necessary research into a lossless tire is worthwhile.

(4) Dirigibles

Dirigibles provide a cost effective method of moving freight. The fuel used in a given trip is much less than in an airplane. Also, the dirigible can transport portal to portal while airplanes require loading and unloading at two airports per trip. This dormant method of transportation should be revitalized. Research into an optimum plastic bag to hold the hydrogen helium mixture should be pursued. Also, investigation into the use of hot air and the requisite plastics technology is worthwhile.

IV. Direct Chemical into Mechanical Energy Conversion

There are two existing procedures for direct conversion of chemical into mechanical energy. One is the salt engine which works on a concentration change of some salt which is known to result in dimensional changes in some polymers. The other is muscle tissue. The attraction of muscle tissue is in the high efficiency involved. Lower bounds of 40 percent have been obtained by feeding animals foods and measuring the work output. This is a lower bound because energy is required for metabolic activities which are in no way connected to muscle work. Estimates of efficiencies for pure muscle range up to 100 percent. Chemicomechanical energy conversion is not a thermodynamic process and is not limited to Carnot heat engine considerations.

Research is needed into the actin and myosin biopolymers to determine how they act as chemicomechanical transducers. Once this is determined it may be possible to make a synthetic analogue which would do a useful form of work. The problem of direct transformation of chemical to mechanical energy is probably a polymer problem exclusively.

V. Energy Savings in Manufacture

(1) Polymer Processes Made More Energy Efficient

Every extant process will have to be examined to see whether we can save energy, or whether it can be replaced by an energy saving alternative. We illustrate the problem by means of three examples that are now in the development stage.

The first example has to do with the paper industry. It turns out that one can make perfectly acceptable paper with half the weight of previous paper by adding some synthetic polymer to the ordinary cellulose to increase the opacity. This large weight savings reduces the overall energy requirements of paper making.

The second example has to do with rubber tires. Tires are energy-intensive, requiring much energy to compound the rubber and carbon black, make the fiber and vulcanize the tires. A one-step injection molded tire which now exists results in large energy savings. Perhaps a little more R&D work will result in a marketable cast tire that will result in much energy savings.

The third example has to do with latex carpet backing. It costs much energy to put the backing on due to heating and drying costs. Perhaps another polymer material would be less energy-intensive.

(2) Polymer Processes

Polymer processes replacing less energy-efficient non-polymer processes. Just what these processes will be again depends on the ingenuity of the manufacturing arm of the business community.

VI. Transformation of Wood-Fiber and Plant Products into Polymers

There are viable industries doing this now. Natural rubber and plastics from soybeans and wood are obvious examples. We wish to point out that if the world oil reserves are as limited as some people now think, then the polymer industry will have to seek alternatives to oil as a raw material for the present high volume production plastics, polyethylene, polypropylene, polystyrene, etc. Intelligent allocation of resources demands that we know what the possibilities are. It may be that crude oil should not be made into gasoline, but rather an alternative fuel be obtained from plants and the oil (or part of it) be used as a raw material for plastics and other petro-chemicals.

VII. Plastic Pipe

There are at least four areas in which plastic pipe has an impact on the energy problem.

(1) Plastic pipe is now replacing metal in gasline feeds into homes. Research is needed to make pipes that stay in the ground without deterioration for the longest possible time.

(2) It has been determined that an optimum method of irrigation is to feed the actual plants drop by drop rather than inundate the whole area. An inexpensive soil resistant plastic pipe is needed. Resistance to UV radiation is also required. To the extent that we save on water we save on the energy needed to supply the water.

(3) Several schemes exist for using the large amount of ocean water at different temperature levels as a gigantic heat engine. Transport of large quantities of fluid through pipe is required. Plastic pipe because of its neutral buoyancy and resistance to corrosion as well as cheap price may be the material of choice.

(4) Beneath every home there is an essentially infinite reservoir of heat in the winter and cold in the summer. The underground temperature in this area is about 55^{o}F. By using it as a base to cool in the summer and heat in the winter our refrigeration and heating bills can be drastically reduced. Accessibility can probably be achieved by drilling two holes to a proper level and pumping water out of one and into the other. Extraction of the heat (and cold) from the water will probably be done in heat exchange units in the basement. Plastic pipes will be needed since presently many pipes used in wells are plastic.

VIII. Transmission of Power in Superconducting Lines

In prototype lines now being designed and fabricated, various plastics are being considered for the insulators. Knowledge of cryogenic properties is an absolute necessity. Three of the most important properties are low temperature dielectric and mechanical response functions and expansion coefficients. Research into the choice of a best material is necessary.

IX. Timed Release of Fertilizers

The fertilizer industry is energy-intensive. More efficient use of fertilizers will save on the energy necessary to their manufacture. The fact of wasteful use of fertilizer is illustrated dramatically by increased nitrogen content of our streams and lakes which result in explosive algae bloom and resulting fish kills. If one could meter the proper release of fertilizer in synchronism with the growth cycle of the fertilized plant then a substantial savings of fertilizer could be effected. Polymer encapsulated fertilizer is one possibility. The polymer can be made to release the fertilizer according to the amount of rain, temperature, sunlight, or time.

X. Waste Polymers as Fuel

An average set of used, ready to be discarded tires represents about 50 lbs. of fuel. By proper processing, they can be made to burn cleanly. Even without processing they can be broken up and added to coal. Other plastics also can be used as fuel. This end use will be facilitated if each polymer were labeled as to type. In the case of tires, both the kind of rubber and the percent sulfur content should be known.

5C - RESEARCH ON SURFACES AND ENERGY SOURCES

I. Introduction

It is generally conceded that fundamental research is unlikely to contribute to the solution of near-term problems. So why bring it up here? First, it is possible that a breakthrough based on research supported now could substantially contribute to solving at least some part of the energy problem. There are examples where the period between research and the useful device is not decades but as short as two years. The laser is one of the best examples. Second, failure to develop a strong basic research program now will just delay the solution or contribution such research can make. Even for the near-term problem a strong basic research program should accompany the efforts in conservation, applied research and development.

Solid surfaces and interfaces have a central role in the processes of catalysis, corrosion and interfacial diffusion which are of critical importance for the development of new energy technologies. To understand these on an atomic scale, scientists are considering the electronic states at surfaces, the bonding of adatoms (chemisorption), where the adatoms are located and how they cluster on the surface, how the surface atoms affect chemical reactions (catalysis), which surfaces of a given material are most effective and so forth. Major advances have been made in determining the microscopic structure of surfaces by improvements in the instrumentation and analysis of such techniques as low energy electron diffraction, Auger spectroscopy and high resolution electron microscopy.

Powerful new theoretical methods have been applied to determination of the electronic band structure and band structure at solid surfaces. These, combined with the newer experimental techniques being developed such as ultraviolet and x-ray photo-emission, hold promise of a truly major advance in understanding the complex physical and chemical processes which occur at solid surfaces. These techniques are being applied to materials systems of interest in catalysis, corrosion and photovoltaic solar conversion.

The following paragraphs focus on problems in all energy schemes which require more knowledge of surfaces for their solution. This is not meant to imply there aren't other problems that must be solved to improve our energy position.

II. Fossil Fuels (Coal Conversion)

Problems exist in pilot plant operation of coal conversion which can be broadly characterized as erosion, corrosion and mechanical. In gasification, parts such as the gasifier, regenerator and auxiliary equipment are exposed to temperatures as high as $1900^{o}F$, pressures to 300 psi and an atmosphere which contains steam, Co_2, Co, H_2, Ch_4 and other gaseous components. In addition to erosion caused by rapidly moving solids and entrained in these gases, corrosion takes place causing carburizing, nitriding, sulfidization and hydrogen embrittlement.

III. Fission

The major cause for excessive downtime in nuclear power plants is due to failure in the steam subsystems. Such failures also occur in fossil fuel plants, but are more noticeable in nuclear plants because of the larger capacity and greater concern for safety. Stress corrosion, which is responsible for the problem, is still not well enough understood.

IV. Fusion

Although the use of fusion as a source of energy is still a long way off it is known that severe problems involving surfaces will have to be solved. First, wall erosion caused by radiation blistering, sputtering due to high energy neutrons, and particle emission and surface layer flaking, must be understood before final design decisions can be made. Investigations are needed concerning particle-surface interactions, gas-surface interactions, photon-surface interactions and the role of surfaces upon irradiation damage.

V. Solar and Geothermal

Solar cells which convert solar radiation to heat require for optimum collection efficiency a surface which absorbs throughout the red and infrared spectrum but does not emit these regions. Currently such selective absorbers are susceptible to corrosion in the presence of water vapor. Research is needed to develop better materials.

Geothermal wells produce anerobic waters containing H_2S and CO_2 resulting in corrosion of tubing, casing and drill pipe. The corrosion is associated with sulfide stress cracking, a form of hydrogen embrittlement. The mechanism by which hydrogen embrittlement occurs is not yet well established.

5D - SURFACES - ELECTROCHEMISTRY

Basic research to further the understanding of chemical and physical processes taking place on surfaces is important to the development of rechargeable batteries for application to utility load-leveling and electric-vehicle propulsion.

Advanced battery systems under development today include Li/LiCi-KCl/metal sulfide, Na/B-Al_2O_3/S, Zn/aq. $ZnCl_2/Cl_2$, and Zn/aq. KOH/B-NiOOH. The ability of any of these systems to ultimately meet the performance and cost requirements cannot be determined as yet because many engineering problems remain unsolved. The lead-acid battery is also a candidate whose performance probably can be improved to meet requirements; however, indications are that the cost will be too high.

A large quantity of good basic research in electrochemistry has been done and is now being done, but the extensive application of the lead-acid battery over a period of many years has not inspired research to define the details of battery operation and create an understanding that could lead to improvements. In fact, improvements have instead been spurred by economic factors such as raw material supplies and costs. As a result, information now needed for advanced development does not exist.

Areas of basic interest that need support are generally common to all battery systems. They relate mainly to the electrode surface and to the separator. Electrode surface investigations should include the study of the morphology of metal deposition during charging and the investigation of the effect of the charging rate on the nature of the deposit and its tendency toward dendrite formation. The battery separator serves several functions. It separates the catholyte and anolyte, restricts the metal growth to the electrode surface and acts as a conductance bridge. Research is needed to define the mechanisms by which conduction occurs in successful separators that have been developed empirically. The stability of useful separator materials to corrosive attack is also an area in need of study. Finally, the search for a good solid electrolyte is underway and additional basic studies to generate a basis for guidance are needed.

5E - HOT CORROSION

In gas turbine machines, the accelerated and/or catastrophic degradation of hot-gas-path parts that is generally associated with impurities in the fuel and intake air is broadly termed "hot corrosion." Over the years as the operating temperatures of these machines have increased, the incidence and severity of hot corrosion attack increased markedly. At the present time, this mode of degradation is a major limitation on the operational efficiency and life of engines used in marine and industrial installations. For turbine driven helicopters and aircraft turbines operated at low altitudes over sea water, hot corrosion problems dictate the almost unacceptably short times between overhauls. Currently, problems with hot corrosion are becoming obvious in commercial aircraft turbines operating exclusively over land routes.

Hot corrosion problems are expected to be severe for machines utilizing coal-derived synthetic fuel oils and low to high BTU gases. This expectation results from the fact that the agents believed to be important in the hot corrosion process are naturally occurring in coal and they are not easily or efficiently removed.

Turbine manufacturers have been addressing the hot corrosion problem with increasing emphasis; but empirically developed alloys, surface protective coatings, air filtration systems, and fuel additives are proving to be only temporary and costly remedies. For the higher operating temperatures desired to effect significant gains in machine efficiency, substantially better materials will be required. The prospects for developing such materials will not be satisfactory until the mechanisms of hot corrosion are elucidated.

A comprehensive model of hot corrosion must be derived and this model must be capable of attributing relative degrees of significance to various gas and condensed phase chemical species plus other factors such as temperature, pressure, thermal cycling, combustion conditons, etc., which are present in real engines under practical operating conditions. The effect of competing and synergistic processes must be explained. Finally, the model must account for the many phenomenological aspects of hot corrosion which have become evident from extended service experience.

Although considerable effort has been directed to phenomenological investigations, testing and immediate problem solving, relatively little effort has gone into basic research to elucidate the mechanisms of hot corrosion. Currently in the United States, some fundamental studies are being carried out at Pratt and Whitney Aircraft (Goebel and Pettit), General Electric (McKee, Spacil, Shores, Fryxell, and Chatterji), United Technologies (Bornstein and DeCrescente), NASA-Lewis Research Center (Kohl, Stearns, and Fryburg), and General Motors (Reising). Numerous smaller efforts in the areas of oxidation and sulfidation complement the direct hot corrosion studies.

In the United Kingdom, the principal hot corrosion mechanistic studies are being performed by Condé at the Admiralty Materials Laboratory, Stringer at the University of Liverpool, and Hancock at Cranfield Institute of Technology. Here also contributions are being made by groups working in the closely allied field of oxidation.

5F - COMPOSITE MATERIALS FOR STRUCTURAL USE

Polymer and metal matrix composites incorporating high strength fibers are a new class of structural materials whose remarkable properties are only beginning to be used to advantage. The properties of interest are very high strength-to-weight and stiffness-to-weight ratios. For example, boron fibers in an aluminum matrix yield a material as strong as high strength steel at a little more than one-third the weight. The high strength stems from the high strength of the boron fibers that are embedded in the aluminum for mechanical and corrosion protection. The load is transferred from the weak matrix to the strong fibers.

The only serious applicaton of these materials has been to aircraft. Composites are cheaper than the wholly metallic structures they replace, and the weight savings for both airframe and engine components can result in fuel savings of the order of 15 percent. No analysis has been made of comparative energy costs for raw material, fabrication, lifetime, and recycling.

Some thought has been given to application of composites to truck construction. The majority of trucks are volume limited, but some 10 percent are weight limited (e.g., tankers) and would benefit. Examination of the flywheel as an energy storage device has also given rise to interest in composites. The requirements are reasonable but not available in any of the currently available composites. The same can be said for windmill blades.

The composites available today are the result of intensive development of a few materials that were the first to show promise. Because of the demands for useful materials, the effort and funding were channeled into these areas. Fibers and fiber-matrix compositions that presented more difficult development problems were dropped even when they showed promise of superior properties.

The current effort by the Air Force and NASA to prove out composites in flight hardware is showing success. The acceptance of the fiber-matrix composite as a useful, reliable material for these applications will increase the demand and thereby spur the development of production methods: these methods will eliminate two important problems, namely the high cost and variable quality that stem from small batch manufacture.

The quality of a composite depends on several factors, some of which are the nature of the chemical and physical bond between the fiber and the matrix, the perfection of the fiber (i.e., freedom from flaws) and the mechanical properties of the matrix material and the stability of the matrix toward environmental attack.

Very little effort has been expended on gaining an understanding of these factors at a fundamental level that would give guidance toward development of new, more useful materials or the indication of directions for further development of the materials now at hand. The efforts that are now underway show promise of yielding such information even in the near term. An increased level of basic research effort in this area is certain to aid in the adaptation of this new class of materials to many facets of the energy program.

Examples of research either underway or obviously needed are:

1. Studies of the chemistry and physics of the fiber-matrix interface to answer questions such as:
   a. How strong should the fiber-matrix bond be?
   b. Does chemical reaction between the fiber and matrix aid or hinder the transfer of load from matrix to fiber?
   c. What factors limit the ductility and impact strength?
   d. How can very brittle but otherwise very desirable fiber materials like alumina be incorporated in composite systems?
2. Studies of the morphology and physical properties of fibers to answer questions such as:
   a. Are the preparation conditions now used producing the best possible fibers?
   b. Would better boron fibers be produced by the use of other substrate materials?
   c. Are properties such as the anelasticity of boron deleterious--can they be used to advantage?

There are many other basic questions of direct importance to the development of fiber-matrix composites. The proper study of these questions requires a multidisciplinary approach utilizing the points of view and capabilities of physics, chemistry, metallurgy, polymer science, and mechanics. It also requires the recognition of the need for adequate support of basic research that must be initiated now if its products are to be available to the development of advanced energy systems.

5G - NONDESTRUCTIVE EVALUATION

The field of nondestructive evaluation (NDE) was included in the report of Panel 7 because of its multiple application to materials problems associated with virtually all energy technologies. Vigorous continuing development of new techniques and the understanding of them, as well as the better interpretation of the results of techniques already in common use, are generally acknowledged to require urgent attention [1,2]. NDE is a major basis for evaluating the reliability of materials and for quality control and is becoming increasingly important as materials are pushed toward their operating limits and as operating systems become more complex.

Research and development in NDE has been encouraged in the past mainly by three Federal agencies: DOD, NASA and elements of ERDA, and the field has grown rapidly. There are now some 30 major laboratories--Federal, university, and private--engaged in such work. Information exchange among investigators is fostered by the American Society for Nondestructive Testing, the American Society for Metals, and the American

Society for Welding, as well as by ASTM and ANSI through publications and organized symposia.

There seems to be a real need for an NDE information center to serve a wide spectrum of users. The center should be located within a large materials laboratory where expertise in NDE exists, to ensure some degree of critical evaluation of methods and results.

Major discernible trends in NDE research are:

(1) A realization that better quantitative measurements are needed both for advances in understanding of what the measurements mean and for increased reliability of practical decisions drawn from them;

(2) A broadening of the concept of NDE to include testing for a full range of physical properties, not just for size and defects, etc.; and

(3) The relatively recent proliferation of applications of new techniques (drawn mainly from basic research in physics and chemistry), and the perception of need for correlation of results given by different techniques.

Priority attention should be given to accurate, quantitative measurements at this point in the development of NDE, for both laboratory and field measurements. It is estimated that the accuracy of a laboratory measurement that can be made to 5 or 10 percent may degrade to 20 or 30 percent or worse when made in the field. Even in the laboratory, the effects of minor materials processing changes or of minor changes in composition may well be hidden in the error band characteristic of the method used; thus, knowledge of incremental improvements may be lost.

Traditionally, advances in accuracy are made by a combination of three factors: improvements in instrument stability, the development of standard procedures, and interlaboratory checks on calibration by the use of standard reference materials characteristic of the material or component to be put under test. All three areas need urgent attention.

Techniques which seem to offer considerable promise for improvement are listed below, with general comments on each. They are not in priority order; all are judged important. Comments should be considered only as providing examples:

Method	Principal Areas of Application, Comments
X-Radiography	Welds, large structures such as pressure vessels; forgings and castings. Needs: develop image enhancement and three-dimensional techniques; better characterize sources and detectors.
Neutron Radiography	Inspection of nuclear components, explosive devices, adhesive joints, observation of seals and fluids inside metal assemblies.

	Needs: develop sources with greater portability; characterize sources and detectors; develop inspection methods using available ranges of neutron energies.
Ultrasonics	Welds, large structures including pressure vessels and pipes. Needs: basic studies of energy dispersion; development of enhanced sensitivity systems using spectral, phase, and amplitude information; development of imaging methods.
Acoustic Emission	Monitoring of components and structures during proof test and in service. Needs: basic studies to allow interpretation of emission in terms of macro- and micro-events taking place in the sample, e.g., crack propagation, movement of dislocations.
Penetrants	Detection of surface-connected cracks and porosity; leak testing. Needs: development of automated systems; improved standards for checking sensitivity.

Magnetic Particles	Detection of surface and near-surface flaws in ferromagnetic materials such as steel billets. Needs: improved standards for determining performance; standardized procedures.
Visual-Optical	Detection of surface flaws related to finish, color, scratches, etc.; strain in transparent materials. Needs: development of automated systems; improved method performance standards.
Infrared	Detection of hot spots in furnaces, vessels, and unbonded regions in honeycomb and other bonded structures. Needs: development of holographic and improved image methods; development of improved heating techniques.
Microwave	Detection of moisture in materials; inspection of dielectric components. Needs: extend holographic methods, reflection studies on surfaces.

Eddy Currents	Alloy sorting, heat treatment verification, inspection of thin metal structures and tubing. Needs: development of improved data handling systems.
Electron Spin Resonance	Characterization of dielectrics, insulators. Needs: general research on applications.
Nuclear Magnetic Resonance	Detection of strains, impurities in coated substrates. Needs: research on application to bonding in thin adhesive coatings.
Holography in General	Strain patterns in structures, physical surface characterization. Needs: continued work on applications using a range of kinds of radiation adaption to special imaging systems.

REFERENCES

[1] Report of the National Materials Advisory Board: Nondestructive Evaluation, NMAB-252, 1969.

[2] COSMAT Report, Volume II: The Needs, Priorities, and Opportunities for Materials Research, 1975.

5H - CERAMICS

The ceramics research funded by Federal Agencies in FY ′76 is approximately \$20m/year, deduced from agency sources in response to requests for budget data in support of "Basic Ceramics Research." In addition, some of the work funded in solid state physics and chemistry, metallurgy, geosciences, semiconductor physics, chemistry and technology, and chemical engineering, also contribute to understanding of ceramics.

A definition of ceramics research, a partial listing of subjects included in ceramics research, and coincident disciplines are given in Table 1. There are redundancies in this listing, indended to suggest the range of subject matter covered by "ceramics." Overlap among the disciplines precludes exclusive delineation of the scope of the various materials′ disciplines.

Improved interactions with other disciplines are needed to promote understanding of ceramics and to extend areas of developed expertise. Thus increased focus of theoretical work on defects, solutes and their interactions in crystalline and glassy systems are needed as well as increased application of measurement techniques commonly used in solid state physics and chemistry to more complex problems. Catalysis has traditionally fallen in the realm of the chemists and chemical engineers; material science could have great impact through increased application of the advanced techniques for suface structure studies, and the understanding of metal/ceramic interactions and sintering phenomena as strengths mettalurgy developed through longstanding coupled efforts between the metallurgy of ceramics disciplines. In the past decade, much of the research work has been funded in support of the "advanced systems." Increased applied research is now needed because of increased demands for improvement of materials for apparently mature technologies such as coal utilization systems and conservation applications in which both improved and advanced systems are under development.

A priority list of Applications Areas for implementation of the ERDA plan is given in Table 2, with further detail of the devices/components needed and ceramics problems associated with them described in the appended lists, in which key words have been taken from common usage for brevity in identifying problems. The research/development needs for each of the Applications Areas are correlated with the ceramics Research Areas in Table 3. For these entries only several of the properties or phenomena with greatest impact or need for development of improved understanding were noted. For the first application area (space and military) ERDA's efforts are complementary to DOD and NASA's more extensive range of problems for which ceramics needs are significant. The latter are listed in Table 2, Part 2, 1, b.

The research areas from which impact is expected are given below in order of decreasing breadth of application with a brief comment on each.

Structure

Most products are crystalline, hence most applications areas would benefit from research of crystals. Improved interaction with efforts in other disciplines and influence on their programs is needed. Fundamental properties of liquids in relation to structure is less well understood, and information about the interaction of combustion product slags with materials is needed. Surface structure studies using newly developed techniques should advance understanding significantly.

B&C

1. Mechanical properties - Increased strengths and failure prediction techniques are needed. Past and current research hs been primarily phenomenological; emphasis on the basic physics and chemistry of slow crack growth is needed.

2. Processing - Techniques to generate flaw free products with structure and chemical control will be vital for many systems. Cements for high and low temperature use provide possibilities not adequately explored.

3. Thermodynamics - An expanded data base on properties of liquids, slags and combustion products with refractories; oxide/nonoxide phase equilibria, battery materials and components interactions are needed.

4. Electrical and optical properties are required beyond the range achievable with present materials. Closer association/coupling with outputs from solid state physics and chemistry is needed.

5. Transport properties - Improved data base on atom movements under combined fields and gradients is needed with increased emphasis on interface phenomena.

6. Thermal properties - Improved insulation, understanding of thermal expansion.

In addition to the ERDA applications area survey, two other working groups have identified areas for focus of ceramics research. ERDA-9 "Critical Needs and Opportunities in Fundamental Ceramics Research," (Meeting at MIT, January 1975) reviewed energy related problems, but also considered how research productivity could be enhanced. The conclusions were that improved characterization of materials under investigation is needed, with increased focus on chemical segregation at interfaces, and that coordinated studies be organized (in which various experts all work on a material/system to generate the multiplicity of information required to understand some phenomenon).

The Committee on Structrual Ceramics (AB-320, NAS, 1975) found a need for development of design techniques for brittle materials and coordinated/integrated efforts on design, materials' properties improvements and characterization, manufacturing methods, and component testing and evaluation in support of the ceramics turbine development. Necessary reductions in processing cost and improved performance and reliability are other objectives noted.

Those groups have not considered the potential for castable refractories, and cements; government sponsorship of research in this area has been negligible. Applications of foamed concrete for lightweight thermal insulation and structural requirements, ocean thermal systems, and vessels for gas-cooled reactors as well as conservation needs for energy-intensive materials, are to be added to the high temperature applications. Another important class of materials not considered were carbon and graphite with multiple current and potential applications.

TABLE 1

Multidirectional Research in Ceramics - to promote general understanding of the physical & chemical structure, properties, processing and relationships among them, using theoretical and experimental approaches, of the dominantly ionic & covalent crystalline, polycrystalline, amorphous or polyphase materials, including liquids, glasses, composites, rocks and minerals

	Interactions with other Disciplines
A. Structure	
I Crystal structure: electronic and lattice defects, solute effects, complexes, order-disorder, dislocations	solid state physics - physical chemistry of solids and liquids - xtallography - crystal chemistry
II Liquid and glassy states: structure & stability, metastability	
III Interface structures: surfaces, dislocations arrays, grain boundaries, interphase boundaries in single & multicomponent systems	
B. Materials Properties and Behavior	
I Thermal properties: phonon spectra, heat capacity, conductivity, diffusivity, thermal expansion	physics & metallurgy
II Thermodynamics: phase equilibria & transitions, thermochemistry, electrochemistry, point defect equilibria, nonstoichiometry	chemistry & metallurgy
III Transport properties: thermal, chemical potential, electrical, and stress gradients/fields - mass and charge flow-surface, bulk, grain boundary & interphase paths - coupled effects	chemistry & metallurgy
IV Electrical, optical & magnetic properties: band structure, excited states, optical absorption phenomena, mobilities n, p, piezoelectrics, dielectrics, magnetic moment, susceptibility, hysteresis and loss	semiconductor physics electrochemistry
V Mechanical properties: elasticity, plasticity (dislocation networks & dynamics), fracture mechanics, fatigue, creep mechanisms, and thermal shock/stress	metallurgy - geophysics - mechanical engineering
VI Irradiation effects: ne trons, electrons/protons, ions IR $\longrightarrow$ γ rays	physics - metallurgy
C. Processing: oxide & non-oxides - heat treatment & environmental effects	
I Crystal growth, cutting, finishing	chemical engineering
II Ceramics. powder preparation, fabrication, hot press/sinter, cementing, and finishing	metallurgy
III Glasses: melt, form, and finish	
IV Composites: component properties, joining	
D. Characterization	
I Raw materials, in process, and products	
II Techniques development (NDE, NDT, etc.), techniques utilization	mechanical engineers
E. Behavior in Complex Environments: corrosion, friction and wear, erosion, machining, catalysis, stress corrosion cracking, irradiation creep, etc.	multiple engineering disciplines

Table 2: Priority List of Applications Areas for Implementation of the ERDA Plan

1. Space and Military
2. Coal-Direct Utilization in Utility/Industry
3. Nuclear-Converter Reactors
4. Oil and Gas-Enhanced Recovery
5. Gaseous and Liquid Fuels From Coal
6. Oil Shale
7. Breeder Reactors
8. Fusion
9. Solar Electric
10. Conservation in Buildings and Consumer Products
11. Industrial Energy Efficiency
12. Transportation Efficiency
13. Waste Materials to Energy
14. Geothermal
15. Solar Heating and Cooling
16. Waste Heat Utilization
17. Electric Conversion Efficiency
18. Electric Power Transmission and Distribution
19. Electric Transport
20. Energy Storage
21. Fuels From Biomass
22. Hydrogen in Energy Systems

Table 2: Appendages: Details of Problem Areas from ERDA and Other Sources

1.a. ERDA Space and Military

Remote power sources - thermionic converters, heat sources, solar conversion

Lasers for isotope separation

Semiconductors for various applications

1.b. DOD and NASA

General problems - metal: ceramic jointing, design with brittle materials

Remote power sources - batteries, fuel cells solar conversion, thermal sources and thermionic conversion

High power laxers - optically homogeneous, low absorption, high strength windows
Erosion resistant electromagnetic windows, impact strength
Mobile power sources - gas turbines

Light weight structural components - filamentary reinforcement

High strength sonic transducers

"Noses" for re-entry vehicles
high strength, thermal shock resistance

2. Coal Utilization

Extraction - mining technology

Beneficiation (S removal) physical/chemical processes

Burner development - corrosion/erosion thermal shock resistant refractories
Handling ash and slags, waste utilization

Stack gas clean-up (SO_2 removal)
dolomite regeneration

Table 2: Appendages: Details of Problem Areas from ERDA and Other Sources

3. Nuclear Fission
   - Ceramic Applications
     - Fuels
     - LWR - UO_2
     - HTGR - UO_2, ThO_2, UC_2, ThC_2
     - Breeders - $(U,Pu)O_2$, carbides, nitrides
     - Control rods - B_4C, Eu_2O_3
     - Waste containment - glasses, xtls

   - Environment
     - High temperature - to 2000°C
     - Large temperature gradient - 1000°c/cm
     - Radiation
     - Thermal shock
     - Composition charge with burn-up

   - Problems
     - Cracking and healing
     - Irradiation enhanced deformation
     - Interaction with clad-fission product chemistry
     - Mass transport-gradient, irradiation, and
     - Compositional effects
     - Plutonium recovery

4. Oil and Gas Enhanced Recovery
   - Drilling technology (see 14)
   - Mechanical and physical properties of rocks

5. Coal Conversion Systems
   - Ceramic Applications
     - MHD electrodes
     - Refractories and cements
     - Catalysts and supports
     - Grinding media
     - Desulfurization beds
     - Wear and erosion resistant materials
     - Corrosion products and barriers

Table 2: Appendages: Details of Problem Areas from ERDA and Other Sources

Environment
- High temperatures
- Reducing gases
- Severe chemical, thermal and electrical gradients
- Slags
- Molten salts
- High velocity particulate streams
- Sulfur and other impurities

Problems
- Reduction
- Corrosion/erosion - hot corrosion
- Vaporization and volatilization of components
- Thermal shock and fatigue
- Creep, fracture - effects of composition, stoichiometry
- Attrition
- Catalyst selectivity and life

8.a. Controlled Thermonuclear - Magnetic Confinement

Ceramic Applications
- First wall insulator - Theta pinch
- Blanket insulation
- Blanket material
- Tritium extractor
- Insulation for coolant channel, superconducting magnets, beam injectors, etc.

Environment
- High electric field pulses
- Thermal and mechanical pulses
- Neutron flux - 10^{10}n/cm^2-sec.
- Neutron fluence - 10^{23}n/cm^2
- Temperature - 800°C - 1200°C
- Molten Li
- D, T, He flux

Table 2: Appendages: Details of Problem Areas from ERDA and Other Sources

- Environment
  - Strength
  - Optical absorption - intrinsic and extrinsic
  - 14 MeV neutron effects
  - Non-linear optical properties
  - Dielectric breakdown
  - Radiation effects on optical properties
  - He, D, T effects on surfaces
  - Liquid Li corrosion

9,15 Solar

- Ceramic Applications
  - Fibers for composites - wind
  - Corrosion products and protection
  - Semiconductors - crystal growth
  - Substrates
  - Protective films
  - Mirrors and supports
  - Absorbing films and coatings
  - Storage media
- Problems
  - Cost - processing
  - Efficiency
  - Lifetime
  - Joining components

10,11,
19 Conservation

- Thermal Insulation
  - Foamed concrete
  - Reflective films
- Automotive
  - Batteries - turbine
  - Sensors
- Electric Load Leveling
  - Storage - thermal

Table 2: Appendages: Details of Problem Areas from ERDA and Other Sources

10^6 Volt Transmission
  Insulators

Superconductor Transmission
  Insulators

Top and Bottoming Cycles

Waste Heat Utilization

Industrial Process Eff.
  Energy-intensive products
    cement, ceramics, glass, steel

14. Geothermal Energy
  Ceramic Applications
    Drilling (Wc substitute)
    Mechanical and physical behavior or rocks
    Corrosion products and protection

Problems
  Wear at elevated temperatures
  Behavior of rocks at elevated temperatures
  Hot corrosion
  Scaling

Also applies to enhanced recovery, oil shale development, and coal mining

20. Energy Storage and Conversion
  Ceramics Applications
    Batteries
      Electrolytes
      Non-corrosive structural members
    Fuel cells
    Hydrogen storage
      Hydride
      Diffusion barrier
    Flywheels
    Superconductors
    Thermal storage

Table 2: Appendages: Details of Problem Areas from ERDA and Other Sources

Problems
- Corrosion
- Grain boundary phenomena
- Low conductivity
- Attrition
- Strength
- Fabrication

22. Hydrogen Energy Systems

Ceramic Applications
- Hydrides
- Diffusion barriers
- Electrolysis electrolytes
- Chemical production of hydrogen
- Fuel cell electrolytes
- H ion conductors

Problems
- Attrition
- Low conductivity
- Low cost coatings

<u>Other Problem Areas</u>

Catalysts

Applications
- Coal gasification
- Coal liquification
- Automotive
- Petrochemicals
- Electrocatalysis
- Photocatalysis

Problems
- Specificity
- Activity
- Poisoning
- Sintering
- Support interactions
- Physical structure

Table 2: Appendages: Details of Problem Areas from ERDA and Other Sources

EPA and Navy
  Incinerators

    Lightweight ceramics insulation (1600°F)

Domestic Consumers of Ceramics Products
  Product cost
  Fracture and personal injury
  Reliability
  Engineering - how to interface with other materials - joining
  Cements
  Fire retardant materials

Ceramics Industry
  Process cost
  Increased fuels cost in energy intensive products
  Competition for new-high technology developments from Government funding with "systems" development organizations

Resource development for coal, oil, uranium, thorium geothermal

Exploration techniques development

Drilling and mining technology
  Cheaper, domestic source replacement for tungsten carbide

TABLE 3

Multidirectional Research in Ceramics - to promote general understanding of the physical & chemical structure, properties, processing and relationships among them, using theoretical and experimental approaches, of the dominantly ionic & covalent crystalline, polycrystalline, amorphous or polyphase materials, including liquids, glasses, composites, rocks and minerals

Priority Application Areas (Table 2)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
A. Structure																										
I Crystal structure: electronic and lattice defects, solute effects, complexes, order-disorder, dislocations	√		√	√		√	√	√	√	√		√		√	√		√		√			√				
II Liquid and glassy states: structure & stability, metastability	√	√			√								√				√		√							
III Interface structures: surfaces, dislocations arrays, grain boundaries interphase boundaries in single & multicomponent systems	√				√																					
B. Materials Properties and Behavior																										
I Thermal properties: phonon spectra, heat capacity, conductivity, diffusivity, thermal expansion	√		√				√	√		√	√				√											
II Thermodynamics: phase equilibria & transitions, thermochemistry, electrochemistry, point defect equilibria, nonstoichiometry	√	√	√		√		√	√				√	√	√			√			√	√					
III Transport properties: thermal, chemical potential, electrical and stress gradients/fields - mass and charge flow-surface, bulk, grain boundary & interphase paths - coupled effects	√	√	√		√		√	√						√			√		√	√		√				
IV Electrical, optical & magnetic properties: band structure, excited states, optical absorption phenomena, mobilities n, p, piezoelectrics, dielectrics, magnetic moment, susceptibility, hysteresis and loss	√	√						√	√	√					√		√	√	√	√		√				
V Mechanical properties: elasticity, plasticity (dislocation networks and dynamics), fracture mechanics, fatigue, creep mechanisms, and thermal shock/stress	√	√	√	√	√	√	√	√				√	√	√			√		√							
VI Irradiation effects: neutrons, electrons/protons, ions IR ⟶ γ rays	√		√				√	√	√																	
C. Processing: oxide & non-oxides - heat treatment & environmental effects	√	√	√		√			√	√	√	√	√			√		√		√	√		√				
I Crystal growth, cutting, finishing																										
II Ceramics: powder preparation, fabrication, hot press/sinter, cementing, and finishing																										
III Glasses: melt, form, and finish																										
IV Composites: component properties, joining																										
D. Characterization																										
I Raw materials, in process, and products	√												√				√									
II Techniques development (NDE, NDT, etc.), techniques utilization																										
E. Behavior in Complex Environments: corrosion, friction and wear, erosion, machining, catalysis, stress corrosion cracking, irradiation creep, etc.																										