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High-Technology Ceramics in Japan

Committee on the Status of High-Technology Ceramics in Japan
日本におけるハイテクノロジーセラミックスの現状に関する委員会
National Materials Advisory Board
Commission on Engineering and Technical Systems
National Research Council

NMAB-418
National Academy Press
Washington, D.C.
1984

This study by the National Materials Advisory Board is a joint effort sponsored by government agencies and private industry. Agencies involved include the National Science Foundation, the Department of Commerce, the Air Force Office of Scientific Research and the Army Tank Command of the Department of Defense, the Department of Energy, and the National Aeronautics and Space Administration. The study was conducted under Grant No. PRA-830[illegible] monitored by the National Science Foundation.

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Abstract

High-technology ceramics are made from extremely pure, composition-controlled, ultra-minute particles formed, sintered, and treated under closely regulated conditions. These properties and processes give superior performance characteristics that allow the materials to be used in a wide range of demanding applications far beyond the capabilities of conventional ceramics. Japan is widely viewed as having a significant national commitment to developing and exploiting high-technology ceramics in order to advance its domestic and international markets. This situation contrasts markedly with that in the United States, where such an intensive effort has not been mounted.

This report presents the findings of a committee formed to assess the situation in Japan, with the objective of providing an understanding of the possible effects on high-technology ceramics in the United States. Another important objective was to establish a basis for possible future cooperation in ceramics science and technology between Japan and the United States. The committee concluded that there is, indeed, a strong commitment in Japan to the rapid development and exploitation of high-technology ceramics. The greatest potential for application of this technology appears to be in the automobile and electronics industries. Cooperation between Japan and the United States would be feasible and welcome, especially in the development of common standards, the exchange of nonproprietary information, and possibly cooperative projects. The committee recommends several steps that should be taken in the United States to advance the field of high-technology ceramics, particularly in view of the effort now taking place in Japan.

(KR)

Preface

Visitors to Japan have reported a remarkable commitment to the development and exploitation of high-technology ceramics in that country; indeed, they have spoken of a "ceramic fever," citing sales of tens of thousands of copies of a popular book on the subject and the attendance of hundreds of thousands of people at ceramics fairs.

There is little doubt that advanced ceramics is a significant "emerging technology" worldwide, affecting such diverse areas as microelectronics, auto engines, sensors of various types, cutting tools, power generation, and even orthopedics. Japan is widely perceived as having mounted a committed national public and private effort to dominate this field by funding substantial amounts of research and development, creating a vigorous educational program, targeting markets, and pursuing aggressive pricing strategies. In contrast, the timetable in the United States for the development and exploitation of high-technology ceramics appears to be more relaxed. The United States is seen as lacking a coordinated research and development program, placing insufficient emphasis on process and product development, and fostering a very limited national commitment.

Of course, perception is not necessarily the same as fact. Thus, during the deliberations of the National Materials Advisory Board (NMAB), questions arose as to whether Japan was as committed to ceramics as reports indicated, and, if so, how the United States might respond. Of particular interest was the question of whether U.S.-Japanese cooperation in high-technology ceramics would be possible, likely, or worthwhile. To seek the answers to these and other questions, the U.S. National Academy of Sciences and National Academy of Engineering, through the National Research Council and its National Materials Advisory Board, established a Committee on the Status of High-Technology Ceramics in Japan. This committee, composed of both U.S. and Japanese members, and assisted by Japanese technical advisors, visited Japan for 2 weeks in August 1983 and conducted discussions with a large number of Japanese experts, including ceramics scientists and engineers, academicians, industrial leaders, government officials, economists, and association and professional society leaders.

The committee's purpose in visiting Japan was to provide an evaluation and interpretation of the situation there—not to gather comprehensive data on Japan's high-technology ceramics industry or to make an exhaustive comparison of its status with that in the United States. This report, therefore, is intended simply to present a concise statement on the type, quality, and state of Japanese work on high-technology ceramics, with the object of facilitating some understanding of its thrust and its potential impact on U.S. efforts in this field.

The initial draft of this report was prepared by the U.S. members of the committee with the assistance of a technical writer-editor. This draft was then sent to the Japanese members of the committee for their amendment and consensus before being submitted to the National Research Council's review process.

It is our hope that the efforts of this committee will pave the way for enhanced multilateral cooperation in high-technology ceramics between Japan and the United States. Opportunities abound for this, and the climate is ripe for mutually beneficial exchanges at personal, company, and national levels.

A. R. C. Westwood
Chairman

Acknowledgments

This study was sponsored jointly by several U.S. government agencies and 16 leading U.S. industrial corporations and institutes, which also contributed to the study by submitting general and specific questions about the Japanese ceramics effort for the committee's consideration and investigation. The complete list of sponsors and their designated technical liaison representatives to the project is given in Appendix A. The support of each of these representatives and organizations is gratefully acknowledged, as is the special assistance of Jane Dionne of the National Science Foundation, which acted as the coordinating agency.

As background for the committee's visit, James Schulman of the NMAB was commissioned to prepare an overview of the Japanese governmental, educational, economic, and cultural institutions, with emphasis on the issues and data of special relevance to high-technology ceramics. The information provided in this summary greatly assisted the committee members in making efficient use of their time in Japan.

The generous hospitality of the organizations visited (see Appendix B) and of their officers and staffs is much appreciated, especially the advice, technical information, and managerial insights of the Japanese executives who participated in weekend discussions at Mt. Hiei. Special thanks must be paid to Shinroku Saito, who served as the U.S. committee members' advisor and high-level Japanese connection, and to his hard-working colleagues, Osamu Fukunaga, Junichi Sato, Akira Sawaoka, and Moriya Uchida.

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Contents

1

Introduction

High-technology ceramics, referred to in Japan as "fine ceramics," are made from extremely pure, composition-controlled, ultra-minute particles formed, sintered, and treated under highly controlled conditions. These properties and procedures give the ceramics superior performance characteristics.

Some of the differences between high-technology ceramics and conventional ceramics are shown in Figure 1. The great diversity of practical applications of high-technology ceramics is shown in Figure 2.

The Committee on the Status of High-Technology Ceramics in Japan was, from the outset, characterized by a number of special features, foremost among them being the joint membership on the committee of Japanese and U.S. experts as well as Japanese technical advisors. The Japanese members provided an intimate knowledge of the industry in Japan and were instrumental in arranging entree for the committee to high-level government, industrial, academic, and economic leaders who are close to the development aspects of ceramics. (Appendix B lists organizations visited as well as other contacts.)

One example of the special opportunities opened up to the committee by its Japanese participants is an extensive weekend discussion they arranged with the top executives of seven leading Japanese corporations, during which a wide range of subjects was candidly discussed—from technical evaluations of the future of high-technology ceramics to technology transfer and general industrial policy.

In addition, the Japanese committee participants were instrumental in arranging visits to a broad spectrum of organizations, including government agencies, financial managers, basic-industry groups, automotive companies, chemical producers, electronics manufacturers, and leading ceramics academicians. This served to place the high-technology ceramics effort in the context of the broad national picture.

To cover as much ground as possible in Japan, the committee was divided into two teams during much of its visit. The team visits were preceded and followed by full committee meetings to discuss findings, conclusions, and recommendations.

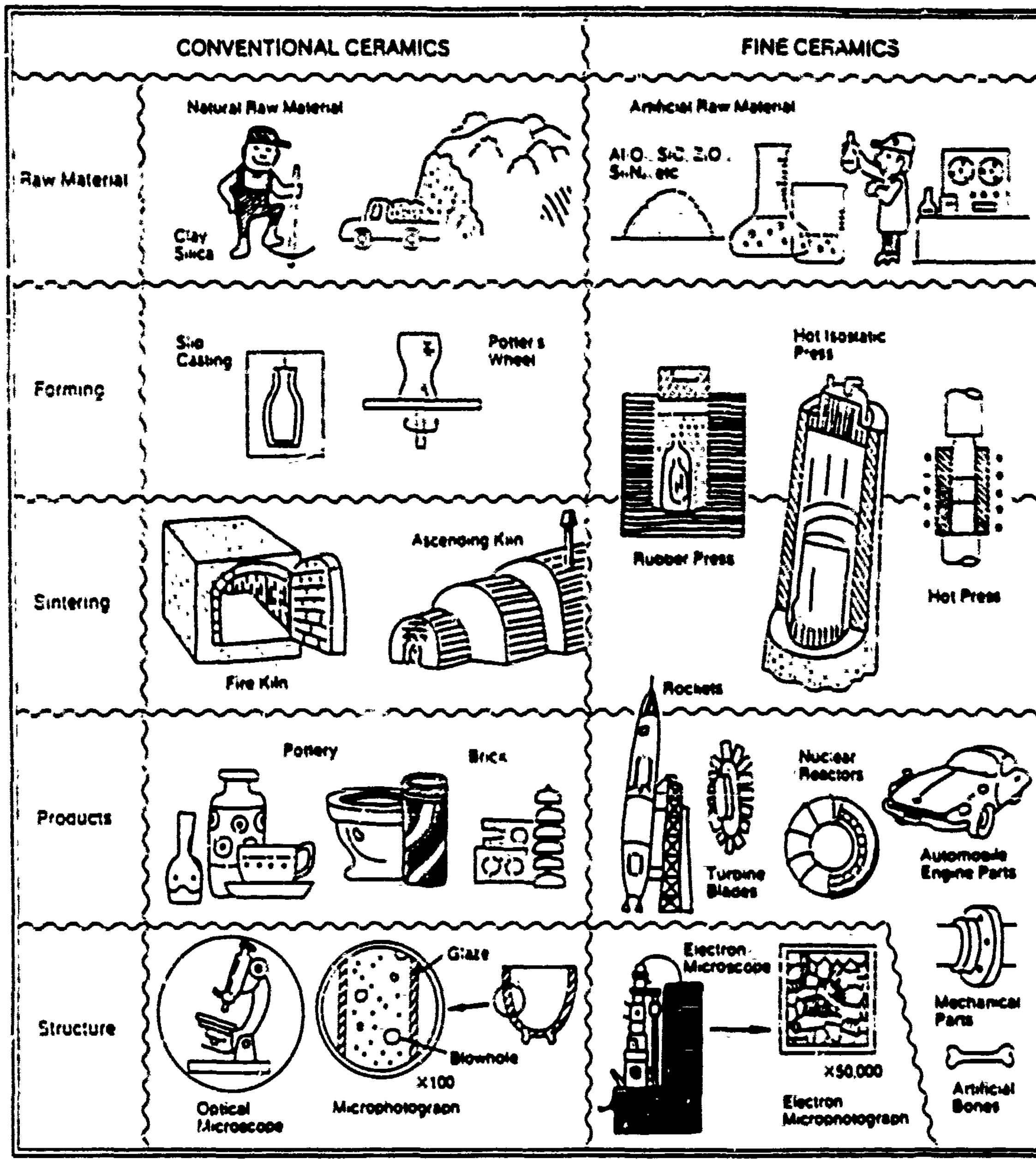

FIGURE 1 Contrast between conventional ceramics and fine ceramics. (Source: Fine Ceramics Office, Ministry of International Trade and Industry, Tokyo)

OBJECTIVES

The committee's objectives were

- To assess the extent of the Japanese commitment to high-technology ceramics and understand the origins and motivation of that commitment:

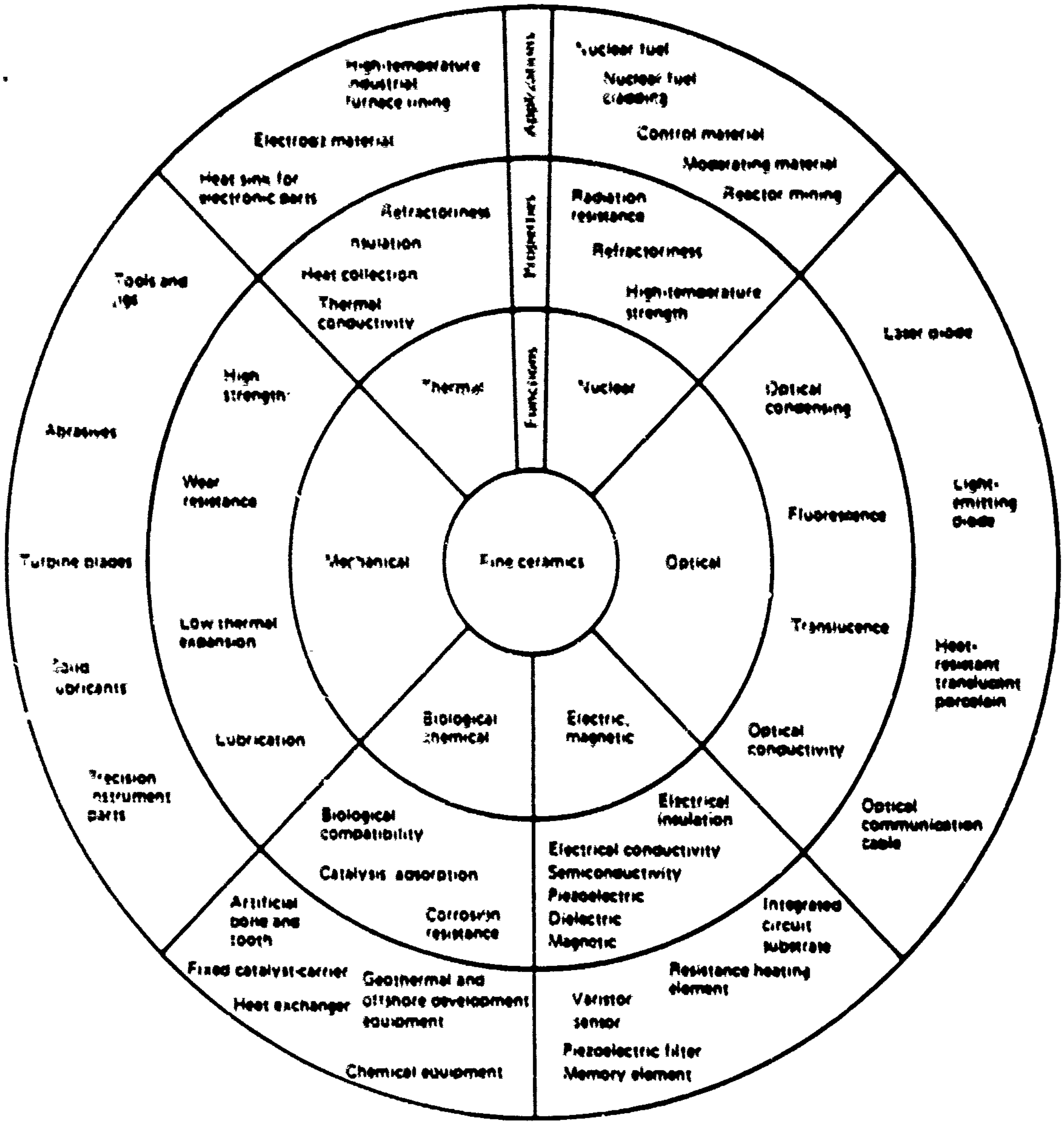

FIGURE 2 Examples of functions and applications of fine ceramics. (Source: Fine Ceramics Office, Ministry of International Trade and Industry, Tokyo)

- To understand the manner in which government, industry, and academia work jointly and separately to develop this field, especially the formal and informal linkages that permit both competition and cooperation to beneficially coexist;

- To clarify the magnitude, location, and time base of the economic opportunities perceived by Japan;

- To assess the status of the science and technology of fine ceramics in Japan; and

• To use the knowledge gained to establish a sound basis for enhanced future multilateral cooperation in ceramics science and technology.

To accomplish these objectives, the U.S. members of the committee visited Japan during the period August 12–28, 1983, for the discussions, observations, and deliberations described here.

JAPAN'S COMMITMENT TO HIGH-TECHNOLOGY CERAMICS

The observations made by the committee confirmed the view that Japan is strongly committed to the rapid development and exploitation of high-technology ceramics. The "ceramic fever" reported by other visitors to Japan is real and evident. In support of this statement, it may be noted that

• More than 2000 Japanese scientists and engineers are working in the field of high-technology ceramics—with perhaps 1000 research engineers working to develop structural ceramic materials.

• The Japan Fine Ceramics Association (FCA), established in July 1982, was quickly joined by more than 170 companies representing the ceramics, chemicals, electrical appliance, primary metals, machinery, automotive, and heavy engineering industries.

• A popular book on high-technology ceramics by a known expert, Professor H. Yanagida of the University of Tokyo, released in March 1983, sold 20,000 copies in the first month and over 75,000 by May 1984.

• A Fine Ceramics Fair, held for 4 days in Nagoya in March 1983, attracted displays from 70 corporations and well over 100,000 visitors. Other regional meetings have excited similar interest.

• The Japanese government is sponsoring long-range research and development programs on high-performance ceramics and basic technologies for future industries through the Ministry of International Trade and Industry (MITI) and functional ceramics through the Ministry of Education.

• Industrial recipients of government ceramics research and development contracts typically commit to the project several times the value of the contract from their own funds.

ORIGIN AND RATIONALE OF THE COMMITMENT

The origin of Japan's commitment is a combination of economic necessity and opportunity. Basic industries, such as aluminum and refractories, are being threatened by third-world countries, and survival thus dictates a move away from commodity to value-added products. There is a need to develop substitutes for critical and strategic metals and to develop energy-efficient materials. There is also the desire to vigorously develop areas where Japan already has a high-technology foothold, such as the electronic and automotive industries.

The motivating philosophy is perhaps best expressed by the text of MITI's announcement of its long-range plan or "vision" for the 1980s:

> The purpose of this vision is to grasp changing political, social, and economic conditions in the world as well as the diversified needs of our nation in the 1980s, and to set forth a basic framework for the formulation and implementation of our industrial policy in this decade. The main theme of MITI's vision is the pursuit of economic security, the maintenance of the vitality of our society, and contributions to the international society. Progressing into the 1980s, Japan is confronted with the problems of how to maintain its economic vitality and further improve the living standards of its people, under energy restriction and in the face of an increasing number of aged people. For a country which is poor in natural resources, the most effective means of solving these problems is to pursue technological development with a view to establishing itself as a country founded on the basis of technology.
>
> In particular, the manufacturing technologies of Japan, for example, in the steel, automobile, or electronics industries, are now on a comparable level to those of any advanced country. They were, however, originally introduced from the United States and Europe after the Second World War, although they were later modified and improved considerably.
>
> As for the capability of creating new innovative technology, Japan is evidently still lagging behind. Especially in the field of technology which serves as the base for the establishment of future industries, such as the space, aircraft, data-processing, bioindustry, or new energy industries, Japan is said to be generally 5 to 10 years behind the United States and Europe.
>
> Therefore, MITI has inaugurated the "Research and Development Project of Basic Technology for Future Industries" for FY 1981. . . . The project deals with revolutionary basic technologies essential to the establishment of the new industries which are expected to flourish in the 1990s.

New materials are one of the "revolutionary basic technologies" identified by MITI, and high-performance ceramics are one of the principal new materials targeted by the program.

EXTENT OF THE COMMITMENT

MITI's perception of the importance of ceramics is shared by industry. Table 1 gives the results of a survey of division directors in 100 important Japanese companies to determine the 10 most significant technological innovations since the 1973 "oil shock." The high ranking of new ceramics (fifth) shows convincingly the widespread belief in the importance of this field, since it represents the consensus of technical managers in many fields and many companies not dominated by ceramic interests.

The Japanese financial community concurs with the judgment of the industrial managerial sector. Figure 3 shows the ratio of 1990 production to 1980 production of a variety of products predicted in the report of the Long Term Credit Bank of Japan for 1983. Production of new ceramics is expected to increase from its 160 billion yen value in 1980 to a 900 billion yen in 1990, a growth of about 550 percent.

The level of commitment in industry varies from company to company. In general, however, industrial research and development is focused on sophisticated production technology and innovative products, with much of the science base

TABLE 1 Ranking of Ten Most Important Technological Innovations Since 1973

Innovation	Number Responding (Number Ranking This Innovation First)	Rating
1. Large-scale integration applications	86 (67)	397
2. Biotechnology	41 (5)	151
3. Fiber optics	39 (4)	129
4. Industrial robots	35 (7)	104
5. Advanced ceramics	42 (0)	103
6. Interferon	31 (0)	86
7. Office automation	23 (8)	77
8. Other new materials	21 (0)	41
9. Super computer	11 (2)	37
10. Space technology	14 (1)	32

SOURCE: The economic industrial newspaper Nikkei Sangyo Shimbun, August 16, 1983

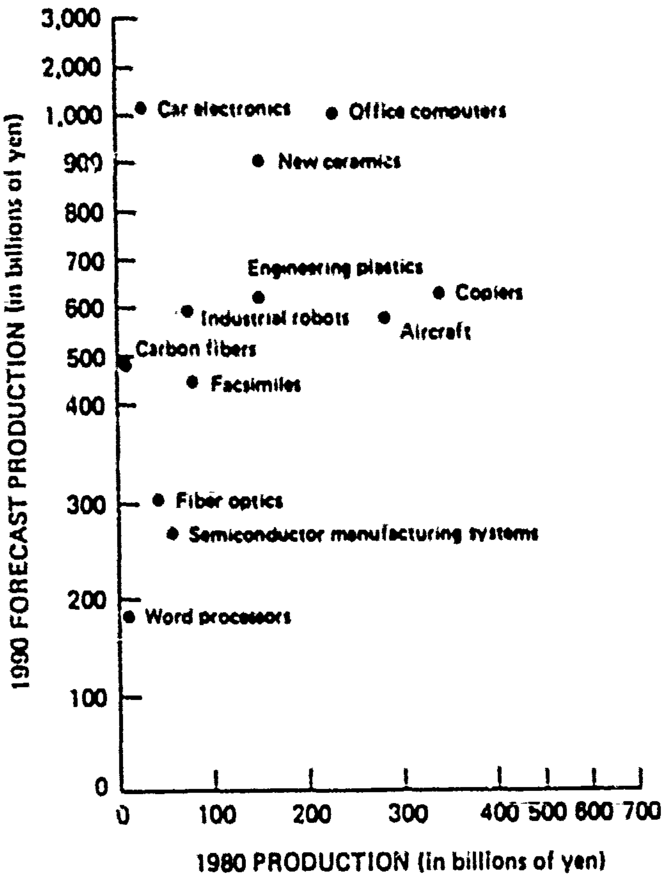

FIGURE 3 Growth forecast for various products, 1980 to 1990. (Source: Long Term Credit Bank of Japan, 1983 Report)

for such developments being provided from abroad. Laboratories visited by the committee were very well equipped, the staffs enthusiastic and highly motivated, and the managements knowledgeable. Typically, industrial ceramics research and development budgets ranged from $2 to $6 million per year.

Although no major technological breakthroughs were revealed to the committee, innovative momentum and intense intercompany competition were evident, such as that between Toyota and Nissan. Management's aim of getting good-quality products quickly into markets and pushing for market share was clear. Although some decision makers were uncertain about the timing of a developing market for high-technology ceramics, few seemed uncertain about its inevitability. So committed are the Japanese to high-technology ceramics, and so confident of their industrial leadership, that a *Japan Times* editorial of August 17, 1983, proclaims that "it is only reasonable that the industrial standards of fine ceramics [should be] initiated here."

2

Conclusions and Recommendations

As a result of its observations and discussions, the Committee on the Status of High-Technology Ceramics in Japan has reached the following conclusions:

• The Japanese view "fine ceramics" as an extremely significant emerging technology because of its wide economic, industrial, and social impact on a large number of fields, of which microelectronics, power generation, production tools, sensors and automation, and automobile engines are the primary examples.

• The Japanese have a committed effort to develop vigorously, and perhaps even to dominate, the field of high-technology ceramics. This commitment is expressed by a well-integrated national effort that includes the government, industry, and (to a lesser extent) the universities and involves substantial research and development funding, a vigorous educational program, targeted markets, and aggressive pricing strategies. The motivation for this commitment is a perceived economic necessity to overcome the national handicap of shortages in indigenous supplies of energy and metallic raw materials.

• The level of commitment varies from company to company, but laboratories are generally well equipped and the typical company's ceramics research and development budget is $2 to $6 million per year. The work force is dedicated, flexible, and technology-oriented and includes many young engineers. The keen competition between Japanese companies forces quick reactions and vigorous pursuit of imaginative applications.

• Management's commitment to long-term research and development appears to be more solid in Japan than in the United States. This attitude, combined with the "high-technology" tendencies of the Japanese consumer, encourages the development of "thin markets" (see Chapter 4) to perfect new products through field experience, thereby providing an edge in developing commercial markets.

• Japanese research and development has until recently focused on sophisticated production technology, and considerable reliance has been placed on foreign research to provide the fundamental base. This situation is now in the process of change, with the inception of government-inspired basic research programs and the initiation of improvements in rather limited intragovernmental and university-industry interactions. As yet, however, the Japanese do not appear to have a technical edge over the United States in the field of ceramics in general.

• Cooperation with the United States would be welcomed by the Japanese and is especially feasible in the development of common standards, in the exchange of nonproprietary information, and in cooperative projects involving university and Japanese government laboratories. In view of the language problem in the United States, timely access to research published in Japanese could be a valuable result of this cooperation.

• Ceramic automobile components have already been introduced in Japan and will become common by 1990 and universal by 1993. The successful achievement of an all-ceramic engine is doubtful: it certainly will not come within the decade.

The committee recommends that all sectors of the government, industrial, and academic communities in the United States take the following steps:

• Examine the potential of high-technology ceramics in the context of domestic and international trade, leading to the development of a sense of commitment appropriate to the U.S. economy.

• Develop a vitally needed mechanism for gathering and disseminating timely information on Japanese ceramics publications, reports, and patents.

• Develop better communications with Japanese counterparts through regular visits.

The committee recommends to U.S. industry in particular that it

• Advance its timetable for the emergence of high-technology ceramics markets.

• Capitalize on research and development funded by the Department of Defense and other government agencies by applying the results to civilian markets.

• Accelerate research and development of production technology for high-technology ceramics.

• Establish a U.S. "Ceramics Industry Association" to facilitate gathering and dissemination of information and to develop a sense of purpose for the industry.

3

Japanese Government Coordination and Management of High-Technology Ceramics Programs

The high-technology ceramics effort in Japan is a product of both government and private industry initiatives. The organizational policies and institutional arrangements that coordinate and manage this effort reflect the close working relationship between Japanese government and business. They also reflect the capacity of Japanese firms to compete vigorously with each other in a manner that is constructive for the national economy.

The Japanese government is a parliamentary system. Its ministerial (departmental) structure is outlined in Figure 4. Ministries with the most important involvement in high-technology ceramics development are indicated in Figure 5, along with some of their implementing laboratories, agencies, and societies.

The Ministry of International Trade and Industry (MITI) is probably the best known of these ministries. It identifies technological fields that should be cultivated in the long-range national interest (a responsibility termed "vision") and undertakes to support research and development in these areas to some limited financial extent.

The Council for Science and Technology is an advisory organization in the Prime Minister's office. This council has the responsibility for establishing general national goals and defining long-range national targets in science and technology. Its advice is implemented via the Science and Technology Agency of the Prime Minister's office.

The Ministry of Education recently instituted a specially funded project for promotion of scientific and technological research on high-performance ceramics. The items selected for the project are surface-active ceramics, reactive ceramics, electronics ceramics and environment-sensitive ceramics, temperature- and pressure-sensitive ceramics, and opto-sensitive ceramics. Research and development

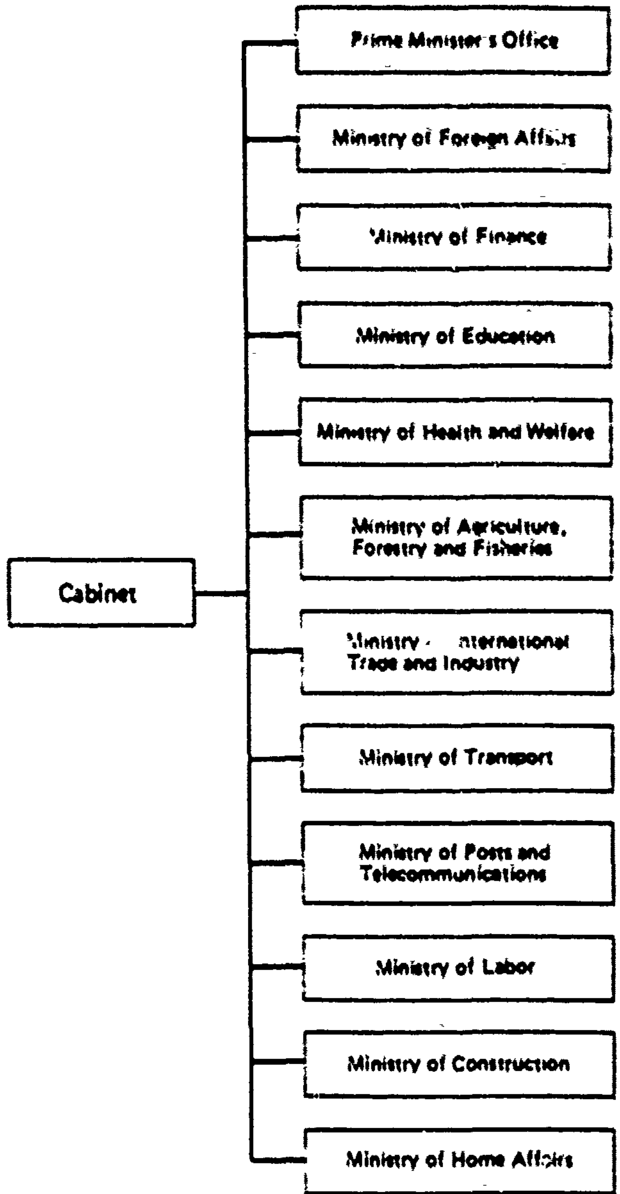

FIGURE 4 Japanese government ministries.

on these items are being carried out at Tokyo University, Tokyo Institute of Technology, Kyoto University, Tohoku University, and Osaka University.

As a result of favorable and interlocking relationships between the Japanese government and business, it is characteristic that, following the formulation of government policies, business accepts government leadership. Hence, ministry support for specific technology areas exercises considerable leverage on the entire national effort. Even so, government research and development funding is generally viewed merely as "seed money" by the industrial community.

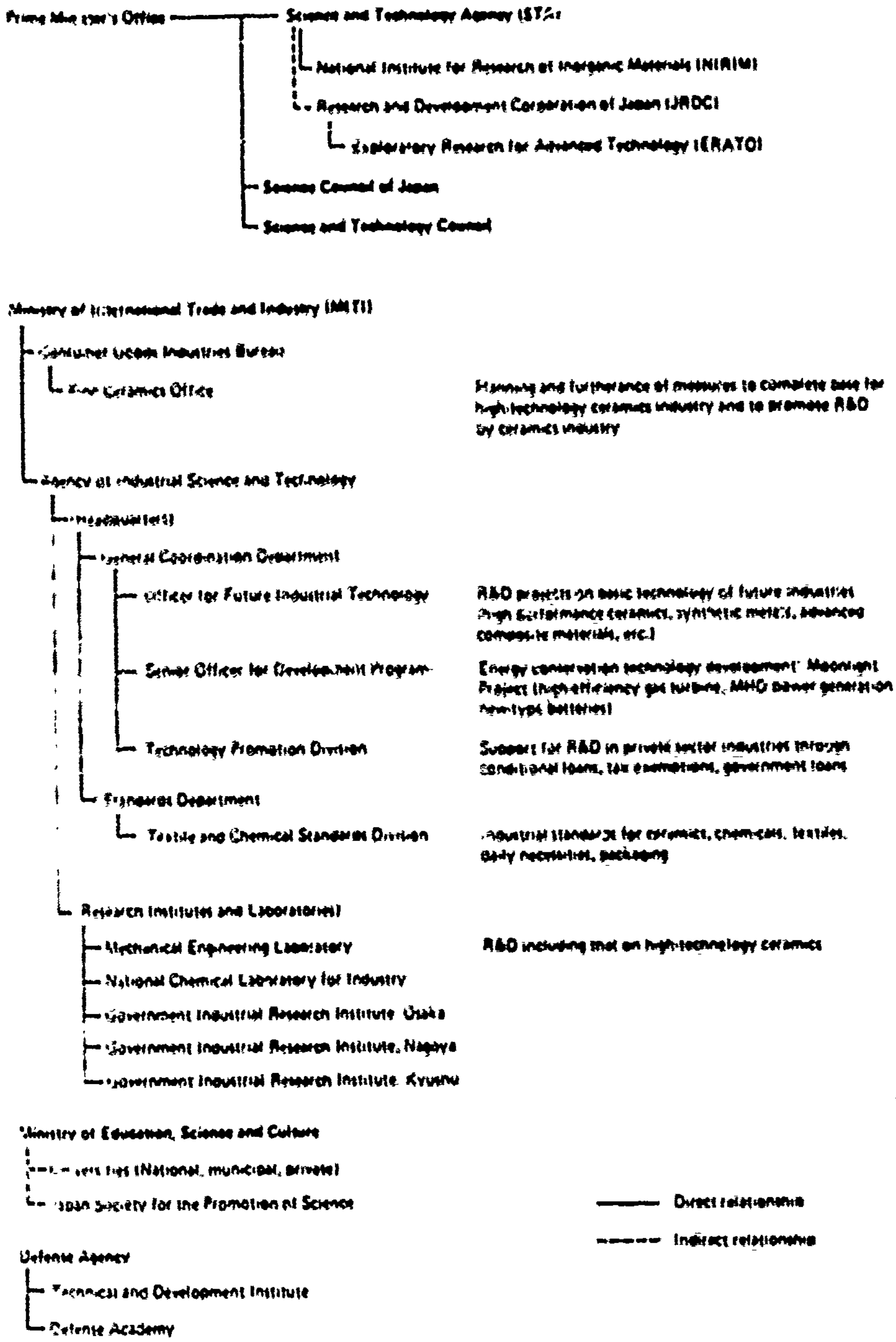

FIGURE 5 Japanese government involvement in ceramics.

MINISTRY OF INTERNATIONAL TRADE AND INDUSTRY

MITI, through its Agency for Industrial Science and Technology (AIST), has sponsored several major technology efforts over the years, such as the energy production- and conservation-related "Sunshine" and "Moonlight" projects begun during the 1970s. In its 10-year "R&D project on basic technology of future industries," begun in 1981, MITI targets 12 research and development areas: among these are biotechnology, electronics, and new materials including ceramics. The ceramics project is coordinated by the Engineering Research Association for High-Performance Ceramics, a nongovernmental group whose staff includes several former members of MITI. The association was set up at the suggestion of a MITI-based advisory committee, and its budget is controlled by MITI. Table 2 identifies the initial group of 15 private companies and 4 government laboratories constituting the initial membership in the association and the task assigned to each company. Selection of the participating companies was made by AIST on the basis of their financial standing, reputation, and ability to contribute to the program's goals. Figure 6 outlines the organizational structure of the project.

The purpose of the association is to stimulate basic developmental work on ceramic materials that are strong and resistant to corrosion and abrasion. The specific objectives for the 10-year program are given in Table 3; the time frame for meeting them is given in Figure 7. Behind these goals lies MITI's view that the slow steps in the exploitation of structural ceramics are (1) industry's inability to manufacture parts reproducibly and reliably and (2) the absence of standards and testing techniques. MITI also considers that the flow of critical information among industry participants, and thus the consolidation of aggregate statistical data, have been inadequate. Accordingly, this project attempts to bring together a representative mix of industrial and governmental participants to address a carefully selected menu of technical problems and to provide an "infrastructure" for dialogue and transfer of information.

In any such joint undertaking, the proprietary nature of some of the knowledge generated can raise difficulties. However, by keeping AIST-sponsored work at the basic end of the research and development spectrum, requiring it to be shared

TABLE 2 Members of the Engineering Research Association for High-Performance Ceramics

Member	Assignment
Toshiba Corporation	Sintering of silicon nitride
Kyocera, Ltd.	Optimization of the sintering process
Asahi Glass	Shaping and sintering of silicon carbide ceramics
NGK Spark Plug	2-step sintering of silicon nitride
NGK Insulators	Development of technical assessment methodology
Showa Denko K.K.	Fabrication of silicon carbide
Denki Kagaku Kogyo K.K.	Fabrication of silicon nitride from silicon powders or silicon halides
Toyota Machine Works	Apparatus for testing bending strength at high temperature
Kobe Steel	Sintering of silicon nitride by hot isostatic processing
Toyota Motors	Measurement of high-temperature strength
Inoue Japax	Machining and fabrication
Sumitomo Electro-Chemical	Minimizing grain size distribution
Kurozaki Refractories	Corrosion tests
Shinagawa Refractories	Thermal fatigue testing
Ishikawajima Harima Heavy Industries	Design of mechanical parts

NOTE: National labs participating in the association are the Government Industrial Research Institute, Nagoya; Mechanical Engineering Laboratory; Government Industrial Research Institute, Osaka; and National Institute for Research on Inorganic Materials. The initial term is 10 years (3 years for basic research, 3 years for model development, and 4 years for production and evaluation). The funding is 13 billion yen or approximately $57 million.

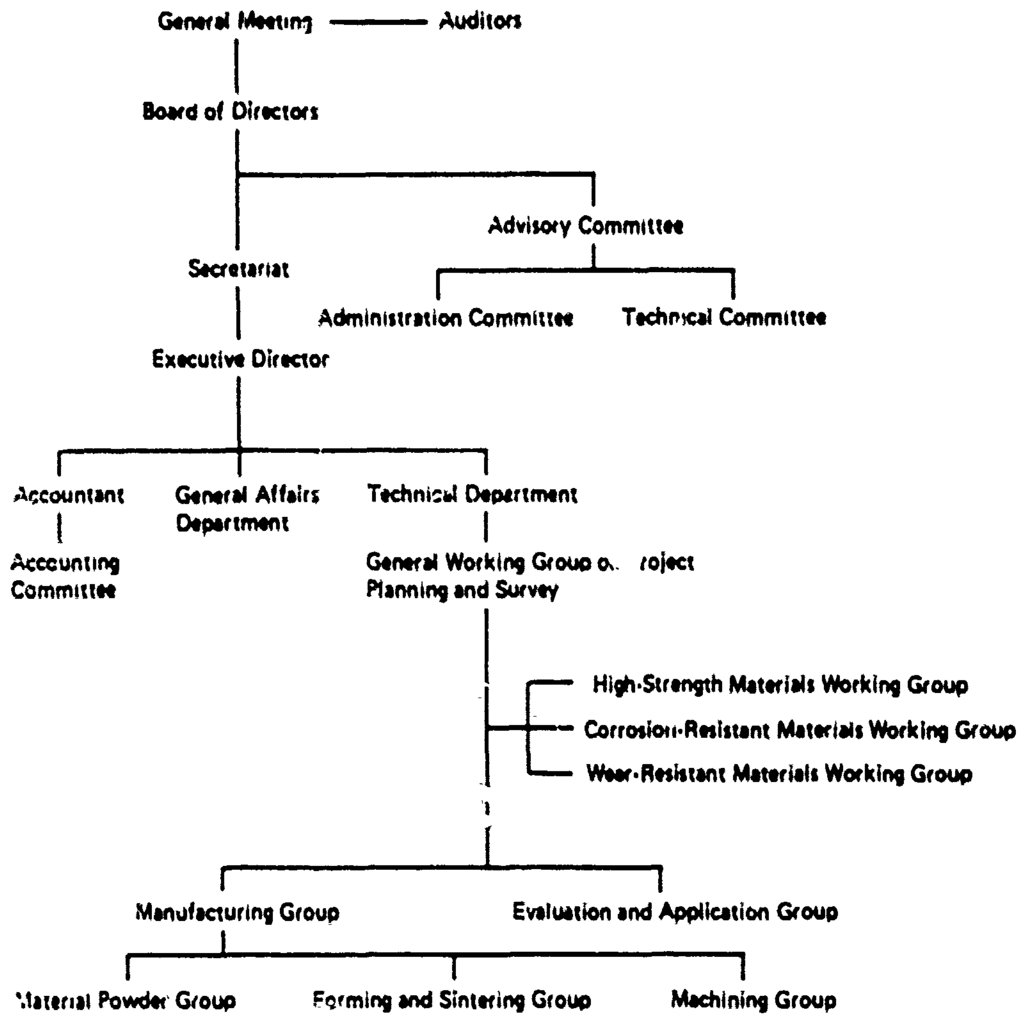

FIGURE 6 Organization of the Engineering Research Association for High-Performance Ceramics. (Source: Engineering Research Association for High-Performance Ceramics)

among member companies, and allowing for a time lag before its wider dissemination. MITI is trying to balance the loss of a potentially proprietary position with the advantages of enhanced availability of information.

The nature of this balancing act became clearer when the committee asked private firms how they regarded their involvement in the MITI program. As mentioned earlier, virtually every company supplemented the funds from MITI with at least an equal amount (and generally much more) of its own funds. MITI's view is that, as each company addresses its perceived market niches by making incremental improvements in existing technology, and as it competes to generate most quickly the necessary manufacturing experience base, it is less inclined to

TABLE 3 Performance Objectives for High-Technology Ceramics

Classification	Objective	Values
High-strength materials	≥ 1200°C in air after 1000 hours holding:	
	Weibull modulus	$M \geq 20$
	Average tensile strength	$\sigma \geq 30$ kg/mm^2
	1200°C in air after 1000 hours continuous loading:	
	Creep rupture strength	$\sigma \geq 10$ kg/mm^2
Corrosion-resistant materials	≥ 1300°C in air after 1000 hours holding:	
	Weibull modulus	$M \geq 20$
	Corrosion resistance (weight gain)	≤ 1 mg/cm^2
	Average tensile strength	$\sigma \geq 20$ kg/mm^2
Wear-resistant materials	Room-temperature	
	Wear resistance	$\leq 10^{-4}$ mm^3/kg·mm
	Surface flatness	$R \leq 2$ μm
	800°C in air after 1000 hours holding:	
	Weibull modulus	$M \geq 22$
	Average tensile strength	$\sigma \geq 50$ kg/mm^2

pay attention to generating fundamental understanding—the necessary foundation for reliable development. MITI's efforts are directed toward ensuring that this foundation of knowledge is built.

Despite the leverage of the MITI program, the main thrust of Japan's high-technology ceramics effort arises from industry. However, the discipline that the MITI program imposes on the generation of the knowledge base serves as a unifying force to hold together a rather disparate group of industry participants. MITI also works hard to mobilize public energy and enthusiasm for the concept and potential of high-technology ceramics. "Ceramic fever" in Japan, exemplified by the observation previously mentioned that a popular book on the topic could sell 50,000 copies in a few months, is not entirely unrelated to MITI's efforts.

It is important, however, to distinguish certain differences between MITI's ceramics project and other, more specific, goal-oriented projects such as the very-large-scale integration (VLSI) effort. In the latter case, the participants were few in number, well versed in the industry, and worked essentially in parallel. The technical problems to be solved were evident, in that everyone knew what was required to get from 4K to 16K to 32K and to 64K, and the market also was quite well defined. In the ceramics program, on the other hand, the mix of participants is broader and does not provide a broad basis of experience in "fine ceramics" per se but instead a range of other industrial experiences that may or may not be adaptable. The mix also contains participants at different points in the industry's vertical structure, and market goals are still being defined. Thus, it may be that the VLSI and ceramics programs have more differences than similarities.

NATIONAL LABORATORIES

Other government-sponsored work on ceramics takes place in the various national laboratories under the jurisdiction of MITI and in the six under the

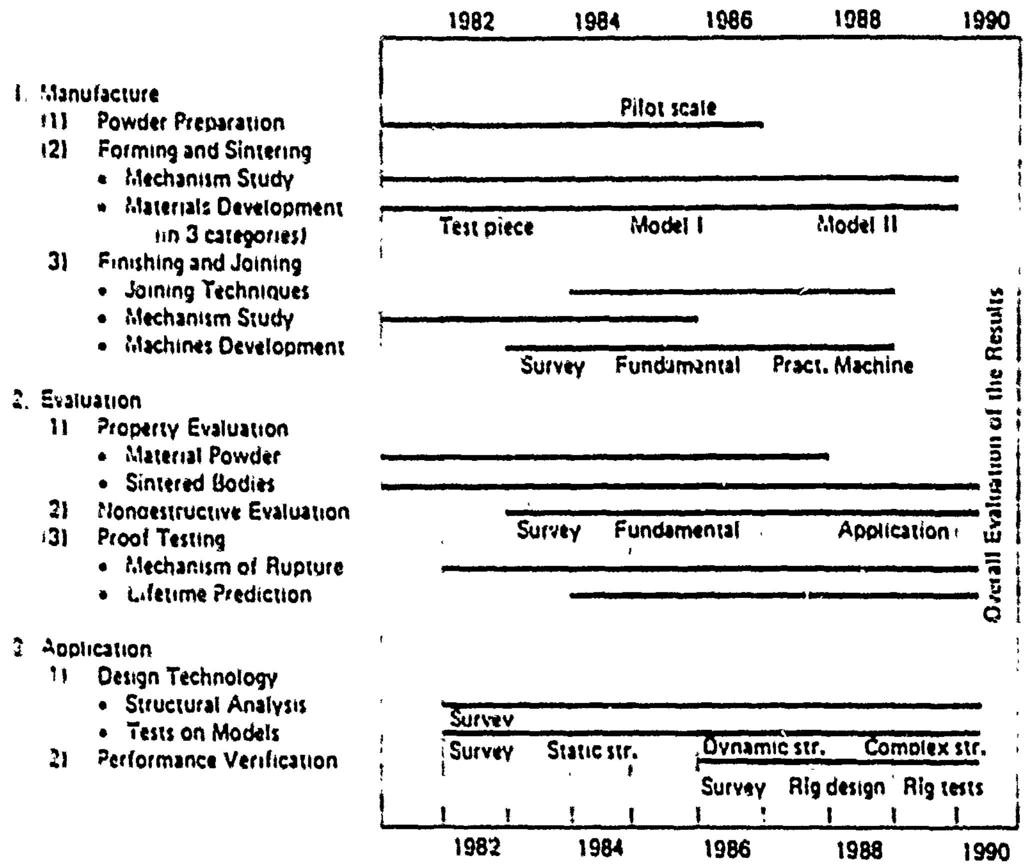

FIGURE 7 Schedule of development program for high-technology ceramics.

jurisdiction of the Science and Technology Agency (STA). Of the latter, the National Institute for Research of Inorganic Materials (NIRIM), located in Tsukuba Science City, has the largest program. Appendix C provides additional information on activities at NIRIM.

Research at NIRIM is conducted by 15 or so individual research groups, each with 6 to 10 members. Materials studied include silicon carbide, diamond, and rare earth aluminates. Contacts with industry are maintained in various ways, such as through a trainee system. At any time some 15 to 20 trainees, with salaries paid by industry, are at work on projects such as the sintering of silicon carbide. Contacts with universities are largely on a personal basis, but NIRIM does have an extensive visiting professor system: 33 such positions are available, each entitling the holder to make occasional visits to NIRIM over a 1-year period, with the institute picking up travel and lodging costs. For the most part, patents are owned 51 percent by government and 49 percent by industry, and technology is regularly passed along to private companies either by license from the Research and Development Corporation of Japan (JRDC) or after a period of specific commissioned research.

MINISTRY OF EDUCATION: UNIVERSITIES

University-based ceramics research is conducted primarily by graduate students, two-thirds of whom receive scholarships from special nonprofit corporations. This typically amounts to about $350 per month, from which they must pay tuition. Many supplement this income by working as tutors. Most technical students go directly into industry after their undergraduate studies and effectively receive their graduate training there. Individual and joint research projects run by professors must compete for funding by the Ministry of Education, which supports on the order of seven new 3-year projects each year at a yearly rate of $8,000 per senior researcher. This money may be used only for equipment, supplies, and some travel and office expenses. Patents derived from work on a government-funded project usually belong to the government, the researcher, or some combination of both.

Paid consulting by professors is not allowed, so there is little incentive for involvement with industry. As one academic researcher summed up the situation, "Pay – Respect = a Constant." Active cooperation between universities and industry in the form of joint research projects is not practiced in Japan. A relationship of the two communities exists on the personal level, however, in which the professor can play an important role in the recruitment or placing of his students in an appropriate industrial job. The role of the universities has primarily been to provide high-quality trained manpower.

Since its inception in the latter half of the nineteenth century, the Japanese modern higher education system has given priority to practical aspects rather than to the purely scholarly or intellectual pursuits that have been largely emphasized in the West. In the case of scientific and technological education, the emphasis has been very strongly to aid Japan's industrial sector. The zeal of

TABLE 4 Number of Higher Education Students by Subject

Country	FY	Total	Cultural and Social Sciences	Physical Science (percent)	Engineering (percent)	Agri-culture	Medical Science	Others
Japan	1970	1,619,649	857,139	42,265 (2.6)	320,029 (19.8)	53,356	72,284	274,576
	1981	2,110,513	1,108,688	55,212 (2.6)	368,770 (17.5)	63,195	129,888	384,760
United States	1970	*	*	*	231,700	*	*	*
	1975	8,727,826	*	*	231,400 (2.7)	*	*	*
	1981	9,403,049	*	*	387,600 (4.1)	*	*	*
Britain	1970	185,872	81,167	45,775 (24.6)	30,261 (16.3)	3,640	20,616	4,413
	1979	245,093	113,157	55,590 (22.7)	35,817 (14.6)	5,124	27,629	7,726
France	1970	572,614	346,689	*	89,455 (15.6)	*	112,275	24,195
	1978	720,335	389,195	*	103,776 (14.4)	*	161,931	65,433
West Germany	1970	407,107	164,514	69,917 (17.2)	39,580 (9.7)	7,065	44,748	85,283
	1979	970,284	455,433	141,653 (14.6)	176,494 (18.2)	24,014	83,238	89,422

* Comparable data not available or not collected.

SOURCE: Keiichi Oshima, "Science and Technology in Japan," Journal of Japanese Trade and Industry, No. 5, pp. 21-22, 1983.

TABLE 5 Holders of Academic Degrees by Subject (Total for Masters Degrees and Doctorates)

Country	FY	Total	Cultural and Social Sciences	Physical Science (percent)	Engineering (percent)	Agri-culture	Medical Science	Others
Japan	1970	13,879	2,847	1,794 (12.9)	4,633 (33.3)	1,026	3,219	360
	1981	21,665	4,124	2,532 (11.7)	8,101 (37.7)	1,695	4,234	919
United States	1970	262,616	102,056	26,520 (10.1)	21,797 (8.3)	3,543	6,215	102,485
	1978	333,809	141,349	22,692 (6.8)	21,292 (6.4)	4,944	16,203	127,329
Britain	1970	12,901	4,183	4,017 (31.1)	2,727 (21.1)	320	835	819
	1978	18,080	6,322	4,374 (24.2)	3,090 (17.1)	501	1,206	2,587
France	1970	7,526	1,702	—	3,049 (40.5)	—	2,775	—
	1977	17,273	2,421	—	5,178 (30.0)	—	9,674	—
West Germany	1970	9,728	2,158	1,995 (20.5)	768 (7.9)	332	4,475	—
	1979	11,033	2,279	2,467 (22.4)	982 (8.9)	469	4,827	9

SOURCE: Keiichi Oshima, Science and Technology in Japan, Journal of Japanese Trade and Industry, No. 5, pp. 21–22, 1983.

the Japanese for education is legendary. Japan rivals the United States in the ratio of students enrolled in higher education to the total population in the relevant age bracket (37 percent in Japan to 45 percent in the United States in 1981) and far exceeds European countries (where the ratio is in the area of 20 percent). Of even greater interest, however, is the spectrum of concentration of Japanese students shown in Tables 4 and 5, where the remarkable emphasis on engineering education is strongly evident. In 1981, for example, Japan had nearly 370,000 students enrolled in engineering programs, which is more than the combined enrollments of Britain, France, and West Germany. This flow of highly trained engineering manpower, willing to take assignments of their employers' choice, is a major asset in achieving Japan's technological and industrial objectives.

The system of higher education in Japan is not without its problems, of which a certain lack of mobility and interaction between the disciplines may be noted, as well as the absence of a strong university-industry interaction mentioned earlier. There is, however, an awareness of these problems, and steps are being taken to correct them.

New programs established by the Ministry of Education are being furthered by research groups composed of professors at institutions of higher learning such as Tokyo University, the Tokyo Institute of Technology, Kyoto University, and Osaka University. Apart from those programs, the Research Laboratory for Engineering Materials of the Tokyo Institute of Technology is conducting research under contract from the Research Development Corporation of Japan (JRDC). JRDC calls on private-sector companies to seek practical uses for inventions for which universities have made patent applications and also promotes R&D on them by funding the relevant expenses in their entirety. JRDC must then be repaid, without interest, in annual installments over a 5-year period. In the event success is achieved, however, repayment is not required, although the equipment used is scrapped. Some recent research contracts let to private-sector companies by JRDC are as follows:

Project	University or Research Institute	Company
High-pressure sintering of BN cutting tools	Tokyo Institute of Technology	Nippon Oil and Fats Co., Ltd.
Manufacture of SiC fiber from organic silicon polymers	Tohoku University	Nippon Carbon Co., Ltd.
Manufacture of alumina powder of high purity and high sinterability	Government Industrial Research Institute, Nagoya	Daimei Chemical Industries, Ltd.
Continuous production of high-performance ceramic film	Seikei University	Mitsubishi Mining and Cement Co., Ltd.
Sintering of sialons	NIRIM	Shinagawa Refractories Co., Ltd.
Sintering of high-purity diamond cutting tools	NIRIM	Toshiba Tungaloy Co., Ltd.
Gas pressure sintering of silicon nitride	NIRIM	NTG
Vapor-phase synthesis of diamond film under low pressure	NIRIM	Mitsubishi Metals Industries, Ltd.

Another feature of JRDC is its Exploratory Research for Advanced Technology (ERATO). Under this system JRDC selects leaders for research programs on basic technological subjects and bears the research expenses. JRDC's current research programs in this category and their leaders are as follows:

Subject	Leader
Ultrafine particles	Dr. C. Hayashi, ULVAC Corporation
Amorphous and intercalated compounds	Prof. K. Masumoto, Tohoku University
Fine polymers	Prof. N. Ogata, Sophia University
Perfect crystals	Prof. J. Nishizawa, Tohoku University
Bioholonics	Prof. D. Mizuno, Teikyo University
Bioinformation transfer	Prof. O. Hayaishi, Osaka Medical College

COUNCIL FOR SCIENCE AND TECHNOLOGY

The activities of the various government institutions are overseen, to a limited extent, by the Council for Science and Technology (CST) in the Office of the Prime Minister. The CST has a special coordinating fund for promoting basic technologies, and three of the projects sponsored recently are related peripherally to ceramics: control technologies for surfaces and interfaces, with 11 participating institutions; creation of new materials in a micro-gravity environment, with 13 institutions; and large-scale high-pressure systems, now in the planning stage. With these, as with other government-funded projects, money is passed along in one of two ways: as direct support of research activities or as a grant to be repaid if the research proves commercially successful.

CERAMICS ASSOCIATIONS AND SOCIETIES

In response to all these ceramics-related initiatives, existing ceramics societies have become more active, and a number of new associations or societies have appeared. Appendix D provides information on some of these, including the Japan Fine Ceramics Association, which was developed in 1982 in response to MITI's efforts in high-technology ceramics. The existence of such groups, together with the government's emerging greater willingness to encourage cooperation by and with universities and industry, is perhaps the strongest evidence yet that the web of relationships surrounding ceramics technology is working ever more flexibly to create a critical mass of effort and involvement. To be sure, all this does not necessarily represent a well-oiled and impeccably running machine for technology development. The committee found no mythical "Japan, Inc." But it *did* find the critical mass, fundamental commitment, and psychological motivation for building a commercially powerful experience base.

4

Japanese Industrial High-Technology Ceramics Activity

BUSINESS-GOVERNMENT RELATIONSHIPS

As pointed out earlier, government agencies' choices of technology areas for support have a significant leveraging effect on industrial activity. This comes about about for a variety of reasons, primarily because the civil servants comprising the ministerial bureaucracy are the cream of the Japanese "meritocracy" turned out by the Japanese educational system and also because important business and industrial figures serve on the multitude of advisory groups that help the bureaucracy formulate programs.

The present Japanese position in high-technology ceramics, however, is not by any means a product solely of governmental ministry leadership. It is, rather, a position attained by vigorous industrial and commercial development of markets for ceramic products. Japan's thrust toward high-technology ceramics is taking place within the context of vigorous private-sector competition and various company strategies.

It should be noted that heretofore much of the Japanese effort has been directed toward applied research and process development, conducted in the technical departments of private companies. In contrast, it is the committee's perception that a significant proportion of the U.S. research effort in ceramics is directed toward basic issues leading to fundamental understanding and is conducted principally in university ceramics and materials science departments and government laboratories. This does not take into consideration the fact that large sums of Department of Defense funding are also spent on applied ceramic research programs.

MARKET DEMAND FOR HIGH-TECHNOLOGY CERAMICS

We focus on Japan's domestic market because, at the moment, Japan seems to offer the world's most active market for ceramics applications in electronics and to display the most vigorous interest in future structural uses. Moreover, it is the market in which Japanese companies hone their skills, amass experience, and develop an understanding of market requirements.

From extensive interviews with Japanese managers and officials, the committee has developed estimates regarding (1) the size of the domestic Japanese market (measured by sales volume) for high-technology ceramics in 1982 and (2) the likely growth in that market during the period 1982–1990 under alternate assumptions about the pace of technological change. These estimates are given in Tables 6 and 7.

Table 6 shows that, as of 1982, electronics applications dominate the ceramics market, with integrated-circuit packages, substrates, and capacitors by themselves accounting for more than half of the $1.36 billion total. Data from the pre-1982 period, omitted here, show the rapid growth of electronics applications to be nothing new. To some extent, however, the "electro-ceramics" category is misleading, because products included in the piezoelectric and ferrite categories may have functional as well as electronics applications. Even so, such uses clearly dwarf those structural applications (heat- and wear-resistant parts, for example) where much current interest centers.

Table 7 summarizes estimates of future market development and suggests that a reversal in the size of the market between electronics and structural ceramics may occur by about the year 2000. Predicted expansion of the market for ceramics for electronics applications to $1.95 billion by 1985 and $3.92 billion by 1990, with attendant growth rates of 20 percent in the immediate future and 15 percent toward the end of the decade, are considered likely to occur without any major technical breakthroughs, significant shifts in patterns of use, or marked change in the general economic climate. With ferrites continuing to grow slowly, and no large increase in the use of ceramics as sensors, a process of evolutionary change

TABLE 6 Market Size of High-Technology Ceramics in Japan, 1982 (in millions of dollars)*

Sector	Application	Japanese Domestic Sales	Percentage of Total
Electro-ceramics	Integrated-circuit packages and substrates	$ 310.0	22.8
	Capacitors	370.0	27.2
	Piezoelectric parts	150.0	11.0
	Ferrites	250.0	18.4
	Other	50.0	3.7
Subtotal		$1,130.0	83.1
Structural Ceramics	Cutting tools	40.0	2.9
	Catalyst carriers	140.0	10.3
	Other hot/wear parts	50.0	3.7
Subtotal		$ 230.0	16.9
Total		$1,360.0	100.0

* Excludes refractory materials, nuclear fuels, spark plugs, and bioceramics. Assumes 240 yen per dollar.

TABLE 7 Estimates of Future Market Growth in High-Technology Ceramics in Japan, 1983–1990

Sector	Period	Average Annual Growth Rate (percent)	Japanese Domestic Sales (millions of dollars)
Electro-ceramics	1983–1985	20	1,950 (1985)
	1985–1990	15	3,920 (1990)
Structural ceramics	1983–1985	20–30	400–500 (1985)
	1985–1990	25–40	1,200–2,700 (1990)

SOURCE Committee estimates based on interviews and internal company documents.

and gradual technical refinement would by itself drive a steady, but decelerating, growth in electronics applications. On the structural side, by contrast, the rate of growth is perceived to escalate markedly, primarily because of automotive applications.

Most of the uncertainty about the rate with which ceramics will find their way into structural applications relates to uncertainty about the pace of technical progress. If progress were rapid, and the cost and reliability of ceramic parts improved fairly quickly, market growth would approximate the upper limit given in Table 7; if not, the lower limit would be applicable. In the 1983–85 period, for example, much depends on the timing of the appearance of ceramic engine parts in regular production vehicles. If ceramic rotors for turbochargers are introduced into 1985 model cars, as now appears likely, overall structural use could grow at close to a 30 percent rate. Even if significant introduction is delayed, there are enough other engine applications either at hand or anticipated that growth is not likely to fall much below 20 percent.

Expansion of the structural market at close to a 40 percent rate between 1985 and 1990 seems not unreasonable. It assumes neither major technical breakthroughs nor the emergence of a full ceramic engine, but merely substantial improvement in reliability and cost, the introduction of important ceramic components in engines (e.g., piston heads and turbochargers), and the increased use of heat- and wear-resistant ceramic parts (e.g., bearings) in nonautomotive applications. In this latter case, growth would still average at least 25 percent, for such is the state of market need that even incremental improvements in process capability would tap a huge potential reservoir of demand.

These estimates do not rest on any radical advance in product or process technology. Should such advances take place, however, the market for structural applications would grow more rapidly, perhaps approaching $10 billion by the end of the decade. The estimates also are given in current dollars. If, as seems probable, costs per unit of production decline between 1983 and 1990, Table 7 understates the volume growth rate—and more so for structural than for electronics applications.

Incidentally, the rates given in the tables do not reflect the degree to which high-technology ceramics represent both a "leveraged" and a "leveraging" technology—i.e., the manner in which their development will affect other technologies, such as microelectronics, and they, in turn, will be affected by such developments. For example, progress in ceramics for a particular application (say, semiconductor chips) may create progress in a complementary technology (super high-speed computers). In automobile engines, the availability of reliable ceramics might permit new design approaches that would allow development of small gas turbine engines, further development of which would require or produce further advances in ceramics technology. In short, because of such linkages, the effect of development of a leveraging technology like ceramics is not fully captured by data on market size alone.

MARKET STRATEGIES: "THIN MARKETS"

High-technology ceramics in Japan is an emerging industry. During such an early phase of industry development, product designs have yet to be established, and several approaches to the same applications will exist side by side. For the most part, uncertainty prevails on both sides of the market, as firms with varying strategies and technical bases vie for market acceptance. Products generally cost more than those of established industries (here, for example, plastics or metals) with which they compete, and it is sometimes only the promise of superior performance advantages in the future that leads customers to "buy in" before levels of cost and reliability improve.

The more quickly they do "buy in," however, the more quickly producers can accumulate needed information about the properties of the technology and their degree of fit with user requirements. The more quickly, too, a producer can experiment with changes in process technique that, if successful, boost reliability and lower costs, further expanding both market demand and the firm's experience base. Gaining experience, then, is the crucial element in an emerging industry like ceramics, especially structural ceramics, because the major advances that build markets are much less likely to come from isolated laboratory work than from the interaction of technical work, production activity, and market response. The kind of experience on which competitive evolution in structural ceramics depends is, first and foremost, an iterative process of learning by doing.

The early development of such an "emerging technology" depends very much on the existence of so-called thin markets—small, often specialized market segments populated by buyers willing to acquire products embodying the new technology, even though the cost may be somewhat greater than that of products already in place. Attracted by improvements in performance or by technological newness in itself, and willing to go along with the potential inconveniences of a technology not fully debugged, the thin markets provided by technology-oriented purchasers give producers the opportunity they need to gain experience, reduce costs, boost performance, and adapt designs to user needs. The Japanese people, the committee was told, are very technology conscious and serve as willing, though highly critical, receptors of advanced products, including, for example, video cassette recorders, miniature tape decks, and twin-overhead-cam automobile engines.

An example of a thin market in operation can be found in the history of the electronic calculator industry. The first such calculators were several times the price of the mechanical adding machines they sought to replace. They were, however, small, light, and portable, and they performed more functions. Enough people were willing to pay the premium these first calculators demanded for producers to be able to increase production, drive prices down, and subsequently improve performance in dramatic fashion. Personal computers are another example.

In the case of Japanese ceramics, the operation of thin markets is already in evidence. In addition to the important experience represented by Japanese dominance of the consumer electronics industry, efforts are well under way to build up experience with structural ceramics, their associated production processes, and new market and supplier linkages. Figure 8 shows the committee's compilation of Japanese views on the evolution of markets for structural applications of ceramics. In the cutting tool and machine part market, where ceramics can provide a decided advantage in performance, market development has already begun to give way to volume production. Thus, for example, several firms stated that continued progress on cost and reliability could make ceramic bearings an important force in the market within 12 to 18 months. Experience gained in these areas is likely to be useful in engine applications that are expected to emerge over the next 5 years.

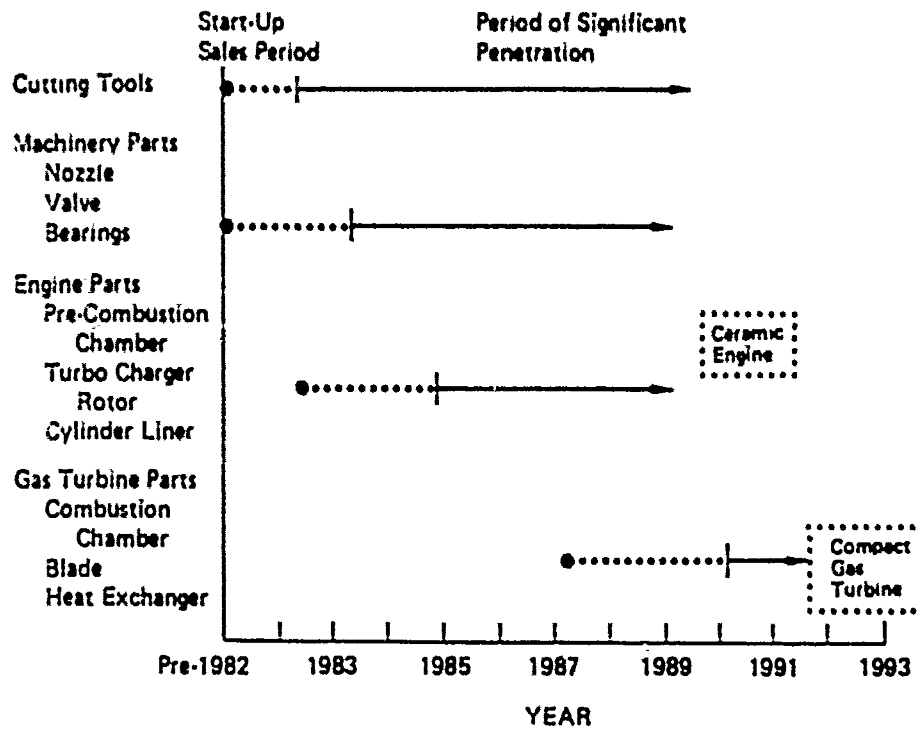

FIGURE 8 Expected evolution of structural ceramics market. (Source: Committee estimates based on interviews and internal company documents)

JAPANESE COMPANIES INVOLVED IN CERAMICS RESEARCH AND DEVELOPMENT

The motivations that have led individual companies to become involved with high-technology ceramics are diverse. For some, ceramics activities are purely defensive—just in case ceramics should turn out to be important. For others, the association with an emerging technology is psychologically stimulating. But for the most part, the underlying motivations are sound, strong, and likely to be translated into aggressive strategies for making growth actually happen.

For example, several companies were deeply concerned about the viability of their actual survival. This group consisted mostly of basic materials producers (cement, aluminum, petrochemicals, and the like) whose core businesses were declining as a result of rising energy costs and third-world competition and who saw in the ceramics area an opportunity to prosper with technology they were confident they could master by adaptation of present skills. Other companies, pressed by the slowing of traditional markets, were more worried about the maintenance of growth. Having developed during an era of expanding markets, and having taken on institutional and employment commitments that only growth could satisfy, they are now confronting the need to diversify. Both of these groups are, therefore, seriously committed.

Traditional ceramics companies are also competing vigorously, with substantial R&D investments, tight cost control, capacity expansion, and aggressive pricing policies. One large ceramic company, for example, has greatly boosted its R&D budget and has priced ceramic automobile parts on the basis of cost levels anticipated sometime in the future. It is also diversifying in other directions.

The following list gives some of the Japanese companies that are actively involved in high-technology ceramics:

TDK Corporation
Kyocera Corporation
Murata Manufacturing Co., Ltd.
Taiyo Yuden Co., Ltd.
Toshiba Corporation
Toshiba Tungaloy Co., Ltd.
Nippondenso Co., Ltd.
Toyota Motor Corporation
Toyota Central Research and Development Laboratories, Inc.
Aisin Seiki Co., Ltd.
Hitachi, Ltd.
Hitachi Metals, Ltd.
Hitachi Chemicals Co., Ltd.
NGK-Sparkplug Co., Ltd.
NGK-Insulator, Ltd.
Asahi Glass Co., Ltd.
Asahi Chemical Industry Co., Ltd.
Ube Chemical Industries Co., Ltd.
Nippon Soda Co., Ltd.
Nippon Carbon Co., Ltd.
Toray Industries, Inc.
Nippon Steel Corporation
Kawasaki Steel Co.
Kobe Steel, Ltd.
Kurosaki Brick Refractories Co., Ltd.
Narita Seitosho
Toko, Inc.
Honda Motors Co., Ltd.
Kubota
Ishikawajima-Harima Heavy Industries Co., Ltd.
Shinagawa Refractories Co., Ltd.
...da Machine Works, Ltd.
...Kagaku Kogyo, Ltd.

Narumi China Corporation
Fuji Electric Co., Ltd.
Fuji Titanium
Nippon Tungsten Co., Ltd.
Sumitomo Chemical Co., Ltd.
Sumitomo Special Metals
Sumitomo Electric Industries, Ltd.
Isuzu Motors
Tohoku Metal Industries, Ltd.
Matsushita Electric Industrial Co., Ltd.
Matsushita Electric Components Co., Ltd.
NEC Corporation
Mitsubishi Mining and Cement Co., Ltd.
Mitsubishi Electric Corporation
Mitsubishi Chemical Industries Co., Ltd.
Fujitsu
Showa Denko K.K.
Oki Electric Industry Co., Ltd.
Sony Corporation
NTT
Toyo Soda Manufacturing Co., Ltd.
Ibiden Co., Ltd.
Onoda Cement Co., Ltd.
Komatsu, Ltd.
Sanyo Electric Co., Ltd.
Showa Aluminum Industries K.K.
Shin-Etsu Chemical Industries
Chichibu Cement Co., Ltd.
Japan Metals and Chemicals Co., Ltd.
Nippon Kokan K.K.
Noritake Co., Ltd.
Nissan Motors Co., Ltd.
Toyo Kogyo Co., Ltd.

Many different company backgrounds and motivations are illustrated in this list. For example, NGK-Sparkplug is a traditional "whitewares" company; Showa Denko is a chemical and steel company looking for completely new markets; Asahi Glass is a top-quality traditional "ceramics" company looking for a new role in ceramics; Hitachi is a high-technology nonceramics company; Kyocera is a new ceramics company attempting to capitalize on its success in electronic ceramics to achieve leadership in structural ceramics; Nippon Carbon is a firm outside the "ceramics" community that has had great impact through development of Nicalon fiber; Toyota is an automobile company interested in ceramic automobile components.

CERAMICS FOR AUTOMOTIVE APPLICATIONS

Everyone in the industry recognizes that the quantum leap in commercial application will come when ceramic parts and components find their way into automobile and truck engines. Even so, the search for precursor (nonengine) applications, exemplified by Nippon Steel's work on ceramics for hot-steel handling equipment, proceeds actively wherever genuine performance advantages appear to outweigh immediate problems with cost and reliability. Indeed, so great is the drive to generate experience that some firms are willing to absorb the development costs in order to facilitate near-term market penetration and achievement of position and share.

For automobile engines, the apparent agenda is to build up ceramic applications one by one until a ceramic-dependent engine is available in the 1990s. Isuzu and Kyocera have already introduced ceramic glow plugs and swirl chambers and have other parts under development. Turbocharger rotors should be available from several suppliers by mid-1985. Industry representatives seemed confident that these applications will, in effect, trigger thin markets in response to performance advantages and the "fashionableness" of the new technology itself.

We believe the Japanese reading of the automotive market to be correct, because the move to ceramics fits the Japanese automotive industry's objective of delivering more power, greater efficiency, and better handling in a technical package that is small, light, and clean. Furthermore, because Japan's domestic market for automobiles has grown mature and saturated, automobile makers are looking for new ways to segment the market in order to rekindle consumer interest. New technology like ceramics may well be one way to do this, for there is the belief in Japan that the use of reliable ceramic engine components will return prestige (and hence sales) to the innovating firm that exceeds any benefit derived from enhanced fuel efficiency, durability, or performance. Toyota's recent introduction of a piston with a ceramic fiber-reinforced metal ring groove has had some good, if limited, effects on piston wear and thermal conductivity, but the company used the introduction quite successfully in a marketing campaign. The excitement generated by Toyota's ceramic piston ring makes sense in a market where technology is a major selling point, and that seems to be the case in Japan. Among the automotive executives interviewed by the committee there was a common view that the current popularity of advanced ceramics (e.g., turbochargers and dual overhead camshafts) was not so much a result of performance (speed limits are low and roads are crowded) as of a desire for things that are new and "high-technology." In this environment there is great competitive value in innovation.

Of late, the long-standing competition between two of the largest manufacturers has intensified, and two smaller firms have also made their presence felt in the domestic market—with, for example, Honda's City (a mini) and Mazda's Familia as product innovators and technology leaders. Having lost domestic market share in the late 1970s and early 1980s, Toyota has chosen to fight back on technological grounds, has introduced 10 new models in the last 18 months, and has actively pursued new engine types, new body shapes, and new applications of electronics.

In this context of market rivalry, Toyota's commitment to ceramics takes on clearer meaning. The company views the development of ceramic components and engines as critical areas in which to achieve significant competitive advantage through innovation. In fact, no fewer than four companies within the Toyota Group are actively involved in ceramics research. Following is a list of ceramic components currently used in Toyota vehicles:

Functional ceramics

Oxygen sensor (ZrO_2)
Knock sensor (PZT)
Backup sensor (PAT)

Electric buzzer (PZT)
Thermal sensor for water temperature (Fe_3O_4-$CoMn_2O_4$-NiO)
Thermal sensor for exhaust gas (Al_2O_3-Cr_2O_3)
Blower resistor ($BaTiO_3$)
Fuel level switch (Al_2O_3-Cr_2O_3)
Heater for intake gas ($BaTiO_3$)
Condenser ($BaTiO_3$)
Motor core (Fe_2O_3-Mn_2O_3)
Insulator for spark plug (Al_2O_3)
Plate of hybrid integrated circuit (Al_2O_3)
Plate of auto choke heater (Al_2O_3)
Light-emitting diode (Ga-P)
Electroluminescence (ZnS)

Structural ceramics

Mechanical seal of water pump (Al_2O_3)
Catalyst pelleted support (Al_2O_3)
Catalyst monolithic substrate (MgO-Al_2O_3-SiO_2)
Ceramic fiber for fiber-reinforced metal piston (Al_2O_3-SiO_2)
Heat insulator for catalyst (Al_2O_3-SiO_2)

Toyota is not alone in this focusing of effort. Isuzu, for example, has a policy of putting at least one new ceramic part in its cars each year.

GENERAL OBSERVATIONS ON INDUSTRY ACTIVITY

Taken together, the strategic motivations of companies at all points along the industry's supply chain and the existence of real market opportunities add up, we believe, to a convincing picture of a technology-based industry emerging into a phase of rapid market expansion. The sheer volume of private-sector effort now being devoted to ceramics-related work, in combination with government- and university-sponsored initiatives, offers strong evidence that a critical mass of participants has already been drawn to the industry. This is significant because an important resource for emerging technology-based industries is information about various technical options, real-life performance of design approaches, customer needs, etc. The larger the mix of participants, the more numerous the interactions among them, and the greater the flow of information, the more likely an industry will grow rapidly.

The commitment of Japanese industry to ceramics is real, and corporate strategies for developing markets are already in place, but a successful outcome to this commitment cannot yet be guaranteed. Some perspective on the situation is offered by comparing this commitment with the much firmer commitment by electronics firms to the development of VLSI technology (without which they could not realistically hope to stay in business). Moreover, among policymakers, high-technology ceramics are only one among several such promising substances worthy of development, others being composites, polymers, and biomaterials. Furthermore, a future shake-out is inevitable. The industry's ultimate vertical structure remains unclear, as do the corporate strategies best suited to it. This is especially true for those Japanese companies whose most attractive international market for ceramics-based technology is the U.S. military services, especially in military telecommunication systems. National trade policies and factors related to national security make access to those markets anything but guaranteed.

5

Technical Status of High-Technology Ceramics in Japan

TECHNICAL GOALS AND THEIR RELATIONSHIP TO ECONOMIC CONSIDERATIONS

Assessment of the status of high-technology ceramics in Japan requires analysis of current or pending major improvements or breakthroughs in technology and applications. Ideally, this should include a comprehensive analysis of developments related to composition, processing, joining, composites, coatings, design methodology, and nondestructive evaluation. A detailed analysis of this sort was not feasible, but it was the committee's clear impression that no *major* technical breakthroughs had been achieved to date by the expanded Japanese ceramics effort. However, there were numerous indications that significant progress was being made through incremental improvements. Some indications of this are given in following sections of this chapter.

The physical limitations of traditional ceramics have long made them the bane of design engineers. The priority given by top management to the solution of technical ceramics problems is a further index of the seriousness of Japan's broad-based ceramics effort. The technical goals set by management are, of course, related to the perceived economic barriers, and the committee attempted to estimate the prices to which unit costs must fall to trigger rapid market expansion of high-technology ceramics. For example, if prices for ceramic components were less than $40 per pound (manufactured), they would find applications in glow plugs, swirl chambers, and turbocharger bearings. If they fell to less than $15 per pound, they would be widely used in cutting tools, special wear parts, and turbocharger housings. Between $10 and $15 per pound they would find ready applications in cylinder liners, piston caps, manifolds, wear parts, and heat exchangers (a very large volume use). From another perspective, we estimate that, with a price below $40 per pound, ¼ to ⅔ of a pound of structural ceramics would be used in an engine. If the price were $15 to $20 per pound, ⅔ pound to 2 pounds would be used; from $10 to $15 per pound could mean that 10 to 20 pounds would be used per engine. One automotive manufacturer, using silicon nitride powder at \$16 to \$40 per kilogram (\$7 to \$18 per pound), produces parts costing under \$80 per kilogram (\$36 per pound). With improved processing the manufacturer expects to reduce that to \$28 per kilogram (\$13 per pound). For the future the manufacturer desires to obtain the powder at \$5 per kilogram (\$2.27 per pound) to produce parts at \$18 per kilogram (\$8.18 per pound).

The key technological problems are mechanical reliability, manufacturing reproducibility, efficient machining technology, and development of nondestructive evaluation techniques. By way of illustration, Aisin has described its technical objectives in ceramics and their relationship to production as follows:

Objectives	To optimize the use of ceramics in automotive parts to take advantage of ceramic heat-, wear-, and corrosion-resistance properties. In addition to product requirements as provided for by design intent and proved by prototype performance evaluation, projects will include, through development of ceramics, manufacturing processes including mixing, forming, sintering, and machining, as well as other phases of production.
Problems to Be Solved	Efficient manufacturing technology Methods to identify defects and to guarantee long product life Design techniques utilizing the beneficial properties of ceramics
Products Developed	Ceramic heat- and corrosion-resistant components: Diesel and Stirling engine combustion components Ceramic wear-resistant components: Valve system, transmission bearings, and new drive-train components
Production Technology	Emphasis on technology development—Injection molding Features: Complicated configuration possible Size accuracy Excellent productivity

A different view is shown by Toshiba's technical objectives, illustrated in Figure 9.

INVESTMENT IN INDUSTRIAL CERAMICS PROCESSING FACILITIES

MITI's programs in support of these industrial objectives have already been mentioned—programs directed at controlling the purity levels and particle size distributions of the raw materials from which high-technology ceramics are made; high-speed, high-volume molding and shaping processes; and uniformity of the microstructure of the final product.

Industrial efforts to achieve these objectives are backed by heavy company investments in ceramics processing equipment. Hitachi now has an automated 4-turret hot press; NGK-Sparkplug has at least three 1-meter-wide alumina tape casters; Murata has two similar casters as well as double roll casters for alumina products; Kyocera has more than 20 such casters at a single site and mechanical manipulators for stacking, cutting, and printing alumina packages; and NEC has a tape-casting ability for very rapid extraction of solvents in the processing of

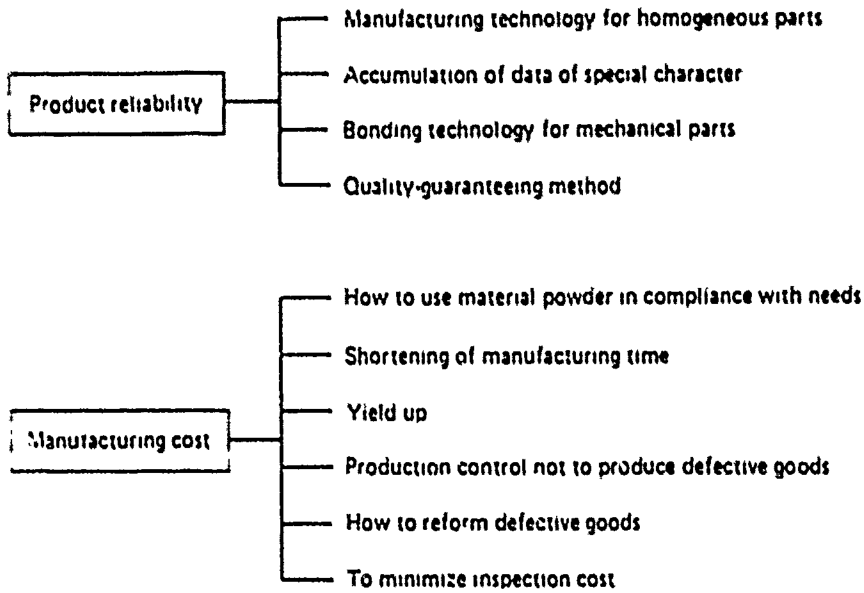

FIGURE 9 Technical objectives of Toshiba research and development. (Source: Toshiba Corporation)

electronic ceramic materials. Showa Denko's program to develop plasma-spray powders is being undertaken in response to the general failure of ceramic coatings to be reliable at thicknesses greater than about 1 mm.

Such investment implies not only commitment but also application of an Edisonian approach to development: make a part, try it out, find out what is wrong with it, then work to improve both material and manufacturing technique. By such an iterative approach, the firms hope to overcome or circumvent the technical obstacles that stand in the way of the perceived potentially substantial expansion of structural applications. The obstacles remain formidable, however: retaining a fracture strength of 30 kg/mm^2 at 1200°C for thousands of hours of operation; providing a room-temperature fracture strength of 40 kg/mm^2; raising the Weibull modulus to over 20; and ensuring fracture toughnesses of 6 to 9 $MPa\sqrt{m}$.

EXAMPLES OF JAPANESE ADVANCES IN CERAMICS

As mentioned earlier, Japan's research and development effort does not appear to have yet produced any *radical* technological breakthrough. This is not entirely unexpected, of course, since the thrust has been toward incremental improvements needed to get new applications into the market, to build an experience base, to reach volumes that make production economically viable, and in general to make sure that the company involved remained up with the competition. But significant progress has been made, as illustrated in the following examples.

- Toshiba reports significant advances in joining silicon nitride parts to steel, both in terms of the materials used to form the bonds and in the physical properties of the joints.

- Mitsubishi Mining and Cement is using chemical precursors to fashion very thin barium titanate layers for multilayer chip capacitors.

- NEC is doing work on chip carriers and packages that allow the faster signal responses needed by super computers. Changing the insulating medium to 50 percent aluminum oxide and 50 percent lead borosilicate glass has pushed the dielectric constant for alumina ceramics below 10. This medium can be sintered below 1000°C and thus is compatible with gold or copper screen-printed ink. NEC has passed beyond the pilot stage with 41-layer packages (about 8 × 8 cm) holding 1000 pins on the back and claims to have printed 60-micron gold wires.

- Nippon Carbon reports success in producing Nicalon silicon carbide continuous fiber by pyrolysis of an inorganic polymer: production is approximately 1000 kg per month. There have been advances, too, in making metal matrix composites with aluminum and silicon carbide fiber.

- Kyocera is attempting to do with structural ceramics what it has already done with electronics applications—that is, establish the market by starting large-scale manufacturing and employing a forward pricing strategy. The company is using silicon nitride to make glow plugs for diesel engines at a rate of 30,000 per month, swirl chambers at a rate of 20,000 per month, and—either in late 1984 or early 1985—turbochargers at an initial rate of 100 to 500 per month, growing to 100,000 per month within 3 years. To ensure performance, Kyocera has installed a hot-isostatic press with a working zone about 50 cm in diameter and 1 m long, the idea being to hot isostatic process (HIP) out defects not removed by sintering. For injection-molded parts, the burnout cycle is about 4 days for silicon nitride and 1 day for aluminum oxide.

- Kobe Steel claims to have reduced the normal HIP cycle from 1 or 2 days to 1 hour. (Ceramists at other companies suggest that this reduction is only for metal parts sintered at 700-1000°C and that so rapid a cycle to high temperatures would thermally shock ceramic parts.)

- NGK-Sparkplug is working on transformation-toughened zirconia and reduction of the burnout cycle for the injection molding of silicon nitride parts from 1 week to 1 day.

- Sumitomo Electric reports advances in the machining of structural ceramic parts (including electrical discharge-machinable Si_3N_4 ceramics) and projected reductions of 10 percent to 20 percent in associated process costs.

- Toyota reports steady, incremental progress in fabricating silicon nitride engine components.

There are, in addition, some 6 to 12 companies new to the ceramics industry that claim to be eager to sell sinterable carbide and nitride powders.

• Nippon Carbon has a license to utilize Professor Yajima's patents (Osaka University) for making continuous silicon carbide fibers from a silicone polymer. These fibers, called Nicalon, have excellent mechanical characteristics and are being considered as the reinforcing fiber in metal-matrix and ceramic-matrix composites. In the United States, the Defense Advanced Research Projects Agency (DARPA) has initiated a multimillion-dollar program to develop comparable technology.

• Hitachi has perhaps the best research capability of all Japanese companies working on advanced materials. It has produced an outstanding material based on silicon carbide with the addition of a small amount of beryllium oxide. Even though its mechanical properties at temperatures up to 1400°C are considered to be excellent, the material is being developed first as an electronic substrate insulator material, because its thermal conductivity is greater than that of aluminum. It is hot-pressed and diamond-machined into small plates to be used as silicon chip carriers. It sells, surface-finished, at between $600 and $1,000 per kilogram.

• Showa Denko's interest in fine ceramics relates to the fact that, as a basic materials company, it is facing limited sales in several of its traditional business segments because of competition from developing nations. Accordingly, drawing on its expertise in abrasives, chemicals, and aluminum, it has begun to develop methods for producing value-added products such as high-purity alumina and β-silicon carbide. For example, it has scaled-up a process for making high-purity aluminum oxide by the alum method and is prepared to sell this product at $20 per kilogram or less. It also has developed production capability for 2000 kg per month of vapor-formed β-silicon carbide and for fine-grinding 30,000 kg per month of submicron silicon carbide produced via the classic Acheson process (sale price about $15/kg). This company's active investment in new equipment and processes is a convincing sign of long-term commitment.

• Murata, Kyocera, and TDK are also developing their own process equipment and beginning to assemble their own ceramic components into subassemblies. Murata has a significant business in high-voltage supplies for TV and in aluminum oxide substrates and packages that are used entirely for internal consumption in building hybrid circuits and subassemblies. Similarly, Matsushita and Hitachi's research and development efforts on electronic ceramics are closely tied to intended end-use in systems produced for sale by the companies.

• Nippon Steel is using the same approach in the field of structural ceramics. Although this company has put together a team of solid-state physicists and refractories engineers to develop silicon nitride technology for markets other than steel, it is simultaneously developing products for use in steel production, thus ensuring an early, in-house market. It is now developing silicon nitride components for furnaces, rollers and skids, hot gas fans, etc.

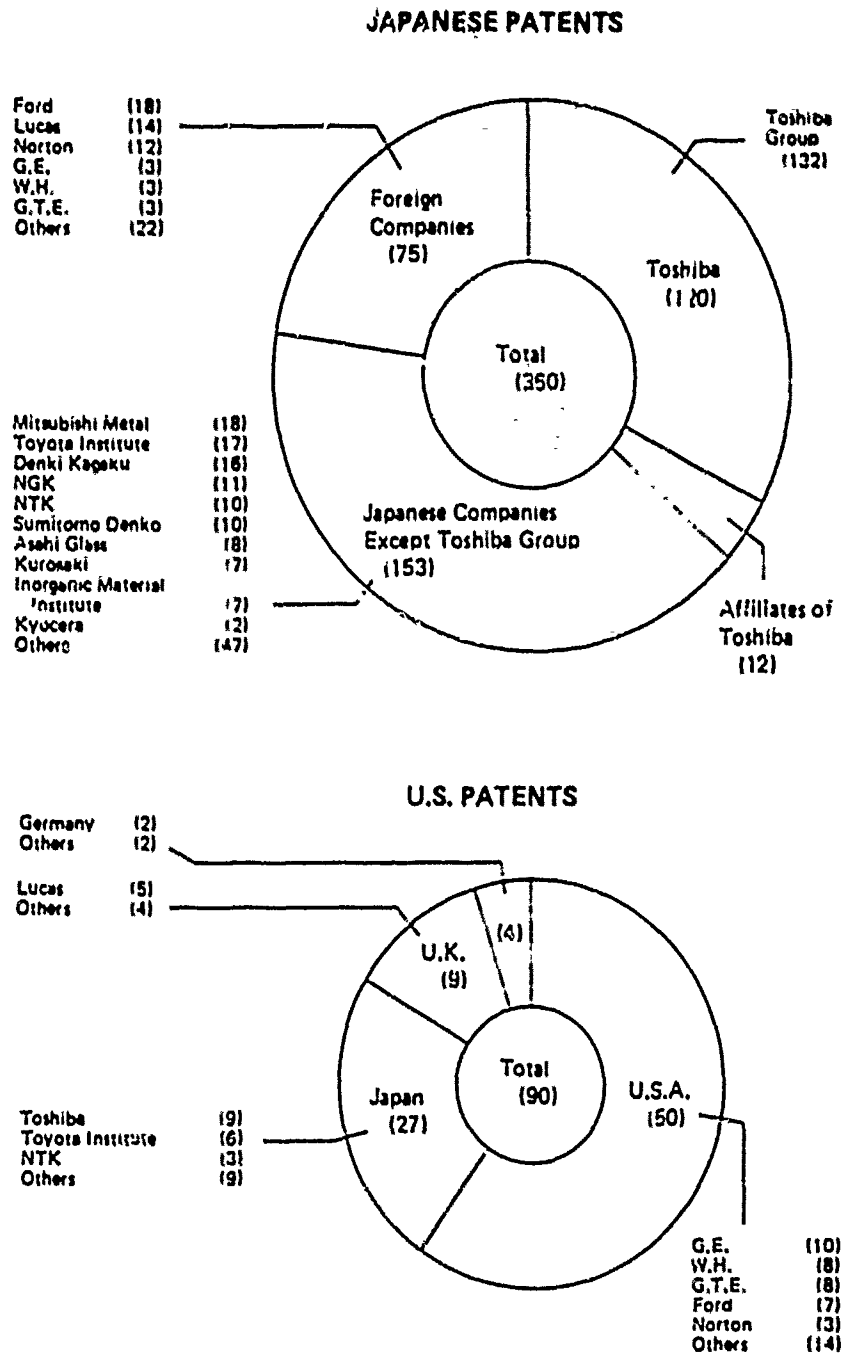

FIGURE 10 Origin of Japanese and U.S. patents on silicon nitride ceramics. (Source: Toshiba Corporation)

JAPANESE PATENT POSITION

An index of the vigor of Japanese ceramics activity is the patent position achieved by Japanese industry. Most of the Japanese companies involved with high-technology ceramics draw extensively on the ample resources of basic scientific work generated in the United States and Europe. This work is used as a foundation for the development of their commercial applications and is supplemented only as necessary. Even so, the Japanese are beginning to amass a substantial patent base in ceramic compositions and processing techniques, and, even though it is Japanese practice to break the equivalent of one inclusive U.S. patent into a cluster of separate patents, the knowledge base represented by these efforts is expanding rapidly.

Toshiba has several key patents for the formulation of sinterable silicon nitride powder and for processing techniques to control grain boundary chemistry and structure. In fact, Toshiba appears to have been responsible for one-third of all ceramics-related patent applications in Japan during the past 10 years, with over 120 patents and patent applications in Japan and about 100 patents and patent applications in foreign countries (Figure 10). But Toshiba is not alone in seeking to establish a strong patent position. Ube Chemical likewise has built a good position in a chemical-based process for making silicon nitride powder. Matsushita has both original and hundreds of follow-on patents—both in Japan and abroad—for its work on zinc oxide varistor compositions and has licensed its knowledge to several companies, including General Electric and Westinghouse.

It is also important to point out that the capital investments of the Japanese companies are still limited to various pieces of equipment and not to production lines or new plants. Indeed, the banking community in Japan eagerly awaits such developments, for not until then will ceramics represent a major financial opportunity for them and the national commitment to ceramics be commercially ratified.

Despite these caveats, however it is clear that the overall Japanese effort in ceramics has several enduring strengths. It is a long-term effort and will not be aborted, although it may be affected by a near-term drain on profits. It is taking place within an increasingly flexible network of support that works to facilitate the early contacts among raw materials producers, fabricators, and end-users so essential to building a commercially viable base of experience. In short, the commitment is real.

6

Opportunities for Cooperation

The present and growing importance of high-technology ceramics in manufacture and international trade prompts serious consideration of the opportunities—and even the necessity—for U.S.-Japanese cooperation in this field. There was general agreement by the committee and all levels of the Japanese authorities consulted that such cooperation would be of value and that many different sectors of U.S. and Japanese society could contribute to it. Several types of cooperative effort were discussed, involving the possible roles of government, private industry, professional societies, universities, and individuals.

MUTUALLY BENEFICIAL AREAS OF COOPERATION

Although barriers to cooperation will obviously continue to exist because of commercial competition, the following cooperative efforts would be of mutual benefit and should be achievable:

- Establishment of common standards of performance, testing, and composition.
- Accumulation and publication of economic data in mutually consistent terms of reference.
- Improvement of availability of published literature on high-technology ceramics.
- Enhancement of interaction between U.S. and Japanese ceramics and ceramic engineering societies.
- Establishment and fostering of individual researcher interactions (especially student, postdoctoral, and faculty).

ESTABLISHMENT OF STANDARDS

In the United States, the American Society for Testing and Materials (ASTM) and the American National Standards Institute (ANSI) are the leaders in establishing standards for the government and private industry. The United States also has a major organization, the National Bureau of Standards (NBS), that carries great weight in this area, and the military departments—notably the U.S. Air Force at Wright-Patterson Air Force Base—have extensive characterization facilities. Nevertheless, no government or other U.S. group has been assigned formal responsibility to interact with a corresponding Japanese organization. Japan currently is considering the establishment of a Fine Ceramics Center, to be funded jointly by government and industry. Such a center would be responsible for formulating standards and tests for high-technology ceramics. Meanwhile, MITI appears to be the most likely Japanese organization with which to interact; indeed, there has been dialogue between MITI and the U.S. Department of Energy's Office of Vehicle and Engine Research and Development concerning the establishment of a U.S.-Japanese program for standards and test development.

The committee believes that this subject should be vigorously addressed and that positive action at the federal level is desirable to designate a formal body to interact with Japan in the matter of standards, testing, and the allied problems of composition and characterization.

ECONOMIC DATA

The interpretation of economic data, even data compiled within a single country, is admittedly difficult because of variations in definitions and institutional accounting practices. Nevertheless, an effort to obtain interpretable economic data on high-technology ceramics would be of great value to both countries. MITI is now undertaking an economic assessment of high-technology ceramics in Japan and expects to issue a preliminary report in 1984.

The committee believes that a similar study for the United States by the Department of Commerce, in the MITI format, would be extremely useful.

SCIENTIFIC AND TECHNICAL LITERATURE

The Japanese are avid readers of western technical literature and are very thorough in information collection, translation, and dissemination. Japanese researchers and technologists, accordingly, are quite knowledgeable about western ceramics research and development and make extensive and profitable use of this information. By contrast, the United States is greatly limited in utilizing the Japanese literature, largely because of the language barrier. Since there is little likelihood of any substantial reduction of this barrier, the United States must overcome this limitation by institutional means, i.e., by using a technical translation organization to provide translations of Japanese publications and patents on a timely basis and make them easily accessible to the U.S. high-technology ceramics community. It is suggested that the Japanese Fine Ceramics Association might undertake this important service for a fee. This would have the additional benefit of establishing a functional bond between the United States and Japan in this field. This or any other means of providing the translations should be accompanied by improved means of dissemination of the information to U.S. researchers and technologists.

The committee believes that urgent attention should be given to the problem of U.S. access to Japanese ceramics publications and patent literature and ceramics-related technical information.

INTERACTION BETWEEN U.S. AND JAPANESE CERAMIC SOCIETIES

There is great potential for cooperation by interaction of the U.S. and Japanese ceramics professional societies, and this activity is clearly already in its initial stages. A most encouraging development is the recent preparation of a comprehensive survey of Japanese ceramics by Japanese experts explicitly for their American counterparts and the publication of these articles in a special "Japan" issue of the *Bulletin* of the American Ceramic Society. This is an excellent beginning and an admirable pattern for future cooperation, particularly if it becomes a regular practice and is reciprocated. The American Ceramic Society has formal connections with the Ceramic Society of Japan and could further broaden its access to Japanese ceramics by contact with the recently established Fine Ceramics Association.

Arrangements involving other more general professional societies are also worth exploring. The U.S. Industrial Research Institute has a committee charged with improving foreign relations. It is possible that this institute, working with its counterpart in Japan, might promote cooperative research and development in scientific areas basic to emerging technologies.

The committee believes that the role of professional societies in promoting U.S.-Japanese cooperation could be further strengthened if the *Bulletin* of the American Ceramic Society would continue its praiseworthy initial effort by publishing an annual review of advances in Japanese high-technology ceramics, preferably commissioned from the Japanese Fine Ceramics Association, and if the Japanese Ceramic Society similarly would publish an annual report on U.S. technology prepared by an American Ceramic Society group.

INDIVIDUAL INTERACTIONS BETWEEN U.S. AND JAPANESE CERAMISTS

Probably most *real* cooperation occurs between individuals who have developed mutual trust—better still, friendship—and a capability for a *quid pro quo*. Relationships of this sort take time to develop; they are not usually achieved by short, sporadic visits but are the product of extended periods of work together, preferably in the same laboratory or institution. Cooperation on this level generally requires the sanction and support of government, industry, and university administrations.

It is well recognized that many Japanese scientists and engineers visit the United States for graduate and postgraduate studies—sometimes at U.S. expense—whereas few U.S. scientists do the converse. This is because more funding, both Japanese and American, is available to support Japanese students in the United States than is available for the reverse arrangement. An important secondary factor that has already been mentioned is the language deficiency of U.S. scientists and engineers, which makes residence in Japan and direct participation in Japanese research programs difficult. It should be noted that Japanese workers, even those with a working knowledge of English, who are being sent to their U.S. companies are generally given a 3-month indoctrination in the United States before taking up their jobs. Some means of providing a similar (or perhaps a 6-month) immersion in Japanese language and culture, in a "Japan Center" such as exists at North Carolina State University, must be provided if American students are to live in Japan and profit from their stay.

The disparity in student exchange between the two countries is recognized in Japan, and some Japanese scientific leaders with whom the committee discussed this problem are taking steps to solicit more government and private funds for support of U.S. students in Japan. They visualize no difficulty in having U.S. scientists visit and work at government laboratories or universities, since only basic research is done at those establishments.

The committee is aware that the health of U.S.-Japanese scientific individual interactions lies largely in the hands of the Japanese. One may hope that they will be sensitive to the open reception and support given to Japanese scholars and scientists in the United States and will be stimulated to reciprocate.*

OTHER TYPES OF COOPERATIVE VENTURES

A number of cooperative activities between Japanese and U.S. companies already exist that provide opportunities for exchange of ceramics technology between the two countries, and Japanese industrial representatives indicated that they are interested in forming more such joint ventures. However, competition is acute in Japan, and the Japanese are concerned that the knowledge gained by a U.S. company from a joint venture might be passed on. They are also concerned that the Department of Defense might object to having Japanese members of the board of a joint venture when the DOD is the customer—even if the technology originates in Japan. These problems merit serious attention. If they can be solved,

*There is a Japanese "Former Fulbrighters Association" that is raising scholarship money for U.S. students to study in Japan. Other private groups are working to establish a center for foreign students to live in while in Japan, since they believe typical Japanese dwellings would be too confining for most U.S. students and western-size apartments are too expensive.

Japanese companies appear to be able to offer the United States extensive experience in component manufacture, such as integrated circuit carriers and multilayer substrates (to 41 layers), and in hot isostatic processing, low-temperature sintering, surface analysis, machining, and other ceramics technologies. It is possible that joint ventures of mutual benefit can be formed between U.S. companies with good market access and a good science base in high-technology ceramics and Japanese companies with expertise in the technologies mentioned.

The committee notes that the United States has no equivalent of the Japanese Fine Ceramics Association (FCA) to represent its ceramics industry to Japan. An equivalent of the FCA could be an "American Ceramics Industry Association" (ACIA), whose charter could be either as broad as that of the recently formed Microelectronics and Computer Technology Corporation (MCC) of the U.S. semiconductor industry, which jointly supports generic research of use to all members, or more modest, concentrating on information collection and exchange between the United States and abroad. The committee recommends that such an ACIA be considered by U.S. government agencies and ceramics industry establishments.

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SHINROKU SAITO is President of the Technological University of Nasaoka and President of the Japan Fine Ceramics Association. In addition, he is President Emeritus of Tokyo Institute of Technology. He holds Baccalaureate and Doctoral degrees from Tohoku University. Professor Saito is also a present or past member of several governmental advisory groups, including current membership on the Council for Science and Technology, which reports to the Prime Minister's Office. He is the recipient of numerous awards and honors as well as honorary degrees. He is widely recognized as a preeminent authority in Japan in ceramic science, technology, education, and policy matters.

HARUO SUZUKI is Chairman and Representative Director of Showa Denko K.K., Tokyo, Japan. A member of the well-known Suzuki family, he is a distinguished corporate executive who is intimately familiar with ceramics in the basic materials industries. A graduate of law, his expertise extends to corporate management, not only in basic but also in high-technology materials industries. Mr. Suzuki heads the recently formed New Material Study Group, in which 33 Japanese companies, most of them leading manufacturers of industrial materials, are represented. He also serves in a number of governmental advisory capacities, including the Industrial Structure Council of the Ministry of International Trade and Industry.

JOHN B. WACHTMAN, JR. is Distinguished Professor of Ceramics and Director of the Center for Ceramics Research at Rutgers University, Piscataway, New Jersey. He recently completed a distinguished career of 32 years with the U.S. National Bureau of Standards (NBS), Gaithersburg, Maryland. From 1978 to 1983 Dr. Wachtman was Director of the Center for Materials Sciences at NBS. A native of South Carolina, he holds the B.S. and M.S. degrees from Carnegie Institute of Technology and the Ph.D. degree (physics) from the University of Maryland. His areas of interest include solid-state science, ceramics, mechanical properties, and effective utilization of inorganic materials. His honors and awards include the Gold Medal of the Department of Commerce, the Sosman Memorial Lecture Award, and the Hobart Kraner Award of the American Ceramic Society, of which he was president from 1978 to 1979. He is also a past president of the Federation of Materials Societies. He was elected a member of the National Academy of Engineering in 1976 and in 1983 received the Distinguished Federal Executive Award from the President of the United States.

Serving as technical advisors to the committee were OSAMU FUKUNAGA, Supervising Researcher, National Institute for Research in Inorganic Materials; JUNICHI SATO, Deputy Chief Manager, Technical Department, Ceramics Division, Showa Denko K.K.; AKIRA SAWAOKA, Professor, Research Laboratory of Engineering Materials, Tokyo Institute of Technology; and MORIYA UCHIDA, Director, Teijin, Ltd.

In addition to the committee members, the mission to Japan included ALAN M. KANTROW, Associate Editor of the *Harvard Business Review*, Harvard University, Cambridge, Massachusetts, as writer-editor; and RICHARD M. SPRIGGS of the National Materials Advisory Board as staff officer to the study. Dr. Spriggs is a former Professor of Metallurgy and Materials Science and Engineering as well as Vice President for Administration at Lehigh University, Bethlehem, Pennsylvania. He currently serves as President of the American Ceramic Society.

Appendix A

Sponsoring Agencies and Corporations and Their Technical Liaison Representatives

Aluminum Corporation of America: Thomas L. Francis, Section Head, Chemical Products, ALCOA Technical Center

AVCO Corporation: Robert L. Johnston, Manager, IRAD Materials and Process Projects, AVCO Lycoming

Carborundum Company: John Coppola, Research and Development

Celanese Research Company: Michael M. Besso, Manager, Exploratory Research

Combustion Engineering, Inc.: Arthur E. Lindemanis, Senior Technology Strategist, Corporate Technology

Corning Glass Company: Harmon M. Garfinkel, Director of Research

Dow Corning Corporation: Henry W. Foglesong, Manager, Advanced Ceramics Program

E. I. Dupont de Nemours and Company, Inc.: Homi C. Bhedwar, Engineering Technology Department

General Electric Company: Gary W. Weber, Engineering Manager, Quartz and Chemicals Department

General Motors Corporation: Fred Kennard, AC Spark Plug Division

GTE Laboratories, Inc.: William H. Rhodes, Senior Staff Scientist

IIT Research Institute: Seymour A. Bortz, Manager, Nonmetallic Materials and Composites, Materials Technology Division

IBM Corporation: Rao R. Tummala, East Fishkill Facility

Lockheed Corporation: Edmund C. Burke, Director, Materials Science Laboratory, Palo Alto Research Laboratory

Norton Company: Donald R. Gorsuch, Director, New Business Development, Materials Division

TRW Inc.: Dwayne E. Morrison, Vice President and General Manager, Ceramics Division, Aircraft Components Group

Department of Commerce: Candice Stevens, Office of Productivity, Technology, and Innovation

Department of Defense (Air Force Office of Scientific Research): Donald R. Ulrich, Bolling Air Force Base

Army Tank Command: Walter Bryzik, U.S. Army Tank-Automotive Command, Propulsion Systems Division

Department of Energy: Robert B. Schultz, Office of Vehicle and Energy Research and Development

National Aeronautics and Space Administration: Thomas J. Miller, Program Manager

National Science Foundation: Jane Dionne, Advanced Technologies and Resources Policy

Appendix B

Organizations and Individuals Visited by the Committee in Japan

Ministry of International Trade and Industry, Fine Ceramics Office, Consumer Goods Industries Bureau, Tokyo
Engineering Research Association for High Performance Ceramics, Tokyo
Showa Denko K.K., Technical Department, Ceramics Division, Tokyo
Toshiba Corporation, Materials Group, Tokyo
Japan Fine Ceramics Association, Tokyo
Professor Hiroaki Yanagida, University of Tokyo
Council for Science and Technology, Tokyo
The Long-Term Credit Bank of Japan, Ltd., Tokyo
The Ceramic Society of Japan, Tokyo
National Institute for Research of Inorganic Materials, Science and Technology Agency, Ibaraki
Optical Fiber Cable Computer System Laboratory, Ibaraki
Tsukuba Research Consortium, Tsukuba Science City, Ibaraki
Hitachi, Ltd., Hitachi Research Laboratory, Ibaraki-ken, Hitachi-Shi, Ibaraki
Matsushita Electric Industrial Company, Ltd., and Matsushita Electronic Components Company, Ltd., Osaka
Professor Mitsue Koizumi, Institute of Scientific and Industrial Research, Osaka University
NEC Corporation, Kawasaki, Kanagawa
Toyota Motor Corporation, Toyota
Toray Industries, Inc., Otsu Shiga
Murata Manufacturing Company, Ltd., Kyoto

Sumitomo Electric Industries, Ltd., Itami
NGK Spark Plug Company, Ltd., Nagoya
Denki Kagaku Kogyo, Omuta
Kyocera Corporation, Cogashima

Weekend discussion at Mt. Hiei Hotel, Kyoto, with representatives from corporations and academic and governmental institutions. Participating in this meeting were

Kenichiro Ando, Toshiba Corporation
Osamu Fukunaga, NIRIM
Toshikatsu Ishikawa, Nippon Carbon Co., Ltd.
Seiichi Ishizaka, Nomura Research Institute
Yoshikazu Ito, Toray Industries, Inc.
Koji Kobayashi, NEC Corporation
Yasutake Kobayashi, Toray Industries, Inc.
Bauri Okada, MITI
Shinroku Saito, Tokyo Institute of Technology
Junichi Sato, Showa Denko K.K.
Akira Sawaoka, Tokyo Institute of Technology
Matsujiro Shibata, Mitsubishi Chemical Industries, Ltd.
Haruo Suzuki, Showa Denko K.K.
Michiyuki Uenohara, NEC Corporation

The comments of these participants have been incorporated where appropriate throughout this report.

Additional individual or small group meetings as well as discussions with representatives of various organizations, including, among others, Asahi Shimbun, International Congress Service, Nippon Steel Corporation, Morimura Brothers, Inc., Nissan Motor Company, Ltd., Nisso Master Builders Company, Ltd., Sasaki Glass Company, Ltd., TDK Corporation, Ube Industries, Ltd., The National Defense Academy, Mitsubishi Metal Corporation, and the American Embassy.

Appendix C

Additional Data on the National Institute for Research of Inorganic Materials

OVERVIEW OF RESEARCH ACTIVITIES AT NIRIM

(Number in parentheses indicates number of researchers in one group.)

Zinc oxide	(8)	Diffusion coefficients of oxides: sintering of oxides, powder characterization, defect structure of ceramics (vacancies, dislocations, grain boundary structure): ZnO varistors: sintering and microstructure: characterization of ferrites and perovskites
Double molybdenum sulfides ($M_xMo_6S_8$) (superconducting and electrodes)	(7)	Sulfides (phase equilibria, crystal growth by vapor transport methods, structure analysis, electric and magnetic properties, spectroscopic properties)
Silicon carbide	(8)	SiC-related materials: sintering, CVD, hot-pressing, crystal structure at high temperature, preparation and properties of thin films, high-performance applications at high temperature
Stannic oxide (oxygen sensor)	(7)	SnO_2: synthesis by vapor phase, flux, and fused salt electrolysis: defect structure, crystal structure in the binary-oxide: gas adsorption characteristics

Potassium tantalate-niobate ($KTa_{1-x}Nb_xO_3$) (optoelectronic: optical memory)	(9)	$KTa_xNB_{1-x}O_3$: crystal growth, glass composite materials, high-pressure phenomena (electrical conductivity, phase transitions, crystal chemistry), defect structure and physical properties (electrical and magnetic properties)
Lithium nitride (started April 1982) (single crystal solid electrolyte)	(5)	Li_3N and BN: synthesis of low-pressure phase (hexagonal BN); single crystal growth; synthesis of high-pressure phase (cubic BN); optical properties of h-BN
Alkali metal titanates $M_2O(TiO_2)_n$ (thin fiber thermal insulator, high resistance to chemical corrosion, to replace nylon and for fixation of rad-waste)	(6)	$M_2O(TiO_2)_n$: synthesis and crystal growth (solid reactions, flux methods, hydro-thermal), mechanism of ion exchange and ionic conduction, thermochemical properties
Diamond	(6)	Diamonds: synthesis of powder, sintering, thin films, mechanism of gas phase reactions, characterization of carbon
Rare earth silicate glass (increased Young's modulus; toughening)	(9)	Glass formation; structure studies (X-ray, neutron diffraction); chemical durability, amorphous materials
Lithium tantalate ($LiTaO_3$)	(6)	Synthesis of single crystals (flux, hydrothermal, Czochralski); phase transition, structure of solid and melts at high temperature; physical properties
Alkali metal vanadates (M_xV_yO)	(6)	Synthesis and phase equilibria; composition and crystal structure; phase transition; physical structure
Zirconium carbide (field or hot cathode electron emitter)	(6)	Preparation of fine powder; growth of single crystals; electron states in solids and physical properties (emission characteristics, surface states)
Barium aluminate ($BaAl_{12}O_{19}$)	(6)	Growth of single crystals (floating-zone); crystal chemistry and phase equilibria; mechanism of crystal growth; characterization (high-precision, polarizing microscope, transmission electron microscopy); physical properties (magnetic, optical)

Hydrogen tungsten bronze (H_xWO_3)	(6)	Growth of single crystals: phase equilibria: catalytic reactions: surface state: bond state: physical properties
Zirconium phosphate $Zr(HPO_4)_2.H_2O$	(8)	Crystal growth of phosphates: sintering of phosphates: chemical properties. physical properties (hydrated crystals. amorphous phosphates)
High-Pressure Research Station	(6)	Scale-up in the effective reaction volume of high-pressure vessels: generation of very high pressure: sintering of diamonds and c-BN: large volume apparatus for crystal growth and sintering of diamonds and c-BN

(Source: American Ceramic Society Bulletin 61(9):924–25. 1982)

SUMMARY DATA ON NIRIM

Founded	April 1966	
Director-General	Dr. Masaru Goto (since August 1. 1983)	
Employees	Director-General	1
	Researchers	116 (69 with Ph.D.)
	Technicians	12
	Administrators	40
Budget	Ordinary Budget. yen 1.603 million ($6.68 million) FY 1983	
Publications	NIRIM News (6 issues per year)	
	NIRIM Research Report (3-4 issues per year)	
	NIRIM Collected Papers (1-2 issues per year)	

Participation in scientific journals and meetings in FY 1982

Oral presentations	c. 226
Printed papers	c. 146

Patent applications c. 46 (FY 1982)

Patent transfers to industry (royalty ca. 4%) via Research Development Corporation of Japan (JRDC)

Potassium titanate fiber
YIG resonator
LaB_6 electron emitter
Cubic boron nitride abrasive
Magnesium titanate gemstone
SiC sintering
Aluminosilicate glass
Sialon sintering

(Source: NIRIM)

BUDGETARY AND PROGRAM DATA ON NIRIM
(in thousands of yen)

Item	Budget for FY 82	Budget for FY 83
Ordinary Budget		
1. Special research expenses	110.167	102.566
2. Ordinary research expenses	355.850	372.375
3. Instruments for research	156.452	148.630
4. Expenses for construction	286.904	102.351
5. Personnel expenses	837.266	877.551
Subtotal	1.746.639	1.603.473
Special Budget		
6. Special Coordination Funds for Promoting Science and Technology	277.894	unknown
7. Research Project on Atomic Energy	24.288	25.566
8. Research and Development Project of Technology for Future Industries	12.826	12.840
Subtotal	315.008	
Total	2.061.647	
Researchers	115	116
Research cost per head (FY 82)		
To total (2.061.647/115)	17.927	
To ordinary research expenses (355.850/115)	3.094	

Special Research Project	Budget for FY 82	Budget for FY 83
Special Research		
1. High-temperature ceramics	55,145	52,449
2. Field electron emitter	31,259	28,607
3. Sintered-materials for optoelectronics	23,763	21,510
Total	110,167	102,566
Special Coordination Funds for Promoting Science and Technology		
1. Large volume high-pressure apparatus for materials synthesis	162,252	unknown
2. Surface and grain-boundary in materials	49,485	41,292
3. New materials creation utilizing gravity-free environments	54,963	unknown
4. High-performance laser sensing systems	11,194	unknown
5. Others	—	unknown
Total	277,894	
Atomic Energy Research		
Radioactive waste treatment and characterization	24,288	25,566
Research and Development Projects on Basic Technology of Future Industries: High-Performance Ceramics	12,826	12,840

(Source: NIRIM)

Appendix D

Key Ceramics-Related Societies in Japan

THE CERAMIC SOCIETY OF JAPAN

Established:	1892
Address:	Shinjuku-ku. Hyakunin-cho 2-22-17. Tokyo 160. Japan
Purpose:	Progress in ceramics science and technology. The established professional society in Japan.
Publications:	*Yogyo Kyokaishi. Seramikksu*
Membership:	5.625 (18 branches throughout Japan)

ENGINEERING RESEARCH ASSOCIATION FOR HIGH-PERFORMANCE CERAMICS

Established:	September 1981
Address:	Minato-ku. Toranomon 1-81-1. Mori Building 10. 8th Floor. Tokyo 105. Japan
Purpose:	Monitors MITI ceramics research for 15 companies and 4 government research institutes in the Next Generation Basic Technology R&D Project.

NEW CERAMICS DISCUSSION GROUP

Established:	June 1972
Address:	Dr. Mitsue Koizumi. Institute of Scientific and Industrial Research. Osaka University. 8-1 Mihogaoka. Ibaraki. Osaka 387. Japan

Purpose:	Meetings, seminars on ceramics in the Kyoto, Osaka region: administers Ministry of Education, Science and Culture project on "New Investigations of Functional Ceramics"
Publications:	*Our Ten-Year History*, newsletter
Membership:	197

JAPAN FINE CERAMICS ASSOCIATION

Established:	July 1982
Address:	Minato-ku, Toranomon 1-22-13, Nishikan-Toranomon Building, 6th Floor, Tokyo 105, Japan
Purpose:	Survey research and cooperation among industry membership
Publication:	*FC Report* (monthly)
Membership:	172 companies: 158 normal members ($1600/year subscription), 14 cooperative members ($800/year subscription): Membership by company type as of April 1983: Ceramics (41), Chemicals (32), Electrical Appliances (25), Steel & Nonferrous Metals (23), Machinery (23), Automobiles (7), Heavy Industry, Engineering (7), Other (14)