A GLOBAL ROADMAP FOR CERAMICS:
Today's Grand Challenges and Critical Enablers

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ABSTRACT

This paper builds on the report of the 1st International Congress on Ceramics, "Global Roadmap for Ceramic and Glass Technology" to describe the current needs of the ceramic field and to recommend further actions by the ceramic community. Key areas of ceramic technology are discussed and recommended actions are proposed.

INTRODUCTION

Two years ago the international ceramics community embarked on an ambitious plan to expand the development and use of ceramic materials worldwide. It was agreed at the 1st International Congress on Ceramics (ICC) that we must define the field of ceramics as broadly as possible and develop a **"**global roadmap".[1] The 1st ICC provided a modern definition of ceramics describing them as any inorganic non-metal, including graphite, glasses and semiconductors. It also took a fresh approach to scientific meetings by focusing on large topical application areas and their roles with industry and in society, through invited presentations with extensive discussion periods, with this aim of establishing a global roadmap for the key areas. This large undertaking roughly defined the areas; gained perspectives on each area from well-regarded experts from academe, government and industry; and identified some of the directions and markers.

The 2nd ICC builds on this foundation with the following themes for high technology ceramics: (1) Electro-, Magnetic-, Optical-Ceramics and Devices, (2) Bioceramics, Biotechnology, and Health (3) Mobility and Transportation, (4) Construction Materials (5) Advanced Energy Technologies-Environment, and (6) New Production Technologies-Nanofabrication. In addition there are numerous crosscutting areas that will directly or indirectly influence the successful transition of science and engineering into commercial successes. These include: measurements and standards, patent issues, regulations with respect to safety and the environment, cyber infrastructure, education, funding, innovation and competitive product development, and public understanding. The key players are researchers, engineers, trade associations, professional societies and bodies, funding organizations, industry, and educators. The roadmap with the accompanying technical papers points the way toward the goal of the greater use of ceramic materials. In this paper, examples of a grand challenge in each of the key areas and enablers for further progress are described. These enablers are discussed from two perspectives: their effect on achieving the grand challenge and the steps necessary to move forward.

COMMUNICATION and INFORMATION STORAGE

Modern communication and information storage devices are composed of multiple layers of complex ceramic compositions and contain additional layers of metals or polymers. Interface science plays an important role in microelectronics, semiconductor processing, environmental monitoring of pollutants, and new nano- and micro- sized structures and devices.[2] Interface science is the study of the boundary between two immiscible phases, sometimes including a thin layer at the boundary within which the properties of one bulk phase change over to become the properties of the other bulk phase. There is a need for fundamental understanding of interaction at interfaces of dissimilar materials. Can we integrate material with different properties such as "ferromagnetic and superconducting", "photonic and semiconducting" and "biological and inorganic"? A simple example of a grand challenge is <u>controlling the structure and properties of complex oxides at the atomic scale</u>**.**

Critical enablers include the following: <u>Infrastructure and support for growth of high quality materials,[3] and advances in characterization and measurement techniques for rapid and accurate property determination at very small scales and having resolution of the order of nanometers</u>. Generally integration of knowledge from various characterization techniques is inefficient and limited (gaps are left between techniques, or apparently conflicting information is obtained). There is also a lack of analytical tools to examine layer-by-layer growth *in situ*. The efficient use of statistical techniques covering a matrix of experimental space,[4] including combinatorial materials science,[5] requires not only accurate, but rapid property determination.

HEALTH and BIOMEDICAL APPLICATIONS

Today glasses and ceramics are being used as hard-tissue replacements (for teeth and bone) and as mechanisms for specialized drug delivery. Next generation ceramics engineered for active participation in biological processes show promise.[6] The eventual goal is to manufacture biomaterials implantable as autologous replacement tissues. A grand challenge is to <u>meet the material needs of future replacement human body parts</u>.

One critical enabler is to have in place is <u>the appropriate education and training of university students in crosscutting material science and engineering</u>. In particular, materials education needs to include the necessary biology content, and/or greater interaction and collaboration between the materials and biological communities. At the 1st ICC, 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 being trained today. The question was raised as to whether materials' education today was providing the optimum mixture of courses needed for the multi-material applications of tomorrow. Of special concern was the need for individuals trained sufficiently in the biological sciences who could contribute meaningfully to the development of the next generation of medical applications of inorganic materials.

Second, better predictive schemes are needed to be able to move materials more rapidly from in-vitro to in-vivo testing, and subsequently for human studies. These will require greater knowledge of interaction chemistry between inorganic and organic materials.

TRANSPORTATION on EARTH and in SPACE

For space and flight applications, there is a need for robust and affordable ultra-high-temperature composites (or ceramics) that can be formed into complex shapes and joined, as necessary, to other materials. A stumbling block towards achieving this goal is the lack of understanding of materials in combination with each other. It is clear that one area where the ceramic community can have an immediate and direct effect on the use of ceramics is that of the availability of property and design data for materials. Access to the most up-to-date, accurate, information is essential to rapid commercialization and quality manufacturing. Information can take many forms, ranging from the most basic electronic and physical properties of materials (ceramics or composites), to citations of technical publications.

Critical enablers are: The integration of research into student learning, interdisciplinary education fostering smart material development, material informatics, efficacious material design approaches, and critical test environments.[7] Informatics includes the science of information, the practice of information processing, and the engineering of information systems.[8] Materials informatics can be applied to better understand the use, selection, development, and discovery of materials. Data must be accurate and easily accessible. The materials expert must know how a given material should be used in a design, and be aware of the stresses on the system. Designers of components, devices, and systems need to be familiar with the available array of materials, including both the properties of interest, (e.g., electrical, optical, thermal, and mechanical) and 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. Engineers, trained in their specialties, need to be schooled in how to choose the kinds of information they need in order to design, build, and operate new and complex facilities.

CONSTRUCTION MATERIALS

An example of a grand challenge is to establish model examples of optimal and environmentally-friendly building materials. Environmentally-benign construction materials and their manufacturing processes are becoming more important as we begin to appreciate the damage that has been inflicted already on this world. Innovative ideas are needed for new materials and processes that will minimize harm to the environment and have the possibility of remediating or mitigating existing problems. One example of how ceramics can play a role was shown by the development of bricks that could be manufactured from fly ash obtained from the waste from coal-fired power plants.[1] These bricks have been shown to actually remove small amounts of mercury from the air. Another example is the use of titanium dioxide as a photocatalyst for a variety of applications, such as, self-cleaning coatings on glass. Sunlight is used to produce a reaction that helps remove pollutants from the atmosphere. The technology to manufacture and use this material in a broad spectrum of applications is only now being developed.

In general, critical enablers include the establishment of standards and international regulations alongside environmental stewardship. For example, better tests and performance standards are needed to help promote development of titanium dioxide technology. The availability of globally accepted measurement methods and standards is as an important factor in bringing new material applications to the marketplace. Standards include formal, documented standards published by ASTM, ISO, etc., and mutually agreed-upon test methods and protocols, and reference materials. While material standards are not a barrier to international trade, in a global market, harmonized methods of assessing properties and performance are critical to efficient trade. The development of specifications for ceramic materials, analogous to those for metal alloys, was identified at the 1st ICC as being important for the selection of these materials.

SUSTAINABILITY of the ENVIRONMENT and ENERGY

The U.S. National Academy of Engineering recently published fourteen grand challenges for engineering in the 21st century.[9] It is easy to see how ceramic materials will play a key role in a number of them. About half of these challenges involve sustainability: make solar energy economical, provide energy from fusion, develop carbon sequestration methods, provide access to clean water, prevent nuclear terror, and secure cyberspace. The first of these, maximizing the use of clean and abundant solar energy, requires advances in materials, manufacturing, cost, reliability, and efficiency of systems.[10]In particular, photovoltaics which maximize energy efficiency will be an important step in making solar energy more competitive in the marketplace.

A critical enabler towards achieving this goal and many others is to provide education in innovation and competitive product development.[11] Competitiveness, i.e., the ability of a company to turn a profit from the sale of a products (or services), was a somewhat understated topic at the 1st ICC, but one that is obviously a major deciding factor with respect to the success or failure of any new product. Unless there are other significant factors such as regulatory requirements, the competitive free-market economy will apply. One example from the energy sector is solid-state lighting, which offers energy savings (with >90% conversion efficiencies), alongside quality enhancements. It is clear that ceramic turbine engines, for example, enjoy only a niche market, primarily because production costs are currently prohibitive in comparison to 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 advantages known to the manufacturer, lower cost materials will be chosen. 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.

EMERGING NANOTECHNOLOGY APPLICATIONS

Although Feynman gave a talk in 1959 entitled, "There's Plenty of Room at the Bottom",[12] having a general bottom-up processing methodology for nanotechnology remains a grand challenge. In this approach, materials and devices are composed of molecular components self-assembled chemically using the principles of molecular recognition.

There are at least four critical enablers to the progression of nanotechnology: dealing with safety aspects,[13] public acceptance of the technology, informatics, and measurements at the nanoscale. It was noted at the 1st ICC and reinforced over the past two years at numerous conferences and workshops that the hazards and risks associated with new technologies and products must be identified and clearly resolved. The point was articulated "global customers will want to do business with companies which have a strong, consistent moral compass and standards on a worldwide scale". This issue is particularly relevant to the rapidly expanding number of products based on nanotechnology, where their potential risks to the environment and health must be addressed immediately, if their promise is to be realized in a timely manner. In addition, robust techniques for measurement of the critical properties of these materials will be needed.[14]

SUMMARY and RECOMMENDATIONS

Examples of scientific and engineering challenges for different application areas were outlined above and a few of the critical enablers were described. Additionally below, pathways for the global ceramics community to move forward expeditiously to achieve some of the above possibilities are explained. A number of these ideas were touched upon or discussed at the 1st ICC.

There are several materials choices in most designs and in the integration of complex systems. It should be recognized that many new applications will involve combinations of materials, e.g., polymers, metals, organics as well as ceramics. Understanding the interactions of these diverse materials will also be important to future developments. In some instances, ceramics will have an advantage, e.g., due to high melting points and stability, however in many cases, other issues, such as extensiveness of the property determination and reproducibility, will determine which materials selected for use. The availability of data on ceramic materials is acknowledged 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.

Materials education and its relevance to the perceived needs for future materials scientists and engineers is a key issue. An international study is recommended that covers the needs of ceramic curricula worldwide, addresses the integration of biology and nanotechnology into materials science and engineering programs, examines the role of masters degrees, lays the foundation for entrepreneurship education, and identifies and describes exemplary models of success.

Major trends in the area of ceramics for consumer products appear to focus on new processing technology (e.g., high-energy milling), the evolution of ceramic production capacity and its dependence on raw material availability, labor force, 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. So-called, "green manufacturing" techniques will grow in prominence in an enhanced effort to reduce both air and water pollution and to conserve energy resources. Concerns over the global environment, e.g., the reduction of greenhouse gases, must be a prime consideration in the future manufacturing and use of ceramics. More energy-efficient and environmentally-benign manufacturing processes must be developed for a wide variety of ceramic products.

Health and safety issues involved in the manufacture and use of ceramic materials must be proactively addressed. Of special importance is the emergence of nanotechnology, where the use of very small particles as both starting materials and as final products for a number of applications are involved. 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. The international ceramics community should assume leadership in developing the measurements and data necessary to ensure the safety of all nanomaterial products with respect to human health and the environment.

In summary, the promise for the increased use of ceramic materials worldwide is bright provided that certain hurdles can be overcome. In this paper, challenges are discussed and approaches for some of their solutions are suggested.

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