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An Assessment of High-Performance Structural Ceramics

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Scientific and Technical
Intelligence Committee

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STIC 86-001
May 1986

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Preface

This document was prepared by the Structural Materials Working Group (SMWG) of the Scientific and Technical Intelligence Committee (STIC). The assessment was made in response to STIC tasking that requested an evaluation of worldwide technology on ceramic materials having structural applications.

We wish to emphasize that the area of structural ceramics is very broad; therefore, the scope of this assessment is limited to those specific applications having the greatest military significance. In particular, that portion of ceramics technology dealing with electronics, optics, and nonstructural properties of these materials is not covered. Initially, it was envisioned that a larger number of topics would be covered, but insufficient data were available to make adequate assessments. Also, it was desirable to limit the size of the document.

Mr. Joey Crider, principal author of this report, acknowledges the support of Dr. Robert Gottschall (Department of Energy), Dr. Steven Wax (Defense Advanced Research Projects Agency), Mr. James Kelly (Office of Naval Technology), and Mr. Marlin Kinna (Naval Sea Systems Command), who reviewed the assessment, and the help of his colleagues on the working group. Grateful acknowledgment is also made to Lt. Steven Tyree, US Air Force Foreign Technology Division, and R. L. Gerrity, Naval Intelligence Support Center, for their contributions to the assessment.

Questions concerning the content of this report should be directed to the chairman of the SMWG, Mr. Roy Frontani, telephone (513) 257-6716, or to the principal author, Mr. Joey Crider, telephone (804) 296-5171, extension 671. Members of the working group are:

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An Assessment of High-Performance Structural Ceramics [redacted] 25X1

Key Judgments

The application of ceramics in heat engines is taking longer than claimed by industry. Ceramics have been improved significantly, yet considerably more improvement is needed before ceramics are practical in most production applications for heat engines. Important developments are:

- Overall, the United States leads the world in ceramics research and Japan in the commercial application of ceramics. Because of the relatively free exchange of information on ceramics, however, industralized countries, both Communist and non-Communist, have access to roughly similar technologic bases.

- High-strength ceramics are of growing importance in the cutting tool industry worldwide. Several Western countries are about to introduce ceramic armor, which may already be fielded by the Soviet Union. Ceramic heat engines may become commercially available within the next five to 10 years, bringing improvements in fuel efficiency and durability.

- The Soviet Union has preceded the West in the development of sound innovative techniques for powder production and consolidation. Quality control of materials has been a weakness in Soviet ceramic technology. The Soviets have been aggressive in moving ceramic technology into application and have frequently been world leaders in applications.

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An Assessment of High-Performance Structural Ceramics (u)

Introduction

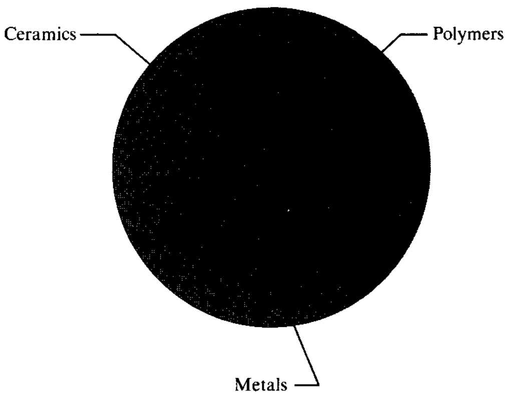
A new family of ceramic materials has emerged during the past 15 to 20 years that has affected diverse areas of technology—microelectronics, heat engines, sensors, cutting tools, power generation, ballistic protection, orthopedics, and missile nosecones. The method of manufacture and the properties of these materials differ greatly from those of so-called traditional ceramics, which include refractory bricks and whiteware. In modern terminology, these new materials are called high-performance, high-technology, or engineering ceramics. In Japan, a country reportedly afflicted with ceramic fever, the term "fine ceramics" is applied. [redacted] 25X1

Ceramics is both the art and science of making solid articles that have as their essential and major component inorganic, nonmetallic materials and the objects thus created. Ceramics are usually subjected to high temperatures (above 800 to 900 degrees Celsius) during manufacture and use. They are produced by many different techniques that have in common the consolidation and densification of fine powders at high temperature. Some techniques also involve simultaneous application of pressure to assist the densification process. [redacted] 25X1

Ceramics, metals, and polymers are three classes of materials; heterogeneous combinations of these materials are called composites (figure 1). (Some composites have special names; for example, cermets, which are metals containing discrete ceramic particles.) Ceramics are technologically attractive because they possess a unique combination of properties that other materials cannot offer. Their outstanding engineering properties include resistance to heat, oxidation, corrosion, and abrasion; high elastic modulus; high hardness; favorable strength-to-weight ratios with high compressive strength; low-to-moderate density; dimensional stability and rigidity. Chemical compounds such as oxides, nitrides, and carbides of widely available metallic elements such as silicon and aluminum make up the majority of high-performance ceramic materials. The natural abundance of these raw materials should permit the eventual availability of ceramics at low costs, potentially allowing them to replace limited sources of more expensive strategic materials such as cobalt-based superalloys. Certain ceramics also have outstanding electrical, magnetic, and optical properties, but the technologies and applications that utilize such properties are outside the scope of this study [redacted] 25X1

Figure 1
Division of Materials Classes

Percent



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The mechanical properties of many of these new high-performance ceramics are now sufficient to allow their use in certain load-bearing applications that

Table 1
Applications of High-Performance Structural Ceramics

	Heat Engines	Armor	MHD	Radomes	Infrared Domes	Cutting Tools	Nozzles	Heat Shields	RAM
Dioxides									
Al_2O_3		***		***	**	***			
ZrO_2	**	*	**			*			
MgO			**						
Ferrites									**
SiC	*	**	*				*		
Carbides									
B_4C		***							
TiC						**			
WC	*					***			
Si_3N_4	***	*		**		***			
AlN	*	*		**	**				
Nitrites									
BN		*				***			
AlON				**	**				
SiAlON	**	*		*		***			
Borides									
TiB_2		**							
Carbons						***	**	***	**
Fluorides									
MgF_2					**				
LiF					**				

*** = Already in use.
** = Major candidate.
* = Minor candidate.

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previously were technologically impossible. (For example, the tensile strength of silicon nitride has increased from under 100 megapascals (MPa) in the mid-1960s to about 550 MPa in 1985.) For purposes of this assessment these materials shall be referred to as high-performance structural ceramics. The ceramic compounds that comprise high-performance structural ceramics are not the silicates and clays used in traditional ceramics. Several oxides such as aluminum oxide and zirconium dioxide are included, but primarily it is the family of carbides, nitrides, and borides that are of engineering significance for these applications. In addition, ferrites are used as radar-absorbing materials, and fluorides are useful as infrared (IR) dome materials. Table 1 summarizes the ceramic materials that are potential candidates for structural applications. The applications of these ceramics that have been identified as pertinent for discussion in this assessment include:

- Heat engines (gas turbines and diesels).
- Armor (combat vehicles, aircraft, and personnel).
- Cutting tools.
- Magnetohydrodynamic (MHD) power generators (electrodes and insulators). [redacted] 25X1

Ceramic materials, however, have one fundamental limitation. They are inherently brittle, which means that they have a limited strain tolerance. If overstressed, they fracture more readily than metals and most polymers because most ceramics cannot relieve stresses by local yielding. Advances in materials technology and system design techniques are helping to overcome the brittleness deficiency. A key factor is the minimization of critical flaws caused by voids and impurities that can lead to failure in service. Exceptional care must be taken throughout all steps in the processing of ceramic materials—from the production of high-purity, ultrafine powders to the forming of green bodies, to the densification of solid articles by sintering or hot pressing, and to final machining. Quality control and nondestructive evaluation are essential to assure the production of high-quality ceramics having uniform and reproducible properties. There are other approaches to the brittleness problem. One is to reinforce a ceramic matrix with another phase or with fibers, which helps to improve tensile strength and resist cracking. Another technique used (especially with zirconium dioxide) is transformation toughening, whereby a stress-induced phase transformation retards cracking. [redacted]

Current Status

Heat Engines

Introduction. All major industrialized countries have ongoing programs to develop ceramic materials for heat-engine applications. Both gas turbines and diesels stand to benefit from this development. Engines with ceramic components can operate at temperatures several hundred degrees Celsius higher than car engines with metallic parts. High-temperature operation in turn provides more efficient burning of fuel and reduced emissions. The lower density of ceramics compared with metals results in reduced inertia, which is especially important for the rotors of turbochargers and gas turbine engines. Replacing metal parts with ceramics also lowers overall engine weight. In the so-called adiabatic diesel engine, ceramics will allow the cooling system to be completely eliminated. This will further reduce weight and volume, improve efficiency, and greatly reduce maintenance, which will reduce life-cycle costs of ground force vehicles.

Ceramic bearings are also under development for critical applications where high heat and wear resistance is important. The first major structural application of ceramics is expected in late 1986 with the commercial adoption of a silicon nitride turbocharger rotor by the Japanese. [redacted] 25X1

USSR. In 1984 a Soviet newspaper stated that researchers at the Institute of Problems in Materials Science (IPROMAT), Kiev, were as successful as the Japanese in developing a ceramic internal combustion engine. [redacted] assessments, however, indicate that the Soviet Union is several years behind the United States, Japan, and West Germany; the exact status of Soviet ceramic heat-engine technology is uncertain. [redacted] 25X1 25X1

The Soviet program began in the early-to-mid-1970s and was prompted by a 1968 UK report that demonstrated the outstanding potential of silicon nitride for engine applications. Between 1972 and 1974 the Soviets began to develop hot-pressed silicon nitride, but properties were and remain inferior to US and Japanese materials. One possible reason is that the Soviets have been less successful in controlling the 25X1 quality of their materials throughout each processing step. On the other hand, the Soviets have developed several advanced powder production and/or consolidation techniques, namely, self-propagating high-temperature synthesis, plasma chemical synthesis, and explosive compaction, and they have the lead in these specific areas. These techniques, which are mature technologies in the USSR, are low cost and yield high-quality products, two factors having major significance in the ceramics field. [redacted] 25X1

One aspect of the Soviet approach that differs from US and Japanese efforts is a greater emphasis on various types of ceramic composites. In 1975 the Soviets began to develop a composition of 40-percent silicon carbide and 60-percent silicon nitride for automotive gas turbine applications. Guide vanes of this particulate composite were tested in the late 1970s at the Institute of Strength Problems, also in Kiev. Even though the ceramic vanes failed rigorous thermal cycling, this same material continues to be investigated. Because of this composite's porosity, its strength properties, as reported in open literature, are not impressive. Its impact strength values, however, appear adequate because the pores act to help arrest cracks. Another composite material that the Soviets may be considering as a candidate for heat-engine applications is mullite fiber-reinforced aluminum oxide. [redacted]

Poland. In Poland, there are at least two research and development (R&D) programs associated with zirconium dioxide. One involves fundamental research on aluminum oxide–zirconium dioxide compounds that contain more than 35 percent zirconium dioxide. The second program involves the characterization of physical properties of zirconium dioxide. Of particular note is the fact that, although research results of this latter program are being made available to the Soviets, the Poles have stated that they are receiving practically no feedback. [redacted]

Another significant program is concerned with developing ceramic seals for gas turbine engines. The seals are actually a cermet comprised of boron nitride and nickel, and are produced by a liquid-phase sintering process. The program, which is assessed to have begun in the early 1980s, has included fundamental compositional investigations, materials characterization, and manufacturing process development. [redacted]

China. The Chinese are very interested in developing ceramic heat-engine components, with the best R&D being conducted at the Shanghai Institute of Ceramics and at Qinghua University, Beijing. They have emphasized processing technologies, although they have not pursued hot isostatic pressing. They have developed both silicon carbide and silicon nitride, but property values of these compounds are not yet equal to those of US, Japanese, or West German ceramics. In 1978 silicon nitride components (presumably blades) for gas turbine engines were observed in China. Hot-pressed silicon nitride has been investigated for apex seals in rotary piston engines. Fiber-reinforced ceramics of lithium fluoride/silicon nitride and zirconium dioxide/silicon nitride have been made with good high-temperature properties, which could have engine applications. One weakness of the Chinese program that must be overcome is the understanding and application of fracture mechanics. [redacted] 25X1

United States. Ceramic materials R&D programs for heat-engine applications began in the United States in the early 1970s and have emphasized the use of silicon nitride. Although diesel engine applications are also of great importance, initial efforts were directed more toward gas turbine engines. The objective was to determine whether gas turbine engine components could be designed successfully with brittle ceramic materials. These efforts did demonstrate that such materials are feasible and that they would survive engine operating conditions. Parallel efforts to develop improved ceramic materials and fabrication processes for complex shapes were also conducted. [redacted] 25X1 25X1

A truck turbine engine with ceramic stator components has been successfully operated for a total of 92 hours under a realistic vehicle operating environment. The objective of current Department of Energy efforts is to design entirely new turbine engines using ceramic components. One effort, being conducted by the Ford Motor Company and Garrett/Air Research, requires an engine operating speed of 100,000 rpm and a turbine inlet temperature of 1375 degrees Celsius. It is clear that progress is being made; a ceramic rotor in an all-metal engine demonstrated 97 percent of design speed before it failed on the first attempt to test this component. Such a result is considered to be quite encouraging. [redacted] 25X1 25X1 25X1

Current developments in ceramic technology indicate that it is likely the first applications of ceramic components will be for diesel engines. One of the primary objectives of such use is to eliminate the cooling system, which is a leading cause of engine failure, especially in combat vehicles. An uncooled diesel has already been demonstrated in a program involving the US Army Tank Automotive Command and Cummins Engine, Incorporated. But this type of engine utilizes ceramics in the form of coatings of zirconium dioxide to insulate the engine and not as monolithic parts. The next step will be the so-called adiabatic or low-heat-loss diesel, which will incorporate ceramic pistons, cylinder liners, and engine head parts. This engine will be about 25 percent more fuel efficient than conventional diesels. Predicted dates for commercial production vary from the mid-1990s to the turn of the century. Beyond this time frame is the goal of a minimum-friction diesel that, because it uses advanced ceramics technology, will have no lubricating system. [redacted] 25X1

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Japan. Japanese ceramic heat-engine technology began in 1978 when the Ministry of International Trade and Industry (MITI) instituted the Moonlight Project to develop gas turbine engine blades. In 1980 the National Institute for Research of Inorganic Materials began a four-year project to develop ultra-high-temperature, heat-resistant ceramics. In 1981 MITI helped establish the Engineering Research Association for High-Performance Ceramics [redacted] 25X1 The Japan Fine Ceramics Association, composed of over 170 companies, was established in 1982. [redacted] 25X1

The Japanese are developing both silicon carbide and silicon nitride for engine applications but are concentrating most of their efforts on silicon nitride. Toshiba is recognized as a leader in silicon nitride development, and their products have the best room-temperature properties. But properties at high temperatures are of greater significance. In December 1984 the Engineering Research Association for High-Performance Ceramics reported on silicon nitride with a tensile strength of 548 MPa at 1,200 degrees Celsius; silicon carbide had a tensile strength of 387 MPa. [redacted] 25X1

Another ceramic that the Japanese are actively developing for adiabatic diesels and turbocharged engines is zirconium dioxide; NGK Sparkplug has operated an adiabatic diesel engine with yttria-stabilized zirconium dioxide for 250 hours. US Naval Research Laboratory tests show that the Japanese material is significantly better than US material and slightly better than that of Australia and West Germany. Nissan Motors is planning to use this material for piston heads in their diesel engine design. Toshiba is using it in the laboratory for cylinder liners, piston caps, and turbine blades. Kyocera (formerly Kyoto Ceramic Company) also is considering zirconium dioxide to insulate pistons and cylinders in turbocompounded engines. [redacted] 25X1

Since 1983 the use of silicon carbide as a reinforcement in ceramics has become popular in Japan. In a silicon nitride matrix, a 40-percent reinforcement of silicon carbide whiskers has been shown to retain strength even when 10-percent porosity is present. Similarly, silicon carbide continuous fibers are also being used; Nippon Carbon's Nicalon fiber is being evaluated around the world and, although properties are not as good as advertised, high potential and interest remains. In 1984 Ube Industries announced a new silicon-titanium-carbon fiber that supposedly can be produced at half the cost of silicon carbide. Interest in this new fiber is also very high. [redacted] 25X1

Japanese successes in the application of ceramics for heat engines have been well publicized. In 1981 NGK Spark Plug Company, Limited, demonstrated the feasibility of a silicon nitride engine when a 50-cc air-cooled piston engine was successfully run for 50 hours. In 1982 Kyocera announced the successful operation of an uncooled silicon nitride engine in an Isuzu Gemini automobile. The production of high-quality ceramic components accounts for much of this success and for Japan's worldwide reputation in the ceramics field. Since 1983 Kyocera has produced 30,000 glow plugs per month, 20,000 swirl chambers per month, and several thousand turbocharger rotors per month. In May 1984 NGK Insulators began production of 500 ceramic rotors per month. [redacted] 25X1

West Germany. From 1974 to 1983 the West German Ministry for Research and Technology (BMFT) funded a ceramics group [redacted] 25X1 with the goal of developing a vehicular gas turbine [redacted] 25X1 [redacted] [redacted] The program was managed by the West German Research and Development Laboratories for Air and Space Travel (DFVLR). The most active firm in the development of ceramic turbine engines has been Daimler Benz (DB), although Motoren Turbinen Union (MTU) and Volkswagen (VW) are also involved. [redacted] [redacted] They believe, as do many US researchers, that ceramic parts for turbine engines will be introduced gradually. [redacted]

The most active German firms now involved in ceramic reciprocating engine development are Deutz and VW, which are developing truck and car engines, respectively. [redacted] [redacted] This is the first non-Japanese effort to make ceramic turbochargers from designs intended for metal parts. Rosenthal, the leading West German ceramic producer, is making a limited number of reaction-bonded silicon nitride turbochargers for about six European engine manufacturers. Working with Deutz, they are using aluminum titanate to achieve ceramic-to-metal bonding and are developing exhaust port liners of this material. Rosenthal is also involved in adiabatic diesel research now being funded by BMFT. The greatest problem, which is common to all countries, has been related to nondestructive testing. [redacted] [redacted]

The West Germans also possess excellent ceramic powder technology. Silicon nitride powders are produced and categorized at the Hermann C. Starck Institute in Berlin. Of particular significance are efforts to improve the high-temperature strength of silicon nitride. The primary emphasis has been to explore nonoxide sintering aids that do not degrade high-temperature strength properties. The high quality of Starck powders, which contain exceptionally low amounts of oxygen, is evidenced by the use of these powders by several Japanese firms, which can make high-quality powders on their own. [redacted]

Sweden. As of 1981 Sweden's ceramic engine program was directed by a committee of influential people drawn from engine companies and ceramic companies [redacted] [redacted]

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In late 1982 a gas turbine engine with a silicon nitride turbine wheel and rotor was successfully road tested by Volvo. The ceramic parts were hot isostatically pressed by ASEA, which has also produced various other ceramic engine components including valve seats and ball bearings. ASEA-produced parts are of very high quality and not easily duplicated by other manufacturers. They have produced the first "flawless" silicon nitride turbine rotors for a US-designed gasoline turbine rotor. The hot-isostatic-pressing unit developed by ASEA, called the Quintus press, may be the best in the world for ceramic production. [redacted]

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The United Kingdom. The UK ceramic engine program is centered around Rolls-Royce (RR) and includes a "ceramic club," which has been established to link material suppliers, manufacturers, government research establishments, and universities [redacted] [redacted]

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In early 1983 Fairey Holdings decided to establish a special subsidiary to exploit its expertise to help close the technology gap between the United Kingdom and the United States and Japan. Emphasis will be placed on injection molding of components such as turbine blades. New ceramics will be researched for engine insulation and turbocharger applications. [redacted]

France. In late 1979 the Ministry of Industry selected Renault to play a leading role in France's development of an advanced high-temperature diesel engine (the government would provide 50 percent of the funds). Renault engineers planned to use ceramics wherever possible. [redacted] Silicon nitride is not as popular in France as it is in the United States and Japan. Like the United Kingdom, France is leaning toward Sialon materials. As of 1980 the French did not have a silicon carbide production facility but planned to get engine components from the United States. The French are not eager, however, to establish close ties to large US companies for the development of ceramic heat engines. At the 1983 Paris Air Show, ONERA displayed posters of ceramic turbine blades. [redacted]

One area in which the French are in a position to excel is the development of ceramic matrix composites. A primary candidate is silicon carbide/reinforced silicon carbide. The firm SEP is a leader in developing this material, which is similar to carbon/carbon but possesses better high-temperature oxidation resistance. This material, in the form of a bladed turbine disk [redacted] was shown by SEP at the 1985 Paris Air Show. [redacted]

South Korea. Although the South Koreans do not have a formal ceramic engine program, they have been conducting materials R&D on heat engine ceramics since the early 1980s. This work is being conducted at the Korean Advanced Institute of Science and Technology, Inha University, Hanyang University, Seoul National University, and Kyung Sang University. Many programs are cooperative between several laboratories and deal with the processing of both reaction-bonded and sintered silicon nitride and silicon carbide. The effects of surface finish as well as the effects of particle size and sintering aids on microstructure and mechanical properties have been addressed specifically. Composites of aluminum oxide with a dispersed phase of zirconium dioxide are also being investigated for improved fracture toughness. [redacted]

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Italy. Little information is available on the status of Italian ceramic heat engine technology. It is known, however, that Fiat has successfully tested a ceramic swirl prechamber for a spark ignition engine. [redacted]

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Armor

Introduction. Ceramic armors provide outstanding ballistic protection against a variety of conventional weapons threats, including small-arms projectiles, fragmenting munitions, and kinetic energy penetrators. Combinations of high hardness, high compressive strength and modulus, high sonic velocity, and moderately low density are important properties. Boron carbide, silicon carbide, titanium diboride, and aluminum oxide are proven candidates. Cubic boron nitride would be an excellent armor if techniques could be developed to produce this material in sizes larger than just a few millimeters. For armor applications, the brittleness of ceramics is a major disadvantage because it degrades the multihit capability of the armor. This problem must be addressed in the design of the armor system. Ceramic armor is attractive for aircraft, combat vehicles, and personnel. In the case of personnel armor, ceramics are still too heavy for the infantryman in battle, but aircrewmen can benefit from the additional protection offered over that of fabric armors [redacted]

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USSR. The USSR is judged to possess the requisite technical talent and scientific and industrial resources to have established a comprehensive ceramic armor development program any time after the mid-1960s.

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[redacted] reported the existence of a Soviet ceramic armor program using unspecified carbides as early as 1966, but confirmation of such a program remains elusive. The Soviets are believed to have first developed glass-ceramic (called Sitall in the USSR) armor that may have been investigated for use as armor in tank turrets and/or the front glacis, even though it is not a high-performance ceramic.This development, which was mature by the early 1960s, is estimated to have been succeeded by the adoption of higher performance ceramics. The most likely Soviet ceramic armor candidates would include silicon carbide and aluminum oxide. High-quality, hot-pressed boron carbide was not available until 1983, and little research has been uncovered on producing titanium diboride (other than powder). The Soviets undoubtedly would be interested in boron-containing materials that absorb thermal neutrons, however, because of the emphasis they place on tank radiation protection. [redacted]

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At some unspecified time the Soviets apparently initiated a ceramic ball-type armor development program. In 1977 the Soviets began production of aluminum oxide balls that allegedly were to be used specifically for an armor application. The balls were to be placed in a steel matrix, which suggests possible tank armor use. It was stated that this program was a reaction to US development of ceramic ball armor. It is conceivable that this ceramic ball armor program is associated with the SMT 1981/3 and/or the T-80 tanks. Both tanks are assessed to employ ceramic armor. [redacted]

Other materials-related research that could have armor applications include the development of mullite fiber-reinforced aluminum oxide and boron carbide, investigations of shock-induced phase transformations of boron nitride, and measurements of shock compressibility of ceramics. Fiber-reinforced ceramics have the potential for improving the multihit capability of ceramic armor. [redacted]

United States. The United States initiated the development of ceramic armor in the early 1960s with lightweight ceramic composite armor, which consists of a hard ceramic tile backed with aluminum or glass-reinforced plastic. The ballistic performance of aluminum oxide, silicon carbide, and boron carbide has been established against numerous small-caliber armor piercing projectiles and fragment simulating projectiles. Boron carbide has been used extensively in the construction of armored crew seats for Army helicopters. This ceramic offers the best ballistic performance but is more expensive than other ceramics, because hot-pressing must be used to obtain a high-quality product. Although titanium diboride is still in R&D, ceramic armor materials in general have reached maturity and await adoption by system program managers. Improved processing technologies that would lower costs is one area for further advancement. This is now being addressed through reverse technology transfer; US researchers are investigating explosive compaction and self-propagating high-temperature synthesis, two processes highly developed in the Soviet Union. Also, if silicon carbide is adopted for heat engine use, high-volume production is expected to lower costs sufficiently to increase the use of this ceramic for armor. [redacted]

Japan. The Japanese Ground Self-Defense Force initiated a ceramic armor program in the late 1970s in support of the Model 88 tank development. [redacted] 25X1 25X1

[redacted] Several leading ceramic materials producers have submitted ceramic tiles for evaluation: Kyocera; Asahi Glass Co., Ltd; and NGK. High-quality, hot-pressed aluminum oxide, silicon carbide, silicon nitride, and zirconium dioxide were ballistically evaluated. [redacted] aluminum oxide was most cost effective and therefore chosen for further testing. Zirconium dioxide is being considered for use near the front of the armor system to defeat kinetic energy penetrators. Japanese experience in producing high-performance ceramics for electronic and heat engine applications will aid them in their armor-development efforts. It is unclear if their armor program will be completed in time to be incorporated in the Model 88 tank. [redacted]

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West Germany. Only recently have the West Germans expressed interest in developing ceramic armors for combat vehicles. A recent model of the Leopard tank has ceramic applique armor on the turret in addition to reactive armor for defeating Soviet 125-mm tank-gun munitions. [redacted] 25X1 25X1

Sweden. As of 1982 Swedish officials were considering ceramic applique armor for Centurion tanks. The impression was given that breakthroughs had been made in this area. In 1983 Swedish defense officials revealed preliminary testing of reactive armor containing glass. [redacted] 25X1 25X1

France. The French have successfully developed ceramic armor systems. [redacted] 25X1 25X1 25X1

Israel. The Israeli Ministry of Defense has the capability to produce high- quality ceramic materials in pilot plant quantities sufficient for armor applications.

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[redacted]

Cutting Tools

Introduction. Cutting tools are used in machining operations to turn, bore, drill, mill, or otherwise shape materials into final dimensions. High-speed machining and/or machining of very hard materials often necessitates the use of ceramic-containing cutting tools, which have outstanding wear resistance and hardness compared with other cutting tools, especially at high temperatures. The use of ceramics allows higher productivity, improved quality, and cost savings. The first ceramic material used industrially (aluminum oxide) was in tungsten carbide cutting tools, which were introduced about 1930. Called cemented carbide or just carbide by the industry, tungsten carbide is in widespread use throughout the industrialized countries. Tungsten carbide is often alloyed with other ceramics such as titanium carbide or tantalum carbide, depending on the specific machining operation. In reality, tungsten carbide cutting tools are cermets and not true ceramics, because they consist of ceramic particles bonded with a metal such as cobalt. Since the early 1970s, superhard materials such as polycrystalline diamond and cubic boron nitride have been widely used. [redacted]

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Technological advances in cutting-tool materials have permitted faster, better, and more economical manufacturing, thus increasing the productivity of military hardware. The major disadvantage of ceramics is their poor resistance to mechanical shocks encountered when making heavy, interrupted cuts. Recent improvements in the toughness of ceramics are being applied to the development of new cutting-tool materials. The leading candidate for heat engine applications, silicon nitride, is also being developed for cutting tools. [redacted]

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USSR. The Soviets began a program in the early 1970s to develop advanced cutting tools. Their objective was to find substitutes for tungsten-containing materials, which were in short supply because of Chinese restrictions on exports of tungsten to the USSR. In 1973 the USSR Council of Ministers issued Special Directive No. 2212, which curtailed the use of tungsten by the civilian sector. This incentive initiated research for material substitutes that continues to this day. The two most successful materials, TN-20 titanium carbide and KNT16 titanium carbonitride, were available by 1982 through joint efforts of the Institute of Problems in Materials Science, Kiev Polytechnic Institute, the All-Union Scientific Research Institute of Hard Alloys, and the All-Union Production Association Soyuztverdosplav of the USSR Ministry of Nonferrous Metallurgy. These materials use molybdenum and/or nickel as the bonding agent rather than cobalt, which is a strategic material in the USSR as elsewhere. Besides being only one-fifth as expensive as cobalt, titanium carbide and titanium carbonitride have been proved by the

Soviets to be 60 to 100 percent more durable than tungsten carbide in the machining of carbon and alloy steels. This ceramic materials development was nominated for the USSR State Prize in science and technology in 1982, 1983, and 1984. [redacted] 25X1

Probably the most significant achievement by the Soviets has been the development of advanced boron nitride cutting tools with improved toughness. Explosive shock compression is used to produce boron nitride powders with a pronounced defect-type crystal structure. When subsequently hot-pressed and sintered into a cutting tool insert, the resulting microstructure is composed of the superhard cubic phase as well as an intermediate wurtzitic phase that imparts a high degree of toughness. Research on this material, called Gesanit-R or Hexanite-P, was conducted throughout the 1960s and was available for use by the machine tool industry by the mid-to-late 1970s. Besides increases in service life, this material reportedly outperforms diamond durability during high-temperature machining operations. [redacted] 25X1

Czechoslovakia. The majority of ceramic R&D in Czechoslovakia is associated with machine tools, with the preponderance of the work being conducted on sintered carbides. Facilities credited with conducting research in this area include the Machine Tools Research Institute in Prague and the Research Institute for Powder Metallurgy in Shumperka. Various carbide powders—boron, silicon, and titanium carbide—are being produced on an industrial scale. Research continues on cubic boron nitride (CBN), even though CBN grinding wheels are already in production. [redacted] 25X1

Poland. Poland is actively developing ceramic tooling, especially CBN. Silicon nitride is attracting some research attention as are both silicon carbide and titanium carbide. Abrasive tools of silicon carbide single crystals have been found to offer substantial advantages over polycrystalline material. The apparent goal of one major program is to develop cost-effective abrasive tools that contain about 40-percent single-crystal silicon carbide. According to Polish technical information, such tools offer 3.7 to 7.4 times better wear resistance than conventional types. [redacted] 25X1

China. Cutting tools represent a major application of Chinese silicon nitride technology. Applied research has been conducted at the Shanghai Institute of Ceramics, and since 1980 a small production line has been in operation at the Shanghai Factory of Ceramics for Electrical Appliances. Shanghai Radio Factory No. 1 has also been associated with the production of silicon nitride cutting-tool materials. [redacted] 25X1

Other facilities conducting R&D on hot-pressed silicon nitride cutting tools include Qinghua University, in Beijing, where a new composition has been developed: titanium carbide particles and cobalt are introduced in the silicon nitride powder along with a magnesium oxide sintering aid. Tool bits made from this material outperformed conventional tungsten carbide tools and existing silicon nitride compositions for machining cast iron. [redacted] 25X1

Chinese research on pressureless sintering of silicon nitride has been reported at the Shanghai Institute of Ceramics, Qinghua University, and Nanking Institute of Chemical Technology. All three groups use yttria and alumina additives to increase densification and use "special" heat treatments to improve high-temperature strength. Although the Chinese work is not specifically related to cutting tools, such applications have been successful in the West and Japan. [redacted] 25X1

United States. Tungsten carbide cutting-tool materials were introduced in the United States about 1930. The next advance came 10 years later, when tungsten carbide began to be alloyed with titanium carbide and/or tantalum carbide. Aluminum oxide was introduced in the mid-1950s, followed in 1957 by synthetic diamonds. The next advance, in 1970, was to coat tungsten carbide with another ceramic such as titanium nitride. In 1973 polycrystalline diamond that is sintered into cutting-tool inserts was introduced. Cubic boron nitride, which is second only to diamond in hardness, was also developed in the early 1970s for cutting ferrous alloys. This material is called Borazon and is widely marketed by the General Electric Company to other industrialized countries. Although not widely advertised, silicon nitride cutting tools have been developed and are commercially available in the United States through sales by Kennemetal, Greenleaf, Iscar USA, and GTE. These firms are even selling their products in Japan, an indication of a high-quality product. [redacted]

Japan. Japan, like the United States, has not advertised the use of ceramics for cutting-tool applications to the same extent that they have for heat engines. Silicon nitride materials are available from numerous ceramic producers including Kyocera, Sumitomo Electric Industries, Nippon Tokushu Togyo, Hitachi Chemical, and Mitsubishi Metals. The Japanese can be expected to pursue the silicon nitride cutting-tool market aggressively as it develops more fully. This market will complement the widespread adoption of computer-integrated machine tools and the requirement for higher performance tool materials with increased toughness. [redacted]

West Germany. West Germany historically has been a leader in the early development of ceramic cutting tools. The use of aluminum oxide was first proposed in Germany in 1905, with patents being issued in 1913. Cemented carbides were introduced in 1926. West Germany's reputation for manufacturing high-quality goods is undoubtedly related to its excellent cutting-tool industry. [redacted]

Between 1981 and early 1983, researchers at the Max Planck Institute developed "superhard" compositions of zirconium dioxide and subsequently worked on other ceramics with equal success: aluminum oxide, aluminum silicate, and beryllium oxide. [redacted]

[redacted]

Sweden. The Swedish firm Sandvik Hard Materials has developed several improved ceramic cutting-tool compositions [redacted]

[redacted]

Austria. In the early 1980s ceramic research for cutting-tool applications was reported at the Institute for Chemical Technology of Inorganic Materials of the Technical University of Vienna. Ceramic compositions were not specified, but it is known that the cutting-tool material was hot isostatically pressed, which implies a high-performance ceramic, and information on this subject was presented in 1981 at an international conference held in Minsk, USSR. [redacted]

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[redacted]

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Magnetohydrodynamics (MHD)

Introduction. Commercial use of the MHD process will depend in part upon the ability to develop materials that can withstand the high temperatures and the corrosive/erosive environment present in many parts of the MHD power generator (figure 3). Ceramics R&D will be especially important if coal is to be used to fuel the MHD system, because the problems of erosion and corrosion are greater when coal, rather than cleaner fuels such as natural gas or oil, is used. Specific work on materials for use in MHD applications is usually not a large part of the overall MHD effort in any country, as the materials technology currently exists to build operating pilot-scale plants. However, long-term operation of these plants will require significant progress in developing higher performance ceramic materials. [redacted]

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USSR. MHD research in the Soviet Union remains the largest program in the world, with work being conducted in their small U-02 facility as well as the U-25 pilot plant facility, both in Moscow. A commercial scale U-500 facility is currently under construction in Ryazan, near Moscow. Materials R&D in these facilities is varied, but typically focuses upon materials for the upstream components, including the channel, combustor, and diffuser. Channel electrode materials that have been investigated include combinations of zirconium dioxide with rare earth oxides and SiC alloyed with several refractory metals. Magnesium dioxide has been used as an interelectrode

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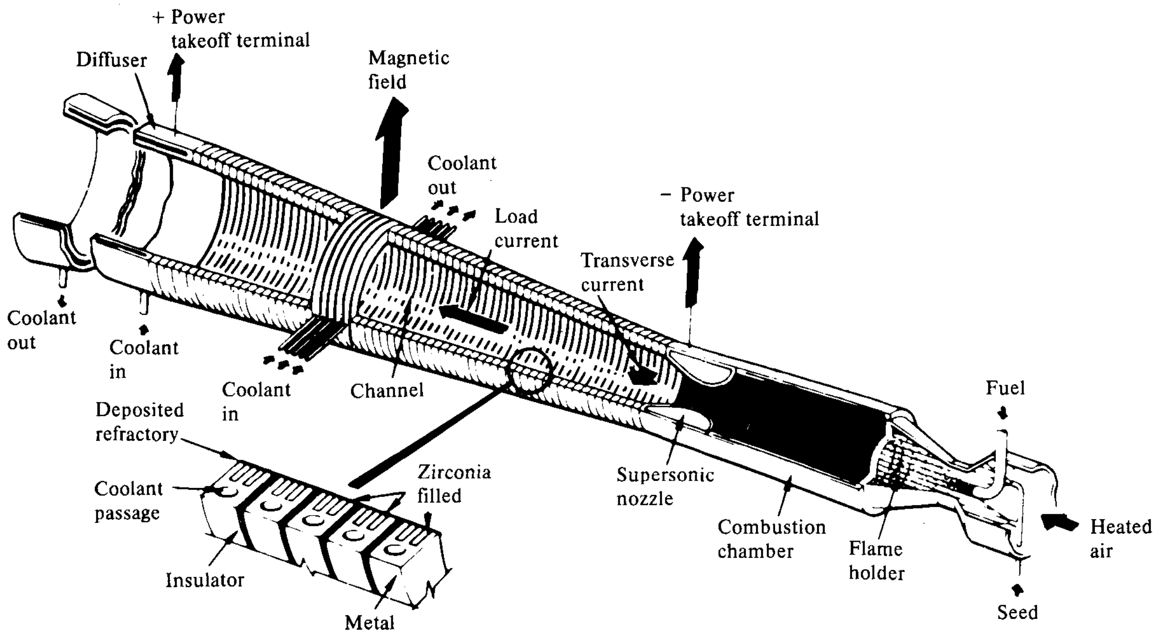
Figure 3
Cross Section of MHD Generator

Typical electrode configuration



[redacted] 25X1

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insulator, as a combustor lining, and as a lining for various downstream components. The Soviet effort in materials research should continue to grow with the rest of their MHD program and will be supported by work in other Warsaw Pact countries, as formal agreements have been signed between the Soviet Union and several of these countries. [redacted]

Poland. MHD technology has been studied in Poland since about 1961, with a shift in emphasis since 1972 from clean-fuel-fired combustors to coal-fired combustors. An MHD flow train at the Institute of Nuclear Research in Swierk is of a sophisticated design with components composed of aluminum oxide, silicon carbide, and magnesium oxide. Channel electrode materials investigated by the Polish include silicon carbide and several combinations of yttrium chromate with various metal oxides. The focus of the Polish work has been combustor technology, which is vital to the success of any MHD pilot plant. Since the Soviets are in the process of developing coal-fired MHD technology, their interest will help to continue the Polish program, as cooperative programs exist between the Soviet Union and Poland. [redacted] 25X1

China. China is actively involved in MHD research at three major institutions. China's large coal resources have been a significant factor in the recent decision to develop coal-fired MHD plants, but existing facilities use petroleum-based fuels. Materials research has been centered on zirconium dioxide and lanthanum chromate channel electrodes and magnesium oxide insulator materials, with additional significant work on combustor materials. Most materials-related work has been carried out at the Shanghai Institute of Ceramics and in the Shanghai silicate industry. China continues to follow MHD developments in other countries and should be able to make use of existing materials technology in its efforts to build a complete MHD pilot plant. [redacted]

[redacted]

United States. Since 1980 the US MHD program has been characterized by a reduction in funding. The focus of the US program has been on components for use in an integrated MHD system, such as combustor work by TRW, generator channel work by AVCO, and downstream component work by the University of Tennessee. Thus, the materials development program has been an add-on to the development of MHD system components. [redacted]

Work at the Montana Energy Research and Development Institute has identified some promising materials for use in high-temperature heat exchangers such as magnesia-alumina spinels. AVCO has run an MHD channel for 1,000 hours using platinum and stainless steel electrodes on a fuel that simulated coal, but little work is being done at present on ceramic electrodes. Work at the University of Tennessee has included the use of aluminum oxide/chromium oxide, because this material is resistant to the corrosion of molten potassium sulfate found in the downstream part of the system. [redacted]

Japan. The slow but continuing and well-planned growth of the Japanese MHD development program is evidenced by the construction of the Mark VII power plant, which is part of the second phase of a program initiated in 1976. The Japanese have shifted their emphasis from oil to coal as a fuel, but some of the work continues to study oil firing. Development of materials for the MHD system is concentrated on channel electrode materials (rare earth oxides, silicon carbide, and chromium oxide) and interelectrode insulator materials (magnesium oxide, zirconium dioxide, aluminum oxide, and Sialon). [redacted] 25X1

India. Since 1980 India has been making steady progress in the construction of a 5- to 15-megawatt pilot plant, but to date it appears the plant has not been put into operation. 25X1 The plant is assumed to have been designed for use with coal-derived liquids, and is designed with a zirconia (ZrO_2) combustor lining and 25X1 aluminum oxide interelectrode insulators. Other materials under study in the MHD program are MgO doped $LaCrO_3$ and $LaCoO_3$-$SrZrO_3$ compounds for use as semihot electrodes. A significant portion of the work on the Indian MHD program has been supported through agreements with the Institute of High Temperatures in Moscow, and as such they probably have access to materials research conducted at the Soviet institution. India appears to be committed to continue MHD research in the near future and will probably start to generate meaningful data from its pilot plant in Tiruchirapalli, but materials-related data take a long time to compile; no significant data is expected in the near term. [redacted] 25X1

The Netherlands. MHD research in the Netherlands has been primarily concerned with closed-cycle MHD power generation, but many of the materials-related problems are the same as those in open-cycle processes. The present design for the closed-cycle generator uses silicon carbide electrodes and boron nitride interelectrode insulators with a coating of silicon nitride protecting the boron nitride. Alumina is used as a thermal insulator on the cold face of the electrodes. This design has not yet been tested, according to available information. The MHD effort in the Netherlands has a long history 25X1 and is expected to continue in the future, with the level of effort dependent upon available funding. [redacted] 25X1

Technology Comparisons

Heat Engine Materials

The USSR lags the United States, Japan, and Western Europe in the development of ceramics for heat engine applications. The Soviet materials approach differs, however, in that they have placed a stronger emphasis on ceramic matrix composites as opposed to monolithic ceramics. The most effort has been devoted to silicon carbide/silicon nitride particulate composites. As a result, Soviet heat engine ceramics have much lower strength than US and other non-Communist country materials. Fiber-reinforced ceramics are also believed by the Soviets to have greater potential than monolithic ceramics. The Soviets are apparently having difficulty in processing silicon nitride to high density and are deficient in injection-molding technology and in techniques for maintaining high purity and high quality throughout all steps in the fabrication process [redacted]

The Japanese are committed to developing high-performance ceramics into a viable industry, with ceramics for automotive engine applications being one of their major markets. Currently, neither Japan nor the United States can claim to be the overall leader in ceramics technology. Japan leads in production of ceramic parts; the United States leads in basic scientific research on ceramics and in purity of powders. [redacted]

There is a perception in the West that the Japanese Government stimulates development activity, guides development in certain directions, and promotes cooperation and technology sharing in ceramics research being conducted by private industry. Although the government is funding research in national laboratories ($100-150 million per year), it provides only a small portion of private industry funding. The Japanese Government views its task as one of assessing long-term economic trends and determining how the nation might benefit the most from these trends. Japanese companies are investing $150-200 million per year of their own funds in ceramics R&D, which amounts to 20 to 50 percent of their total ceramic R&D budget even though sales from fine ceramics account for less than 1 percent of total sales. This combined effort is estimated to be three to six times that of the US R&D effort. [redacted]

West Germany leads Western Europe in the development of structural ceramics but lags the United States and Japan. The West Germans possess an outstanding capability in most aspects of ceramics technology, including materials R&D, production of high-quality powders, and fabrication of ceramic components. West Germany is assessed to have the same technology level as the United States and Japan for design of a ceramic engine but to lack specific plans to do so. Because of uncertainties with reliability, the economics of high-volume production, and proof of improved performance, European manufacturers are not yet willing to commit ceramics to the engine production line. [redacted] 25X1

Sweden ranks next, and the firm ASEA excels in component fabrication. The United Kingdom, which in the late 1960s was the first to become interested in 25X1 the use of silicon nitride for structural applications, has only recently renewed its research interests. UK firms are now promoting the Sialon family of ceramics. Other non-Communist countries, including France, Italy, Ireland, and South Korea, have strong interests. But most of the world is waiting to see how successful the United States and Japan will be in adapting ceramics in heat engines. These developments are expected to be incremental, with the all-ceramic engine being a long-term goal. [redacted] 25X1

In summary, the three principal participants in the competition in the West to develop ceramics for heat engines are the United States, Japan, and West Germany. The United States was the earliest to undertake significant R&D in this area, with large funding commitments beginning in 1971. However, it should not be forgotten that a major contribution toward demonstrating the feasibility of ceramics, particularly silicon nitride, came from the work of Godfrey in the United Kingdom in the 1960s. West Germany initiated an effort in the mid-1970s, and this program has had some successful demonstrations. The last to enter the competition was Japan, the country that poses the greatest challenge to the United States in terms of early commercial application of heat engine ceramics. Figure 4 provides a comparison of this activity. [redacted] 25X1

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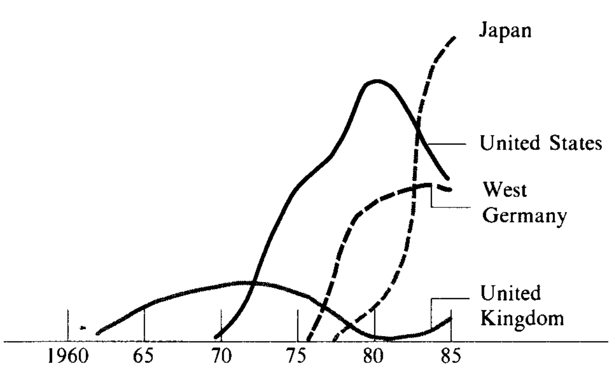
Figure 4
Generalized Comparison of Structural Ceramics Activity for Heat Engines, 1960-85

Relative level of effort



[redacted]

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Armor Materials

The Soviets are assessed to have been the first to field ceramic tank armor. They have possessed this technical ability since the mid-1960s, and the most likely candidates for this armor are aluminum oxide or silicon carbide. The United States is currently developing ceramics of higher ballistic performance for armor applications, namely boron carbide and titanium diboride. These materials are costly to process and have received much less research attention in the USSR. Only since 1983 have the Soviets demonstrated a capability for hot pressing a high-quality boron carbide. Still, either titanium diboride or boron carbide would be of high interest because of Soviet requirements for providing tanks with radiation protection [redacted]

West Germany, Japan, Israel, and France are all on the verge of incorporating ceramics into the main armor system of a tank. The United States technically could have done so already but was not able to accept the disadvantages associated with poor multihit capability and increased cost. [redacted] 25X1

[redacted] 25X1

[redacted] 25X1

Cutting-Tool Materials

With respect to cutting tools, both tungsten carbide and aluminum oxide are widely available and represent very mature technologies. The Soviets have basically the same materials as all other industrialized countries. Overall quality in terms of wear resistance may be lower, but Soviet manufacturing capabilities are not being limited by cutting-tool materials. One technological aspect in which the Soviets hold a lead is shock compression of boron nitride powders to achieve a sintered cutting tool insert with improved toughness. Japan is only examining the feasibility of this technique, whereas the Soviets are in commercial production. [redacted] 25X1

The most significant aspect of ceramic cutting-tool technology that relates to structural ceramics is the development of silicon nitride. Techniques being developed for heat engine applications are equally applicable to cutting tools. That is, improvements in toughness will allow faster machining operations and fuller utilization of numerical control. Japan and the United States can be considered in the forefront of this technology, followed by West Germany. Once these materials are commercially available, they can be expected to be in use by all the industrialized countries. [redacted] 25X1

Japan and the European countries appear to be larger users of ceramic cutting tools than the United States. This is because of the relative difficulty of obtaining tungsten following World War II. For 1982 it is estimated that the value of ceramic tool production in Japan was $5.5 million, while by comparison, the largest European supplier, Feldmuhle A.G. of Germany, alone had a $12 million sales volume. In the United States it is estimated that total ceramic cutting-tool sales amounted to about $20 million, much of which represented imports and constituted only about 1.5 percent of the total cutting-tool market. [redacted] 25X1

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MHD Materials

The USSR has a clear lead in the overall development of MHD power systems, and is only slightly behind the United States in the development of ceramic materials for MHD applications. The slight US lead is the result of the US commitment to the use of coal fuels, which cause more severe erosion and corrosion and therefore require higher performance materials. Currently, Japan is clearly lagging the United States, while both China and India are lagging by a more substantial amount. The potential exists for the Japanese to apply their expertise in heat engine and electronic ceramics to MHD materials developments. As the various countries switch from clean fuels like natural gas to coal, they also will be faced with the need to develop higher performance ceramics. Given the current lack of emphasis in the United States on materials R&D for MHD applications, the present US lead may soon diminish. [redacted] 25X1

Future Prospects

Heat Engine Materials

The uncooled diesel engine is expected to be the first new, commercial engine system to take advantage of the properties of ceramics. The uncooled diesel may become commercially available in the late 1980s or early 1990s. It is anticipated that the uncooled diesel will result in fuel consumption savings of 10 to 15 percent compared with fuel consumption when using current diesel engine technology. The adiabatic diesel and/or automotive gas turbine engines could be introduced commercially as early as the mid-1990s. These engines are expected to provide fuel consumption savings of approximately 20 to 30 percent compared with consumption rates with current diesel engine technologies. Ceramics are unlikely to penetrate the aerospace engine application area to a significant degree until well into the next century. (This latter projection probably does not take into consideration the efforts to develop carbon/carbon engine hardware which, if successful, could see significant application in cruise missile engines within the next 10 years.) [redacted] 25X1

The Soviet Union is expected to remain behind the United States, Japan, West Germany, and Sweden in the application of ceramics for heat engines. The one advantage the Soviets appear to have is in ceramic composites, which may prove to be excellent candidate materials. In spite of the R&D that the Soviets have devoted to composites, this class of materials is still considered to be in only the early stages of development [redacted] 25X1

In the future, unless the United States makes a concerted effort to increase its advanced ceramics program, Japan will take the lead in this technology. Japan already dominates both the supply of advanced ceramic powders and the electronic components business, of which Kyocera has 70 percent of the world market. Japan has a larger, more organized R&D program, and Japanese businesses are willing to accept short-term losses to gain a long-term product market. [redacted] 25X1

Japanese companies are aggressively pursuing a position of world leadership in ceramics. Kyocera is committed to becoming the world leader in manufacturing of heat-resistant automotive and gas turbine engine parts by 1990. Ube Industries, Limited, plans to increase its production of silicon nitride powder from 6 metric tons per year to 100 metric tons by late 1985 [redacted] 25X1 [redacted] 25X1 Similarly, Toyo Soda announced that it would triple its production of fine powders beginning in 1985. [redacted] 25X1

West Germany and Sweden are expected to maintain a high degree of capability in fabricating heat-engine components. Present methods of hot isostatic pressing will probably have to be replaced with more cost-effective techniques, assuming that sufficient property values can be achieved. In Germany, the BMFT has identified further ceramic engine research as one of five major research areas through 1988. Because the West Germans want their automotive industry to remain competitive with the United States and Japan, German automotive companies will probably contract with US and Japanese companies for ceramic engine parts. They will continue, however, to lag the United States and Japan. Sweden will also lag but will manage to have a place in the ceramic industry through the leadership of companies like ASEA and Hoganaes. [redacted]

The United Kingdom will become more active in the near future as it makes up for time lost during the past 10 years when very little effort was being applied in this area. The Collyear Commission has recommended an expenditure of $18 million over a five-year period with over half of this amount to be spent by government. The commission also recommended the establishment of a materials-coordinating group to set up consortiums to develop key technologies. The United Kingdom will still continue to lag the United States, Japan, and West Germany. [redacted]

Armor Materials

The non-Communist world has yet to field a ceramic armor system on a combat vehicle. It is difficult to predict who will be first, but Japan, France, Germany, Sweden, and Israel are all contenders and will probably beat the United States, in spite of all the R&D effort the United States has placed in the area of armor. The presence of ceramic armor on Soviet tanks, while highly likely, must still be confirmed. The only use of ceramics in personnel armor will be in that for aircrewmen and in other limited applications where the excessive weight and restraints on mobility can be tolerated in order to gain the protection. Overall, the adoption of ceramics for armor will be dependent on the decision by system program managers to incorporate these materials at the onset of design. This will allow the problems associated with multihit capability to be minimized through mechanical design techniques. The use of ceramics will be most appropriate where a high degree of ballistic protection is required with a minimum weight penalty and where the increased cost can be tolerated. The adoption of ceramics in heat engines should create a large-volume market that will serve to lower the costs of these materials for armor applications. The most likely candidate, which has excellent potential for both applications, is silicon carbide. [redacted]

Cutting-Tool Materials

The greatest future impact of ceramic materials on the machine-tool industry will be the widespread availability of silicon nitride for cutting-tool inserts. This proliferation will follow the course of ceramic heat-engine materials, since advances in one area will benefit the other. Japan can be expected to try to 25X1 dominate this market, with the United States and West Germany providing the most competition. Because the Soviets have not devoted many resources to development of silicon nitride for heat engines, they cannot be expected to benefit from the use of silicon nitrides as cutting-tool materials. [redacted] 25X1

Table 2 contains some optimistic projections regarding US sales growth of high-performance ceramic cutting tools and the possible cost savings resulting from the substitution of such tools over the period 1990 to 2000. Among the assumptions on which this 25X1 table is based is the estimated potential for ceramic cutting tools to capture 50 percent of the market now held by carbide tools. It is also assumed that both material improvements and process controls will result in improved ceramic cutting-tool reliability. [redacted] 25X1

Because European and Japanese manufacturers have had more experience and greater commercial success to date with high-performance ceramic cutting tools, they may be significantly further along the so-called learning curve than the United States, and thus in a better competitive position to capture much of the future growth projected for this ceramic market. It is anticipated that the beneficial interaction with other high-performance ceramic applications will also be greater in Europe and Japan because of the greater integration of individual ceramic manufacturers. [redacted] 25X1

While there are benefits to substituting ceramic cutting tools for tools made from strategic materials, these benefits have probably been exaggerated. Rather, the principal benefits of increased use of ceramic cutting tools are in areas of improved machining productivity. The future consequences for the US competitive position are difficult to determine but do not appear to be beneficial because of the clear lead of Japan, the possible lead of European countries, and the more advanced R&D being performed in both 25X1 places on ceramic cutting tools. The Soviets can be expected to become more interested in the use of silicon nitride cutting tools to replace tungsten, the supply of which is becoming increasingly critical in the USSR. [redacted] 25X1

Table 2
Projections for US Cutting-Tool Market [a]

Million 1982 US$

	1990	1995	2000
Total US sales of carbide and ceramic cutting tools	704	740	777
Total US sales of advanced ceramic cutting tools as a percentage of carbide plus advanced ceramic tools	5.0	10.8	20.4
Total US sales of advanced ceramic cutting tools	35.2	79.9	158.5
Total US cost savings from substitution of advanced ceramic cutting tools	118	269	533

[a] Source: Charles River Associates, January 1984
NOTE: The demand referred to here is sales of carbide plus advanced ceramic cutting tools. (U)

[redacted]

MHD Materials

The present ranking in MHD materials development, in which the United States holds a slight lead, is expected to continue until 1990, mainly because of the long delay between research advancements and implementation. Slow but steady progress is likely worldwide with the present rate of funding. The performance of existing ceramic candidates has yet to be established for long-term commercial applications, so future needs are not really certain. (Existing generators have not operated long enough [thousands of hours] to determine if these materials will survive in a coal-fired, full-scale MHD environment. Odds are that further improvements will be necessary.) [redacted] 25X1

Japan poses the greatest threat to the US lead in MHD materials development. This postulation is based on Japanese expertise and progress in other aspects of advanced ceramics, namely heat engines and electronics. If Japanese efforts are directed to MHD materials development to an extent comparable to that of heat engines, a significant breakthrough could result. Even so, basic research successes would not impact system developments for the next 20 years. At present, however, the Japanese MHD program is experiencing a decrease in the level of funding, which will have a major impact on the probability of future success. [redacted] 25X1

Technology Transfer

Introduction

The technical exchange of information related to ceramics is believed to have occurred somewhat freely between individuals, through joint ventures, and through governments that have had specific target technologies. The primary motivation in the exchanges appears to have been the promise of commercial gain or the use of information for military applications. Records of transfers are somewhat sparse, primarily because the ceramics field is so large and diverse and because no one was monitoring or recording the multitude of exchanges of all types that were taking place. [redacted] 25X1

In many countries that are leaders in the ceramics field, the training of scientists in leading universities has taken place for many years. An example of this is the current situation in which many Chinese students attend universities in the United States. [redacted] 25X1

A few of the technical transfers are listed below and can be used as a reference to the types of exchanges of which we have record. [redacted] 25X1

Meetings and Conferences

During the conference entitled "Ceramics for High-Performance Applications III—Reliability" held in July 1979, the Japanese firm Kyocera described a breakthrough in very-high-quality, single-phase silicon carbide—FC-201. Dr. Hamand described the Japanese Moonlight Ceramic Heat Engine project regarding gas turbines, magnetohydrodynamics, and waste heat utilization. The West German and US programs were also reviewed. An agreement was signed by the West Germans with the International Energy Agency implementing an agreement for a program of research and development on high-tem perature materials for automotive engines. The US Department of Energy was a signatory and the Japanese planned on joining this interagency agreement to exchange information and papers on ceramics for auto engines and gas turbines. [redacted]

The Fourth International Meeting on Modern Ceramics Technology was held in Italy in mid-1979. The joint effort of the Fiat Research Center and British Ceramics Research Association to find a method for producing and densifying reaction-bonded silicon nitride (RBSN) engine parts was described. During private discussions it was revealed that in Europe hot isostatic pressing was being actively explored for diesel engine parts, and in Japan for magnetohydrodynamic systems. [redacted]

In September 1980 a group of Japanese ceramic engineers visited the USSR for 30 days and toured Soviet ceramic research facilities in Moscow. The flow of information included many Soviet questions concerning West German, UK, and US ceramic programs as well as those of the Soviets and the Japanese. [redacted] [redacted]

USSR. In December 1981 ASEA of Sweden accepted a contract for isostatic presses at Voest-Alpine of Austria to be added to equipment destined for the Soviets. A US company could not bid because of restrictions imposed by the Coordinating Committee for East-West Trade Policy (COCOM). [redacted]

During a visit [redacted] to the Mechanical Engineering Research Institute (MERI), Kiev, a wide variety of analytical equipment, principally of US, West German, and Japanese origin, was observed. The laboratory maintains three US and two Japanese electron microscopes, several X-ray defractometers and nuclear microprobes from West Germany and Japan, and several US differential scanning calorimeters, gas chromatographs, and spectrometers. [redacted] 25X1

Early in 1978, Dorst Company of West Germany made 10 ceramic powder compacting presses for the Soviets. Because of a foul-up, the Soviets insisted on an old design that was no longer in production, and it was made up and delivered. [redacted] 25X1

In late 1978 the All-Union Institute for Design of Heat-Resistant Materials, Leningrad, received a request to design and construct a production shop for the fabrication of aluminum oxide balls up to 70 millimeters in diameter. The balls reportedly were to be used for a new type of Soviet tank armor. [redacted] 25X1 [redacted] 25X1 the Soviets had heard about earlier US work on ceramic ball armor and wanted to follow a similar concept. The Soviets had experimented with porcelain balls, but opted for alumina, which parallels early-to-mid-1970s US Navy ballistic experiments. 25X1 [redacted] 25X1

A delegation of Soviets visited Japan in June 1981 and toured the Kokubu Plant (Kaghoshima Prefecture) of the Kyoto Ceramic Company. During this time this company was engaged in developing ceramic materials for tank armor. [redacted] 25X1 25X1

A Soviet publication containing an article on the penetration of fused quartz provided a clear indication of the Soviet interest in penetration of glass- or ceramic-cored laminated tank armors. From the references, we also inferred that the Soviets had a large data base of Western literature that contained published information on Western weapons R&D. Their work on advanced tubular shaped charges that could be used to defeat laminated glass-cored armors and cause disruption by shockwave interactions implied they were aware of US armor work. [redacted] 25X1 25X1

Most recently the Soviets have expressed interest in obtaining Kyoto developed ceramics for use in Soviet tank engines (for example, pistons) and in ceramics recrystallization technology for armor penetrator applications (for example, projectile tips). At least one Soviet technician is a trainee at a Kyoto ceramics plant. [redacted] 25X1 25X1

Various aspects of Austrian ceramic cutting-tool technology have been transferred to the USSR. In 1981 student exchanges occurred with the Technical University of Vienna in the area of inorganic materials. During this same time this facility was conducting research on hot isostatically pressed ceramic cutting tools of unidentified composition, and a presentation was made on this topic at an international conference in Minsk, USSR. [redacted]

In 1981 the Austrian firm Metalwerk Plansee built a turnkey plant in Kasakhstan (south-central USSR) for producing titanium nitride coatings on tungsten carbide cutting-tool tips. [redacted]

Czechoslovakia. Automated rotary presses, believed used to fabricate ceramics such as tungsten carbide and boron nitride, are being purchased by the Czechoslovaks from the Japanese. The particular presses are manufactured by the Sugahara Company, Ltd. [redacted]

At least two Czechoslovak facilities have obtained Japanese sintering systems. Known facilities include the Tatra Machine Tool Company and the Ceramics Research Institute of the Czechoslovakia Academy of Sciences, both in Prague. The sintering system, produced by the Yoshizuka Company, represents circa 1980 Japanese state of the art. The equipment is alledgedly being purchased for automotive, aircraft, electric motor, valves, and gear applications. The Sumitomo Electric Company and the Mitsubishi Mining and Metals Company use identical equipment for tungsten alloy penetrator manufacture. Clearly, this particular sintering system can be used for the manufacture of numerous components for military equipment and could be used to sinter ceramic as well as metallic parts. [redacted]

China. joint US-Chinese Seminar on Microstructure and Properties of Ceramic Materials held in Shanghai in May 1983 was attended by 15 Chinese and 14 US participants. In addition, there were approximately 20 official Chinese observers and an equal number of unofficial observers [redacted]

There is an active exchange program between researchers of the Shanghai Institute of Ceramics (SIC) and the National Inorganic Research Materials Institute of Japan. [redacted] 25X1 25X1

Implications

The transfer of US technical literature in the area of basic materials science, in which the United States is a clear leader, represents the most significant area of technology transfer. This same type of information is transferred at technical meetings and symposiums. The United States also benefits from foreign R&D in those specific areas in which the United States is behind other countries; some US researchers recognize the positive aspects of technology transfer and view it as a viable part of the overall US program that must not be constrained. In terms of actual hardware, the sale of hot isostatic presses by the Swedish firm ASEA is of greatest significance. These presses are in use around the world and will continue to be available to proscribed nations, as Sweden is not a member of COCOM. [redacted] 25X1 25X1 25X1 25X1

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Implications

Heat Engines

There is no doubt that the United States has accumulated the largest amount of direct experience with ceramic heat engine parts, and has freely shared such experience through open-literature publications. There is also no doubt that all of the US experience has not yet added up to an application that is an unqualified success, yet the effort to develop ceramics for heat engines continues to be reasonably well supported, based on the promise of increased fuel efficiency and potentially lower cost nonstrategic materials. [redacted]

The Japanese efforts to develop ceramics for heat engines, and probably the related programs in other countries as well, have benefited greatly from US research and have had some visible, but again, not unqualified, success. Because of the closed nature of Soviet and other Communist Bloc programs, we do not have enough detail to permit a reasonable judgment of where these countries stand with regard to even the seriousness of their intent to incorporate ceramics into heat engines. We do note that a few ceramic materials, (for example, mullite-reinforced aluminum oxide and silicon nitride–silicon carbide composite) are being investigated by the Soviets, and are not under active study elsewhere. And even though the Soviets have a lead in some aspects of ceramic processing (for example, self-propagating high-temperature synthesis, explosive compaction, and so forth), this alone does not suggest that they are able to make better ceramic components. [redacted]

Advances in design capability and better understanding of the heat engine operating environment developed through experience gained in US programs have had a significant influence on efforts to develop better ceramic materials, not only in the United States but in other countries as well. These efforts have not yet succeeded in producing a hoped-for breakthrough in materials, such as a ductile ceramic, and it has been recognized for some time that the inherent properties of ceramics that make them attractive for high-temperature, corrosive-environment applications lessen such a possibility. Nor is it likely that the flaw-free ceramic will be made soon, since no large-scale process for making materials can yet be controlled well enough to eliminate defects totally. Current ceramic materials development efforts are therefore aimed at producing ceramics with some useful forgiveness, measured in terms of increased resistance to the cracking (toughness). At this time, we also lack component operational experience that would quantitatively relate improved toughness in ceramics to increased heat engine component reliability. [redacted]

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The use of ceramics for heat engines is still a promise that has not been realized. Brittleness will continue to be the dominant ceramic property, and this will govern the acceptance by engine designers to an extent far greater than the accumulation of isolated, one-of-a-kind, hardware operational successes. It will be useful to watch closely the already announced intention of a Japanese auto manufacturer to introduce a ceramic rotor turbocharger in 1986. This date has been slipped several times already, and may be slipped again. [redacted]

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Armor

The aspect of armor technology that will benefit most from ceramic materials is tank armor. Ceramics will allow kinetic-energy munitions (long rod penetrators) to be defeated with less weight penalty than other armor materials. Even though brittleness and associated low multihit capability will continue to be a problem, which must be addressed through proper armor system design, ceramics are ballistically the best all-around armor materials. The USSR is assessed to have already developed and fielded ceramic tank armor. The United States has conducted sufficient materials R&D and exploratory development, but has not devoted enough attention to manufacturing processes related to the total armor system. As a result it appears that Japan, France, Israel, Sweden, or West Germany might field ceramic tank armor before the United States. This will have a significant effect on combat survivability of tanks, particularly against kinetic-energy threats. Other non-Communist countries can be expected to follow the lead countries.

[redacted]

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Cutting Tools

Although future manufacturing capabilities are not critically dependent on ceramic cutting tools, there are some distinct advantages in productivity to be provided by new materials such as silicon nitride. For example, computer numerical control allows increased machining speeds, but without improved cutting-tool materials wear is too severe. Silicon nitride will provide excellent wear resistance and also will be tough enough to permit interrupted cuts to be made. In the near term, this will be the largest market for high-performance ceramics. [redacted]

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MHD

Sufficient ceramic materials R&D has already been conducted to meet the immediate needs of MHD power generator designs. It appears that materials developments are outpacing systems developments. Higher performance ceramics may be needed in the future, but requirements have not yet been identified.

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Appendix B

Glossary

Amorphous	Noncrystalline; having no crystal lattice structure.
Elastic modulus	Elastic stress per unit elastic strain.
Ferrites	Compounds of ferric oxide with another oxide.
Cermet	A material composed of discrete ceramic particles in a metal matrix.
Glacis	The front slope of a combat tank hull.
Green bodies	Compressed ceramic powder prior to agglomeration by sintering.
Hot isostatic pressing	The fabrication of ceramic shapes from powder by the simultaneous application of heat and nominally equal pressure in all directions.
Hot-pressing	The fabrication of ceramic shapes from powder by the simultaneous application of heat and pressure.
Injection molding	A process for shaping ceramic bodies by mixing a plasticizer with the ceramic powder and then injecting it into a die.
Liquid-phase sintering	Sintering of a ceramic body under conditions in which a liquid phase is present during part of the sintering cycle.
Mullite	A form of aluminum silicate having the chemical formula $3Al_20_3$ $2Si0_2$.
Plasma chemical synthesis	A ceramic powder production process in which the compound is chemically formed in the heat of a plasma.
Reaction bonding	The production of ceramics by a process in which sintering and chemical reaction between two or more components take place simultaneously. Also called reaction sintering.
Self-propagating high-temperature synthesis	A ceramic production process in which the elemental components are ignited and the subsequent exothermic reaction chemically forms the ceramic compound by a self-sustaining combustion wave.
Sialon	A ceramic compound composed of silicon dioxide, aluminum oxide, and silicon nitride.

Silicates	A family of compounds containing silicon, oxygen, and one or more metallic elements, with or without hydrogen. Examples are asbestos, mica, feldspar, clays, and cement.
Sintering	The agglomerating of ceramic powders to form a solid body by heating.
Sitall	A Soviet name for glass-ceramic materials that are formed in the glassy state and then heat treated to produce a crystalline material.
Slip casting	A process in which a ceramic slurry (slip) is poured into a plaster mold that absorbs the water, leaving a solid body in the shape of the mold.
Whiteware	Ceramic articles made from clays; earthenware.

This appendix is Unclassified.

Appendix C

Bibliography

The following is a list of documents that will give more information to the interested reader.

Bell, John. "The Ceramics Age Dawns," *New Scientist*, 26 January 1984, pp 10-21. (U)

Katz, R. Nathan. "High Temperature Structural Ceramics," *Science*, Vol. 208, 23 May 1980, pp 841-847. (U)

Katz, R. Nathan. "Ceramics for the Army of the Eighties," *Army Research, Development, and Acquistition Magazine*, Vol. 21, No. 6, November-December 1980, pp 1-4. (U)

McIntyre, Ruluff D. "Ceramics—A Material Whose Time Has Come," *Materials Engineering*, June 1983, pp 19-24. (U)

Sanders, Howard J. "High-Tech Ceramics," *Chemical and Engineering News*, 9 July 1984, pp 26-40. (U)

Charles River Associates Inc., "Technological and Economic Assessment of Advanced Ceramic Materials," CRA Report No. 684, August 1984. (U)

Ceramic Bulletin, Vol. 64, No. 2, 1985. (U)

This appendix is Unclassified.

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