A GLOBAL ROADMAP FOR CERAMICS

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INTRODUCTION

This roadmap summary is organized essentially along the same topical lines as the 1st International Congress on Ceramics, but subjects are grouped together somewhat differently based on ideas brought forth in the presentations. In this summary are set forth the key issues, which I and the Roadmap Editors believe will most critically impact the growth of ceramics. Where appropriate, I have cited papers contained in this book by the author's last name.

The current status of ceramic technology was recently summarized as part of the National Research Council report, *Globalization of Materials R&D: Time for a National Strategy* (National Research Council, 2005, Washington, DC, ISBN 0-309-09693-0). This report points out that the field of ceramics has continued to expand and is "challenging the traditional view of technical ceramics." The wide variety of new applications involving inorganic films and nanostructured materials was used as an example. Other examples of the expanding role for ceramics are new microwave materials needed for high-performance wireless systems and active optical materials to replace passive optics. Efforts in new and improved materials for bioceramics, power sources, sensors, filters, and other areas are rapidly expanding. The suggestion was also put forth that ceramics will play a key role in the use of hydrogen for energy applications.

The above-mentioned report, coupled with other evidence, suggests that the field of ceramics is much broader than is usually assumed. Many individuals easily identify ceramics as pottery, bathroom fixtures, dinnerware, and the like. Others who are a bit more informed realize that ceramics are used in technical applications such as spark plugs, catalytic converter substrates, electrical insulators, and so on. The majority of individuals outside the ceramic/materials community however, are unaware of the multitude of engineering applications and the importance that ceramics have on their lives. For example, without ceramics, cellular telephones would not exist. Optical glass fibers serve as the backbone for the transmission of information. They have provided a technological breakthrough in the area of telecommunications. Information that was once carried electrically through hundreds of copper wires can now be carried through one high-quality, transparent silica (glass) fiber. Using this technology has in-

Global Roadmap for Ceramics and Glass Technology. Edited by Stephen Freiman

creased the speed and volume of information that can be carried by orders of magnitude over that which is possible using copper cable. See the chapter "Ceramics and the National Science Foundation" by Madsen for a table of important ceramic applications.

For the purposes of this roadmap, ceramics will be defined as "any inorganic nonmetal." This would include semiconductors such as silicon, materials for use at elevated temperatures such as graphite, and inorganic glasses. The point of this definition is that if the properties and behavior of a material resemble that of classical ceramics, then ceramic experts can contribute to its development and use. Another consideration is the fact that the ceramic component must be considered as part of a larger system.

TECHNICAL GOALS

In order to summarize key issues, the various application areas for ceramics are grouped into broad technical categories. These include Electronics, Medical Applications, Environmental Preservation, Transportation, Energy, Optics and Photonics, Hard Materials/Armor, High-Temperature Applications, and Consumer Products. As noted previously, these topics do not correspond exactly to the Congress sessions, but rather reflect the results of the Congress presentations and discussions. Issues that cut across all application areas were discussed during the Congress. These issues, including Innovation, Education, Measurements and Standards, Intellectual Property, Health and Safety, Materials Informatics, and Economics, will also be summarized.

Electronics

One of the primary uses of ceramics for electronics is in the packaging and substrates for Si-based microelectonics, mobile communications components, and piezoelectric actuators for the automotive industry. As noted in the overview of Part 5 by Green and Cook, the trend in electronics is toward smaller, more highly integrated devices that can be produced at lower cost with greater yields. Electronic packaging will continue to increase in complexity, and will be multimaterial in nature, for example, containing ceramic, metallic and polymeric components, so that lower-temperature processing procedures will be essential. A number of presentations (e.g., the chapter by Dimos et al. in Part 5) focused on the growing use of low temperature cofired technology as a means of producing packages that will include both imbedded passive and active components.

It appears that in the future, the bulk properties of piezoelectric materials will be less of a concern than their proper integration and functionality in ever smaller and more complex packages. It appears likely that new methods of producing multilayer films of materials will become increasingly important.

Another future application for electronic ceramics was reported to be in ultracapacitors based on carbon structures for use in combination with batteries in hybrid vehicles (speaker Miller). Finally, a recent publication in *Science* (16 June 2006) discusses the promise of flexible inorganic electronic components composed of materials such as gallium arsenide.

Medical Applications

The first generation of medical applications of ceramics has been as replacements of hard tissues, bones, and teeth. Successful products include hip replacements (balls and cups), ceramic crowns, and the filling of bone defects with ceramic powders. Second-generation biomaterials, for example, "bioglasses," interact with the body to elicit particular tissue responses. They are being developed for use as coatings and porous scaffolds in orthopedic applications. Third-generation biomaterials will be aimed specifically at targeting biological reaction pathways involved in tissue engineering of entire joints (see the chapter by Jones and Hench in Part 3).

What are the critical issues? Hench, in his plenary presentation stressed the point that an intimate knowledge of biochemistry, cell function, and physiology will be essential to the development of future ceramic materials. He pointed out that this requirement usually necessitates engaging collaborators from the biological community and, eventually, physician and dental practitioner partners as well when the application progresses to animal models and clinical trials. He also reminded us that human biology is immensely complicated, and that the interactions with introduced inorganic materials are even more so.

There appear to be three primary challenges to the future development of bioceramic materials.

1. In-vitro and in-vivo experiments and clinical trials. As indicated, cell-based models are a necessity, and in-vivo tests are not just a luxury. Animal models and clinical trials raise ethical and liability issues with which most ceramists are unfamiliar.
2. Engineering the material. A set of physical, chemical, and reactivity properties and an unfamiliar environment are involved in biomedical applications, leading to design challenges.
3. Control over purity and morphologies. Even minor impurities in materials introduced into biological environments can have unanticipated physiological effects. Engineering therapeutic atomic constituents compatible with desired phase stability poses a challenge. Morphological control is very important in biological processes, and control over structure at all length scales is required (evolution has had a long time to perfect the natural product).

Environmental Preservation, Health, and Safety

Several of the speakers, beginning with Dr. Inamori, spoke of our responsibility as citizens of the world to preserve and protect the environment, including reduction of greenhouse gases, avoidance of pollution, maintaining natural resources, concern over the safe manufacture and use of nanoparticles, and ensuring the availability of clean water. More environmentally friendly manufacturing processes were promoted as one means of achieving the goals of reduced air and water contamination. The use of recycling as a means of preserving more of our natural resources was encouraged.

Environmental remediation techniques involving the use of photocatalysis are growing rapidly, particularly in Asia, as a possible means of reducing air pollution (see chapters by Lee et al. and Watanabe and Yoshida in Part 7). Although photocatalysis shows significant promise, a greater understanding of the performance of TiO_2 as the fundamental material in such systems is needed. In addition, it was recognized that harmonized evaluation techniques will be required to determine the performance characteristics of particular photocatalytic products. The use of ceramic capacitors for the deionization of water was reported by the Corning Corporation (speaker Miller) as a means of water purification.

The point was also made that the development of new ceramic products is not the only path toward environmental preservation. Kelly and Venturin (see their chapter in Part 7) expressed the opinion that companies must now exert what they termed "product stewardship," which they define as the rational and ethical use of technology. The hazards and risks associated with new technologies and products must be identified and clearly dealt with. They articulated the point that "global customers will want to do business with companies who have a strong, consistent moral compass and standards on a worldwide scale."

Takahashi's presentation summarized Toyota's position with respect to company priorities. He made it quite clear that environmental sensitivity, energy savings, and safety were paramount in Toyota's strategic thinking.

Transportation

Ceramics have found a significant market as components in diesel engines (see chapter by Yonushonis et al. in Part 10). However, decreased funding by federal agencies, for example, DOE, in this area may affect future developments of new materials. In addition, next-generation diesel engines will have improved fuel economy and standards. The EPA has mandated emissions reductions through particle trapping. It is estimated that there is \$500 million invested for manufacturing plants to produce the required catalysts.

The turbine engines used in military and commercial aircraft rely on ceramic thermal-barrier coatings to operate at combustion temperatures close to the melting point of existing superalloys. These coatings will continue to play a crucial role as combustion temperatures are pushed higher to improve efficiency. Ceramics have also found a niche market as components in ceramic turbine engines used for auxiliary power generation (see chapter by Van Roode in Part 10). In this application, durability and manufacturing cost are key issues in the selection of materials. Increased fuel costs and regulatory pressures will be major factors in the selection of ceramics over other materials for such applications.

Advanced ceramics and ceramic matrix composites will be increasingly used as hot-section components for industrial engines, aircraft, utility gas turbines, and auxiliary power units. However, development of such components will rely more heavily on private funding as government research funds become scarcer.

It is predicted that ceramics will find increasing use in numbers of applications that can take advantage of their high melting points and stability. High-density hafnium and zirconium borides and carbides are being developed for rocket combustion chambers, thrusters, nozzles, and thermal protection systems. Ceramic matrix composites are of interest for rocket nozzles, turbine exhausts, and combustion liners.

Energy

As the world has become increasingly aware of the limitation in oil reserves, the efficient production and use of energy has become a topic of paramount importance. The point was made by Takahashi that we will reach the peak of oil production in 2010, and that oil prices will continue to rise. A number of speakers touched on the contributions that ceramics could make toward the greater use of alternative energy sources. In particular, the use of solid oxide fuel cells appears to be one route to energy conservation. Takahashi indicated that one of the primary issues facing the widespread use of fuel cells is the cost of manufacturing. He suggested that costs of fuel cell drive trains must be reduced to 1/100th of current levels for fuel cells to have commercial viability. Other significant factors which arose are: durability and reliability, the need to increase the power plants' operating lifetimes by a factor of five, enhancing their energy output for SUV's and other heavy vehicles, substantially boosting onboard hydrogen storage capacity, and having access to fueling stations at regular intervals. Solid oxide fuel cells were also mentioned as significant areas of growth for both Corning and Kyocera (speakers Miller and Lanthorne, respectively). Lanthorne also indicated that gas turbine engines, fuel injection components, and solar energy products were viewed as future directions for Kyocera, all of which would contribute to energy efficiency and conservation.

Another speaker at the Congress (Marra) predicted that the safe use of nuclear technology is also likely to increase. He pointed out that ceramics will play a role in various stages of the nuclear cycle. Of particular importance are glasses for nuclear waste storage. Ceradyne (speaker Moskowitz) views materials for nuclear waste storage as an expanding direction for the company.

A number of papers described the state of the art with respect to the use of high-temperature superconductors as transmission lines for energy distribution. There have clearly been impressive engineering achievements made since the discovery of high-temperature superconductors. However, fairly significant reductions in manufacturing costs will be necessary if high T_c materials are to replace copper wiring in large-scale applications.

Optics and Photonics

Glasses, single-crystal, and transparent polycrystalline ceramics play an important role in display technology and in optical communication and medical technology through their use in fiber optic cables. Future applications include the use of glasses as substrates for single-crystal silicon (Morse in Part 8), solid-state lighting that makes use of wide-bandgap materials such as gallium nitride, important new biomedical and forensic applications (see chapter by White in Part 3), new solid-state lasers (see chapters by

Pascucci and Duclos et al. in Part 8), and many more. In order to realize these applications, we must find ways to be able to achieve transparency by minimizing grain growth in polycrystalline materials, develop improved sinterable nanosize powders having higher purity, and find ways to improve the strength of bulk optical materials.

The future of traditional glass technology was also a topic of discussion. The consensus was that future glass manufacturing will be subject to greater controls as part of an effort toward energy efficiency. Significant effort is being placed on accelerating the melting and fining processes (see chapter by Arribart in Part 8). Waste gas cleaning to reduce air pollutants will also be expanded. The point was made that faster methods, such as combinatorial ones, are also needed to explore new regions of glass composition. Two presentations (Kurkjian and Prindle, and Brown, in Part 8) emphasized a need to increase the strength of glasses to enable a wider range of applications.

Hard Materials/Armor

Ceramics are of increasing importance as long-wear materials for bearing-surface applications. Three major industries that have worked at the development of these types of products have been the automotive, defense, and orthopedic industries. From the use of ceramics as high-temperature ball bearings to the development of ceramic on ultrahigh-weight polyethylenes and ceramic on ceramic orthopedic products, ceramics have been very important to the increase of service time for these products.

In the field of ceramic armor, both the development of ceramics that will withhold the shock of a blast for more than one offense and transparent ceramics able to withstand the shock of a blast trauma are making ceramics important materials to develop for defense issues. Moskowitz discussed the increased use of boron carbide as the armor material of choice during his plenary lecture.

Consumer Products

Major trends in the area of consumer products appear to be new processing technology (e.g., high-energy milling); the evolution of ceramic production capacity and its dependence on raw material availability, labor force, and market share; the effect of rapid industrial growth in Asia on market and manufacturing trends; and the role of government in establishing regulations, patent law, and trade treaties. More energy-efficient manufacturing processes must be developed as fuel costs will continue to increase. So called “green manufacturing” techniques will grow in prominence in an enhanced effort to reduce both air and water pollution. The previously noted concept of “product stewardship” will also be important as will the identification of life cycle costs rather than simply the costs of manufacturing.

CROSSCUTTING ISSUES

In addition to the specific technical problems that need to be solved, there are some broad economic, political, and social issues that were raised by both technical presenters as well as plenary speakers. Whereas individually we may not be able to solve these broader problems, collectively we can bring the issues to the attention of those who can bring about the necessary changes.

Innovation

One of the recurrent themes throughout the Congress was the dependence of future growth of ceramic technology on the innovative ideas of today. The point was made by two of the plenary speakers (Miller and Cherukuri) that significant numbers of innovative ideas are required to generate only one or two commercial applications, and that only when products based on these ideas are brought to market can businesses grow and new ideas be resourced. Both speakers emphasized communication, both within and external to an organization, as being important to the innovation process.

Education

The need for educated and trained engineers and scientists who will be the innovators of tomorrow was strongly expressed. The success of the ceramics industry of the future will depend on the availability of talented individuals. The question was raised as to whether materials education today was providing the optimum mixture of training needed for the multimaterial applications of tomorrow. Of special concern was the need for individuals to be interdisciplinary, in particular for them to be at least conversant in the biological sciences, and able to contribute meaningfully to the development of the next generation of medical applications of inorganic materials (speakers Miller and Hench), and nanomaterials. The need to make students more aware of the global nature of the materials community and to make the public more aware of the dynamics of student nationalities was also expressed. It was recognized that teaching has changed markedly in recent years; for example, team teaching, more hands-on laboratories, materials-by-design approaches, and high-technology access to research (see chapter by Faber in Part 2). Hench suggested forming an international commission to examine materials curricula and related issues worldwide in order to determine their efficacy in training the materials scientists of the future.

Measurements and Standards

The ability to measure accurately and easily the crucial properties of new ceramic materials will be a significant factor in their success. Kaiser and Cook pointed out in their chapter in Part 2 a number of measurement issues that should be addressed in the near future. In particular, as devices and components shrink in size, approaching the nanometer scale, new measurements will be needed to assess their properties and performance.

The availability of standards was also noted as an important factor in bringing new material applications to the marketplace. By standards is meant not just formal, documentary, standards published by ASTM, ISO, and others, but also mutually agreed upon test methods and protocols, reference materials, and so forth. The point was made by Freiman and Quinn in Part 2 that although material standards are not a barrier to international trade, in a global market, harmonized methods of assessing properties and performance are of critical importance. They also described an organization whose mission is the development of the technical underpinning of standards—the Versailles Project on Advanced Materials and Standards (VAMAS). VAMAS carries out its mission through prenormative collaborations between laboratories around the world.

Intellectual Property

Intellectual property (IP) issues arose as a topic of concern throughout a number of presentations at the Congress. Two primary points were put forth as most important in inhibiting our ability to capitalize on innovative ideas (see the chapter by Sayre in Part 2). The first is the incompatibility of the rules governing patents and the patent process in different locations throughout the world. The primary difference is the "first-to-invent" policy of the United States versus the "first-to-file" policy in force in most other countries. This difference in policy creates confusion among inventors and increases the cost of filing. Although there are ongoing discussions aimed at abolishing this difference, until the problem is solved, obtaining patent protection globally will remain difficult. A second problem is the amount of time required to obtain a patent. Such delays can directly impact the rate at which a new product can be brought to market. More detail on other IP issues is provided in the aforementioned NRC report, *Globalization of Materials R&D.*

Materials Informatics

One of the areas in which the ceramics community can have an immediate and direct effect on the use of ceramics is by extending the availability of property and design data for materials. Data and, more importantly, information, are the lifeblood of industry. In fast-moving fields involving new technologies, access to the most up-to-date, accurate data is essential for rapid commercialization and quality manufacturing. Data can take many forms, ranging from the most basic electronic and physical properties of materials to citations of technical publications. But more than data are needed. We can describe the entire variety of data, information, and delivery mechanisms as materials informatics.

Engineers trained in their specialties frequently do not know how to choose the kinds of data they need in order to design, build, and operate new and complex facilities. The materials expert must know how a given material should be used in a design, and be aware of the stresses on the system. These data must be accurate and easily accessible. Most designers of components, devices, an so on that could involve the use of ceramics may be unfamiliar with available materials, including both the properties of interest, for example, electrical, optical, thermal, and mechanical, as well as the chemistry and structure of the material. A comprehensive and easily accessible database of such information would significantly improve the chance of these materials being selected for the job at hand.

The development of specifications for ceramic materials, analogous to those for metal alloys, was also identified as being important for the selection of these materials. Kapoor and Gray in their chapter in Part 1 also foresaw a trend toward more demanding material specifications at a company such as Saint-Gobain.

Economics

Economic considerations such as the ability of a company to profit from the sale of a device, product, and so on, was a somewhat understated topic at the Congress, but one which is obviously a major deciding factor with respect to the success or failure of any new product. If the ceramic component is the critical element in the system, as it is in a cellular telephone, the raw material and manufacturing costs may not be as important. However, for most applications for which there is a choice of materials, it is essential that the manufactured cost of the ceramic component be such that the end product is economically competitive. Unless there are other significant factors such as regulatory requirements, the competitive free-market economy will apply. It is clear that ceramic turbine engines, for example, enjoy only a niche market, primarily because production costs are prohibitive compared to those of metal components. If high-temperature superconducting cables for electric power transmission are to achieve widespread use, their costs must be decreased to compete with existing copper technology. Unless there is a significant performance advantage in the eyes of the consumer, lower-cost materials will be chosen. Quantitative models for understanding the economics of ceramic manufacturing have been developed (speaker Clark), which can be used as a guide. One must also recognize that as new ceramics are developed, other materials will be improved as well, so there is continual competition for a place in new applications.

WHERE DO WE GO FROM HERE?

As a final step, we propose a set of actions for the global ceramics community that could facilitate the achievement of the technical goals. Comments on each follow in no priority order:

- Materials education was viewed as a major issue by a number of both speakers and participants. Current university materials curricula and teaching methods were questioned as to their relevance to the perceived needs for future materials scientists and engineers. It was recommended that there be formed an international committee to study materials curricula and related issues worldwide to determine what changes, if any, should be instituted to insure that a well-trained and diverse workforce exists. We concur with this recommendation. Another charge to this committee would be to examine to what extent more extensive training in chemistry, biology, and other sciences should become a major part of materials science education. It is also recommended that professional organizations such as The American Ceramic Society, the European Ceramic Society, and the Ceramic Society of Japan give thought to ways to provide continuing education to scientists and engineers working in the field of ceramics and other materials.

- Energy costs and the need for energy conservation will grow in importance in the coming years. We recommend that funding agencies give a high priority to the development of materials that can contribute to energy efficiency and conservation. Increasingly, the ceramics industry must also look for ways to conserve energy and other scarce natural resources. Glass manufacturing facilities appear to already set energy conservation as a high priority.
- The availability of property and performance data for both current and potential ceramic materials was pointed out to be a major factor in the selection process for any application. It is recommended that an international effort be initiated to create and make available through the World Wide Web the necessary data that will facilitate the materials selection process.
- Intellectual property issues were expressed as a continuing concern, not just for the ceramics community, but for all of the innovation and development process. Harmonization of patent laws throughout the world would be an important step toward creating a level playing field for the international ceramics community. Influencing change in international law and regulations is somewhat beyond the capabilities of the ceramics community, but we must continue to bring these issues to the attention of those who can effect change.
- Concerns over the global environment must be a prime consideration in the future manufacturing and use of ceramics. The expanded utilization of ceramics can be an important step in environmental protection. More environmentally benign manufacturing techniques must be developed for a wide variety of ceramic products. We strongly suggest that the ceramics community must also adopt the principles put forth in the Congress regarding “product stewardship.”
- Biomedical applications involving ceramics are growing rapidly. In order to achieve their full potential, ceramic scientists and engineers must partner with their counterparts in the biology and life sciences, and be prepared to work with physicians and dental practitioners in the final testing and evaluation of new products. It is recommended that the professional ceramic societies plan joint meetings and workshops with those in the biomedical areas. Increased opportunities for education in these areas would be an additional important step toward accelerating the development of new biomedical products.
- Continuing concerns over health and safety issues involving the manufacture and use of ceramic materials must be proactively addressed. Of special importance is the emergence of nanotechnology, involving the use of very small particles as both starting materials and as the final products for a number of applications. Public perception of risks associated with nanoparticles must be proactively addressed. The effect of the chemistry and physical nature of these particles on human tissue must be determined in order to ensure that no significant health and safety risks are being incurred.

This roadmap for the future of ceramics describes some of the technical goals for ceramics over the next few years, and sets forth some ideas of what could be done to help reach those goals. The topics addressed in the Congress and this chapter were never intended to be all encompassing and will certainly change with time as new issues arise and technology advances.

This Congress was instituted as the inaugural event in a continuing series of international meetings led in turn by The American Ceramic Society, the European Ceramic Society, and the Ceramic Society of Japan. The second Congress will be held in Verona, Italy, June 29–July 3, 2008; the third is planned for Japan in 2010. It is hoped that these future meetings will build on the results of this Congress and help to provide a clearer view of the future of ceramics.

ACKNOWLEDGMENTS

The valuable comments and editing provided by Mark Mecklenborg, Greg Geiger, Lynnette Madsen, and the Roadmap Editors are gratefully acknowledged.