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TITLE: CERAMICS FOR FUSION APPLICATIONS

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CERAMICS FOR FUSION APPLICATIONS

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ABSTRACT
Ceramics are required for a variety of uses in both near-term fusion devices and commercial powerplants. These materials must retain adequate structural and electrical properties under conditions of neutron, particle, and radiation; thermal and applied stresses; and physical and chemical sputtering. Ceramics such as Al₂O₃, Y₂O₃, BeO, Si₃N₄, and SiC are currently under study for fusion applications, and results to date show widely-varying response to the fusion environment. Materials can be identified today which will meet initial operating requirements, but improvements in physical properties are needed to achieve satisfactory lifetimes for critical applications.

INTRODUCTION
As designs for fusion devices become more detailed, requirements and operating conditions for ceramics are specified with greater precision. Although applications vary with the nature of the device, the following items can be considered generic to most designs of advanced fusion machines:
- Ceramics for high heat flux applications of the first wall
- Insulators for lightly-shielded or unshielded magnets
- Electrodes for RF heating systems
- Insulators for lightly-shielded or unshielded magnets

Additional requirements include insulators for neutral beam injectors and divertors, for suppression of magnetohydrodynamic effects, and for diagnostic systems. It has also been suggested that large sections of a reactor structure itself could be made from ceramics, to reduce the radioactivity of the facility [9].

The subject of ceramics for fusion devices has been reviewed earlier by Clinard [1-10]. Examination of these works reveals an interesting history of the fusion ceramics needs and understanding of their operating environment, as well as a record of the slowly but steadily evolving data base. This review is intended to bring the reader up-to-date with respect to these fusion ceramics. Some

[1-10]
on the three major ceramics applications cited above), and to draw the reader's attention to likely areas for future work. It is hoped that the latter will prove useful to researchers seeking to develop new or improved ceramics for fusion applications.

**CERAMICS FOR HIGH HEAT FLUX APPLICATIONS**

Ceramics are in competition with metals and with laminated (perhaps ceramic/metal) systems for use as first wall armor, limiters, divertors, and heat sinks. Ceramics typically offer the following advantages for these applications:

- Low activation
- Low atomic number for minimal plasma contamination
- High operating temperature
- Resistance to chemical sputtering
- Absence of problems with toxicity
- Low cost of starting materials
- Immunity to magnetic forces (if an insulator or semiconductor).

This list represents an impressive argument for the use of ceramics for high heat flux components. However, it must be recognized that the intrinsic brittleness of these materials presents severe problems in a high thermal flux environment, that must be addressed by careful selection of candidate materials and application of brittle material design techniques.

High heat flux materials can be subjected to heat loads ranging from 30 W/cm² (first wall, normal operation) through 100-300 W/cm² (shut-down, thermal excursion, and divertor injection or fusion to the divertor plate) to 10 kW/cm² during brief plasma disruptions. The last value presents severe problems of survivability for most materials, but it is hoped that improvements in instrumentation and feedback systems in advanced machines will allow the worst consequences of disruptions to be avoided.

Requirements for high heat flux ceramics are dominated by the need for good performance under thermal stress conditions, so it is apparent that a candidate material should have high thermal conductivity and a low coefficient of thermal expansion. It prevents crack initiation and propagation. But stress should be high and elastic modulus low, so it is the thermal conductivity and a low coefficient of thermal expansion. It prevents crack propagation to the most important consideration. The needs with regard to the last two parameters are reversed since prevention of propagation often implies unintentional formation of a range of crystal, which will reduce thermal conductivity, it appears that prevention of crack initiation is the more useful consideration here.

Insulator and ceramic materials for this application include SiC, AlN, B,N, BN, and MgO. The first two are noted for good performance under
conditions of high thermal and mechanical stress; alumina is reasonably good under these conditions, and can serve as a standard of comparison for competing materials. MgAl₂O₄ is generally considered somewhat inferior to Al₂O₃ as a structural ceramic, but recent work by Smyth et al. (ref. 11) has shown that careful control of impurity content can result in a spinel with strength comparable to that of alumina. BeO is probably the least attractive of these materials because of its toxicity.

One of the most promising materials for high heat flux applications is a new form of SiC, Hitacem SC-101 (ref. 12). Reduction of impurity content in this sintered product has resulted in a value of thermal conductivity equal to that of aluminum and four times that of conventional polycrystalline SiC (Table 1). Thermal shock studies of SC-101 (ref. 13) show unexpectedly good performance, equivalent to that of fine-grained graphite.

TABLE 1
Comparison of physical and electrical properties of high-purity polycrystalline SiC with those of other materials (ref. 12).

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Conductivity, W/m·K at RT</th>
<th>Electrical Resistivity, Ω·cm, at RT</th>
<th>Thermal Expansion Coeff., 10⁻⁶/°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hitacem</td>
<td>270</td>
<td>10.1</td>
<td>3.7</td>
</tr>
<tr>
<td>SC-101</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structural</td>
<td>2.5</td>
<td>1.1</td>
<td>1.2</td>
</tr>
<tr>
<td>SiC</td>
<td>100</td>
<td>10.1</td>
<td>0.6</td>
</tr>
<tr>
<td>Alumina</td>
<td>100</td>
<td>10.1</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Lifetime of plasma-facing components may be relatively short because of sputtering erosion, but it is nevertheless envisaged that neutron fluences in the sufficient to cause significant structural changes. Ceramics vary widely in their response to irradiation damage, with some being badly degraded by doses as low as 10¹⁴ n/ cm² and others demonstrating little change, in an environment in properties at 10⁶ times that dose (ref. 14). SiC falls in the middle range, with moderate swelling, little strength change, and (along with most insulating
ceramics) a reduction in thermal conductivity [ref. 1]. Swelling of this ceramic at temperatures below 1300 K appears to saturate at low doses, implying resistance to gross damage at very high fluences.

Laminar structures (e.g., ceramic bonded to a water-cooled metal substrate) offer an attractive combination of properties, and are under study for use in near-term fusion devices. However, problems resulting from differential swelling of the two materials, plus damage associated with the interface, mitigate against use of such systems where neutron fluxes are high. An example of the consequences of differential swelling for an otherwise attractive pair of materials (SiC on graphite) is shown in Fig. 1. Here the SiC layer swelled to a saturation value of 1.5 vol% early in the irradiation test, while the graphite progressively densified to a value of 2 vol% greater than that of the as-fabricated material. The result was almost complete delamination, which in a fusion device could lead to further destruction of the protective layer and consequent exposure of the graphite to chemical attack from the hydrogen isotopes of the fuel.

![Fig. 1](image)

**Fig. 1.** Microcracking at the interface between SiC and graphite after irradiation to 10^24 n m^-2 at 140 K (ref. 14).

Composite ceramics can offer improved structural properties for high heat flux applications, but are subject to irradiation-induced degradation from another source, namely, differential swelling between additive phase and matrix. The consequence can be high internal stresses with ultimate separation along phase boundaries. A similar problem affects ceramics with zinc-blende crystal structures such as AlN and ZnS, where intergranular swelling within each grain can generate damaging levels of stress [ref. 15] and limit materials lifetime. Since anisotropy can be strongly temperature-dependent,
(ref. 16), it is necessary to specify irradiation temperature before the extent of this problem can be judged. In both composite and anisotropic ceramics some relief should be available by using fine particle or grain sizes.

If it becomes possible to reduce sputtering (for example, by reduction of plasma edge temperature), then it will be desirable to have ceramics capable of sustaining very high damage levels. Unfortunately, there are essentially no data available for these materials beyond about 20 displacements per atom (dpa), which is equivalent to a year's exposure at the first wall of a 2 MW/m² reactor, whereas lifetime of the facility might be twenty years or more. This is an area where further studies are clearly needed.

Development of ceramics that can withstand intense damage levels will require both a fundamental understanding of damage effects and innovative materials selection. An example of the latter is the use of materials that can periodically be restored to their undamaged condition by thermal cycling. One possibility is to allow first wall materials to operate at very high temperatures (utilizing cooling by radiative means only), but defect aggregates such as voids are notoriously difficult to remove by annealing.

An intriguing idea is to use materials that can exist in either crystalline or amorphous forms, and to vary the operating temperature so that damage acquired at elevated temperatures can be erased by periodic operation at lower temperatures where damage causes conversion to the amorphous condition. This suggestion has recently been proposed for metallic systems (ref. 17), but since ceramics can also undergo such temperature-dependent transitions (e.g., ref. 18), the principle can also be applied here. The cyclic nature of operating temperatures for high heat flux components makes this approach particularly appropriate, but accommodation would have to be made for the characteristic low thermal conductivity of ceramics in the disordered state.

DIELECTRICS FOR RF HEATING SYSTEMS

Most conceptual designs for fusion devices call for the use of RF beams to heat the plasma. Possible coupling modes and their operating frequencies include ion cyclotron (about 10⁸ Hz), lower hybrid (10⁷-3 x 10⁸ Hz), and electron cyclotron (10⁷ Hz). Corresponding methods for transmitting the energy to the first wall and plasma might involve coaxial cables, waveguides, antennas, and/or windows. Applications for ceramics might therefore include stacks for coaxial cables, a high dielectric constant filler for waveguides, antenna standoffs, and windows.

The most difficult of these applications appears to be windows for use at millimeter wave frequencies (3 x 10⁸ Hz). The failure mode is likely to be thermal stress-induced fracture resulting from absorption of energy from the beam; thus materials requirements are high strength, load dimensional
stability, high thermal conductivity and good transmissivity. A compliant mounting system for the window could significantly reduce thermomechanical stresses.

The function of the window is to separate the first wall environment (including residual J-T fuel) from the RF source and the other remote systems of the facility. The portion of the waveguide from the source to the window may be filled with SF$_6$ gas to improve transmissivity. Location of the window with respect to the plasma has not yet been determined, but since best waveguide performance will be attained if the window is located near or at the first wall, severe neutron and other fluxes must be anticipated.

The window itself will probably be of laminar design, with a flowing coolant between the two elements. Candidate materials include $\text{BeO}$ (primarily because of its high thermal conductivity), $\text{MgO}$ (presently used for gyrotron windows), $\text{MgAl}_2\text{O}_4$ (because of its generally good radiation resistance), and $\text{Si}_3\text{N}_4$ (an insulator known for its high strength and thermal shock resistance). Conventional $\text{SiC}$ is a semiconductor, but the high-purity form discussed earlier demonstrates good insulating properties (Table 1) and is therefore also considered a candidate material for this application.

Little is known about the effect of neutron damage on dielectric losses, which are proportional to the product of loss tangent (tanδ) and dielectric constant ($K$). First results at mm wave frequencies for heavily-damaged ceramics, recently obtained by Frost (ref. 19), are shown in Table 2. It may be seen that both $\text{Al}_2\text{O}_3$ and $\text{BeO}$ suffered a doubling of lossness at room temperature as a result of this exposure. This work also identified a potential problem not heretofore considered: the consequences of reflection of a portion of the intense beam back to the source, as a result of detuning of the window induced by changes in dimensions and dielectric properties.

Calculations by Fowler (ref. 20) have shown that under realistic conditions a doubling of $\text{Ktanδ}$ leads to an increase of a factor of two in energy absorbed, and that in turn results in a doubling of stress. The consequences to window lifetime can be serious: Frost used results from Ferber et al. (ref. 21) to show that the lifetime for a $\text{BeO}$ window can be reduced from one year to less than a day by such a doubling of stress.

Additional significant degradation will result from the reduction of thermal conductivity that accompanies irradiation damage in most ceramics. This can be partially offset by the increase in strength that often accompanies formation of defect aggregates such as dislocation loops and voids (ref. 22). However, in polycrystalline forms of materials such as $\text{Al}_2\text{O}_3$ and $\text{BeO}$ with non-negligible crystal structures, this strengthening can be more than offset by stresses resulting from in situotropic swelling.
Even if it is possible to locate RF windows in areas where neutron doses are low, a considerable increase in lossness may result. Working in the range of approximately $10^4-10^6$ Hz, Fowler (ref. 20) found increases of as much as an order of magnitude in $\text{Al}_2\text{O}_3$ at $10^{22}$ n/m$^2$, and a dependence on neutron energy. More recently, Pells et al. (ref. 22) assessed the behavior of two forms of alumina plus aluminum oxide nitride at doses up to $10^{24}$ n/m$^2$ between 1 and 65 MHz and reported complex and sometimes large dependencies on dose, frequency, and nature of the starting material.

TABLE 2
Room-temperature dielectric properties of alumina and beryllia at 95 GHz after irradiation to $8\times10^{21}$ n/m$^2$ at 650 K (ref. 19).

<table>
<thead>
<tr>
<th>Material and Condition</th>
<th>Dielectric Constant (K)</th>
<th>Loss Tangent (tanδ), $\times10^{-4}$</th>
<th>Ktanδ, $\times10^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Al}_2\text{O}_3$:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>control</td>
<td>10.28</td>
<td>4.5</td>
<td>4.6</td>
</tr>
<tr>
<td>irradiated</td>
<td>10.10</td>
<td>9.7</td>
<td>9.8</td>
</tr>
<tr>
<td>$\text{BeO}$:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>control</td>
<td>6.65</td>
<td>3.0</td>
<td>5.3</td>
</tr>
<tr>
<td>irradiated</td>
<td>5.34</td>
<td>17.4</td>
<td>10.2</td>
</tr>
</tbody>
</table>

It can be seen from this discussion that many facets of radiation response come into play when considering the window application. Changes in strength, density, and thermal conductivity are fairly well understood (refs. 14 and 23); however, a fundamental understanding of loss mechanisms in irradiated ceramics is needed, both with respect to post-irradiation effects and to temporary changes concurrent with generation of structural damage and absorption of ionizing energy. Once that is in hand, it should be possible to develop improved forms of candidate materials for this application.

If it is necessary to locate RF windows at the first wall of a fusion device, then irradiation by other than neutrons must be considered. Ion bombardment may have deleterious effects both from implantation (perhaps leading to blistering) and from physical erosion (sputtering). Chemical erosion, although much less than that for elemental materials such as graphite, might present a problem at elevated temperatures. Finally, deposition of impurity layers could reduce transmissivity or increase reflectivity. It may
be desirable to provide localized shielding for the window (by either physical barriers or magnetic fields) in order to reduce the deleterious consequences of the first wall environment.

INSULATORS FOR LIGHTLY-SHIELDED MAGNETS

The intense magnetic fields required for containment and shaping of the plasma are generated by either cryogenic or normal (near-room temperature) coils. The former have damage-sensitive components such as the superconductor, its stabilizer, and polymeric insulators, so that shielding is required. The latter type of magnet uses a copper alloy conductor, water cooling, and ceramic insulators, so that reasonably good radiation resistance can be anticipated. In principle the ceramic insulator could be either in bulk or powder form; however, concerns about electrical resistivity and thermal conductivity of the latter (ref. 24) indicate that only the bulk form should be used. Coils of both types are massive, difficult to repair, and represent half the cost of an advanced fusion device; thus the materials chosen for this application should if possible last the lifetime of the machine.

There is a trend toward compact reactors, which implies less shielding and greater use of normal coils. In some designs the inner conductor is just behind the first wall, so that neutron fluxes are high. However, the first wall serves as a shield for particulate and electromagnetic radiation. A lifetime dose of 100 dpa or more is likely for the inboard ceramic insulators of such magnets.

Candidate materials for this application include Al₂O₃, MgAl₂O₄, SiC and Si₃N₄. Alumina suffers from anisotropic swelling (refs. 15 and 16), so that high grain boundary stresses and ultimately a catastrophic loss of strength restrict lifetime for this ceramic to doses on the order of 20 dpa. Nevertheless, its high state of development and good starting strength (necessary to resist large magnet forces) makes this material a likely choice for intermediate-term machines.

Tests of spinel to a damage level of 20 dpa show excellent resistance to neutron irradiation. At temperatures of 660 K and greater, swelling of single-crystal material is near zero and strength is actually enhanced by irradiation damage. This behavior is attributable to the fact that most irradiation-induced defects recombine harmlessly, while the remaining precipitate into dislocation loops whose strain fields apparently strengthen the material by crack deflection (refs. 14 and 15).

Polycrystalline spinel also performs well, but shows a lower level of swelling and less strength enhancement than does its single-crystal counterpart (ref. 14). Transmission electron microscopic (TEM) examination reveals the presence of small voids formed near (but not in) grain boundaries after irradiation at
elevated temperatures, apparently as a result of preferential annihilation of nearby interstitial atoms at grain boundaries (ref. 25). This unusual microstructure is shown in Fig. 2. At lower irradiation temperatures, areas near boundaries are denuded of the interstitial dislocation loops that are formed within the grains (ref. 26). It is not clear whether these grain boundary effects are intrinsic to polycrystalline spinel or whether adjustments in composition could mitigate the problem.

Fig. 2. Voids arrayed near grain boundaries in MgAl₂O₄ after irradiation to 2×10^{26} n·cm⁻² at 1100 K.

The improvement of strength or fracture toughness that accompanies accumulation of neutron irradiation damage in cubic polycrystalline ceramics or single-crystal materials is a phenomenon of great importance to all fusion applications. Examples of results obtained, for several single-crystal materials and test temperatures, are shown in Table 3 along with a description of the dominant damage microstructures observed by TEM. One of two mechanisms is thought to be responsible for the observed enhancement of mechanical
properties: either crack deflection by strain fields around dislocation loops, or crack pinning, blunting, branching, and jogging as a result of passage through an array of fine voids (ref. 27). Considering that these improvements in mechanical properties are observed in unoptimized materials, there appears to be ample opportunity for further exploitation of these strengthening phenomena.

TABLE 3

Changes in strength and fracture toughness, along with characteristic damage microstructures, resulting from elevated-temperature irradiation to a dose of $2 \times 10^{26}$ n/m$^2$.

<table>
<thead>
<tr>
<th>Ceramic (ref.)</th>
<th>Irradiation Temp., K</th>
<th>Change in Strength</th>
<th>Change in Fracture Toughness</th>
<th>Damage Microstructure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al$_2$O$_3$ (ref. 27)</td>
<td>925</td>
<td>--</td>
<td>+20%</td>
<td>38Å dia voids</td>
</tr>
<tr>
<td>Al$_2$O$_3$ (ref. 27)</td>
<td>1100</td>
<td>--</td>
<td>+110%</td>
<td>90Å dia voids</td>
</tr>
<tr>
<td>MgAl$_2$O$_4$ (ref. 14)</td>
<td>680</td>
<td>+42%</td>
<td>--</td>
<td>200Å dia interstitial dislocation loops</td>
</tr>
<tr>
<td>MgAl$_2$O$_4$ (ref. 14)</td>
<td>315</td>
<td>+75%</td>
<td>--</td>
<td>300Å dia interstitial dislocation loops</td>
</tr>
</tbody>
</table>

It is difficult to conduct neutron irradiation tests at temperatures close to that of a magnet's water coolant, using a sodium-cooled fission reactor as a test facility. (For example, the sodium in the EBR-II reactor operates at about 650 K.) Nevertheless, in one instance it was possible to carry out a long-term test at 410 K in a water-cooled reactor, to a damage level of 25 dpa (ref. 26). This work showed that while spinel was strengthened, a small amount of swelling (0.3 vol%) did occur. If tolerable swelling is taken to be 3 vol% (ref. 24), a relatively short lifetime of 4.3 y is calculated for a 3 MW/m$^2$ machine (ref. 10). It is apparent that materials must be developed with even greater dimensional stability than that of conventional spinel, in order to meet the needs of lightly-shielded magnets.
FISSION VS. FUSION NEUTRON DAMAGE

It is important to consider differences between fission neutron (≈1 MeV) and fusion (14 MeV) neutron damage, since the high-dose data base is totally from fission reactor studies yet the environment of a D-T reactor is dominated by a softened fusion neutron energy spectrum.

Higher-energy neutrons have the potential for creating damage cascades different from those formed by fast fission neutrons, and also generate much greater quantities of transmutation products. The former topic is currently being assessed by Kinoshita (ref. 28) who has irradiated a large number of ceramics in the RTNS-II 14 MeV neutron source. Early results have shown the presence of contrast effects in Cr<sub>2</sub>O<sub>3</sub> that represent the first reported observations of cascades in ceramics.

Transmutation products are generated relatively rapidly in the environment of high-energy fusion neutrons. Of particular concern are the transmutation gases H and He, which could significantly affect damage microstructures. However, metallic products may also play an important role in altering electrical properties or insulators. Calculated concentrations of several transmutation products for four ceramics (ref. 3) after exposure for a year at the first wall of a 2 MW/m<sup>2</sup> machine are shown in Table 4.

TABLE 4
Transmutation products (in atomic parts per million) for four candidate fusion reactor ceramics (ref. 3).

<table>
<thead>
<tr>
<th></th>
<th>SiC</th>
<th>BeO</th>
<th>Si&lt;sub&gt;3&lt;/sub&gt;N&lt;sub&gt;4&lt;/sub&gt;</th>
<th>Al&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>880</td>
<td>206</td>
<td>1334</td>
<td>912</td>
</tr>
<tr>
<td>Helium</td>
<td>3190</td>
<td>5040</td>
<td>1516</td>
<td>1574</td>
</tr>
<tr>
<td>Carbon</td>
<td>--</td>
<td>1138</td>
<td>656</td>
<td>1248</td>
</tr>
<tr>
<td>Magnesium</td>
<td>916</td>
<td>--</td>
<td>910</td>
<td>368</td>
</tr>
</tbody>
</table>

It is of critical importance to carry out simulation tests of transmutation effects in ceramics, both to obtain experimental data for a fusion environment and to establish correlation parameters for the present fission reactor-generated data base. One approach (ref. 10) is to introduce the transmutation products H, He and C by irradiating isotopically-tailored ceramics in a
mixed-spectrum fission reactor. In this scheme displacement damage would be
generated by the fast neutrons, and transmutations by the thermal neutrons. The
key reactions to be utilized are \(^{14}\text{N}(n,\mu)^{14}\text{C}\) and \(^{12}\text{O}(n,a)^{14}\text{C}\). A study of this
type may require special fabrication techniques to assure that adequate
concentrations of the special isotopes are retained in the oxides, nitrides,
and/or oxynitridos chosen for evaluation.

REFERENCES
Eng. and Design/Fusion, 2 (1985) 111-143.
2. S. Holmes-Siedle, Radiation effects in the fusion power programme, Nature,
3. H. Revel and S. R. Hopkins, Ceramic materials for fusion, Nuclear
4. W. Clinard, Jr., Electrical insulators for magnetically-confinement fusion
5. W. Clinard, Jr., Ceramics for applications in fusion systems, J. Nucl.
8. W. Clinard, Jr., G. F. Hurley and R. W. Kiiffky, Ceramics for fusion
9. P. Bells, Radiation effects in ceramic materials for fusion reactors, J
10. W. Clinard, Jr., Ceramics for fusion devices, J. Mater. for Energy
11. R. Smyth, O. Moreto and W. C. Seymour, Engineering ceramics of magnesium
aluminum oxide, work presented at the Annual Meeting of the American Ceramic
Society, Chicago, IL, April 30, 1986.
12. T. In and O. Asai, Development of SiC ceramics having high thermal
conductivity and electrical resistivity, Japan Fine Ceramics Association
Report. vol. 1 no. 4; see also Y. Takeda, K. Usami, K. Nakamura, J. Ogihara,
T. Maeda, T. Miyoshi, S. Shinohara and M. Ura, Grain-boundary structure of
highly resistive SiC ceramics with high thermal conductivity, Advances in


