SPECIAL PURPOSE MATERIALS FOR FUSION APPLICATION[†]

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Abstract

Originally in 1978 the Special Purpose Materials Task Group was concerned with tritium breeding materials, coolants, tritium barriers, graphite and silicon carbide, ceramics, heat-sink materials, and magnet components. Since then several other task groups have been created, so that now the category includes only materials for superconducting magnets and ceramics. For the former application copper-stabilized Nb_3Sn (Ti) insulated with polyimides will meet the general requirements, so that testing of prototype components is the priority task. Ceramics are required for several critical components of fusion reactors either as dielectrics or as a structural material. Components near the first wall will receive exposures of 5-20 MW-year/m². Other ceramic applications are well behind the first wall, with lower damage levels. Most insulators operate near room temperature, but ceramic blanket structures may operate up to 1000°C. Because of a meager data base, one cannot identify optimum ceramics for structural application; but $MgAl_2O_4$ is an attractive dielectric material.

[†]Research sponsored by the Office of Fusion Energy, U.S. Department of Energy under contract DE-AC05-84OR21400 with the Martin Marietta Energy Systems, Inc.

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1.0 Introduction

In the development of materials for fusion reactors, primary emphasis has been placed on the blanket structural material and on plasma-materials interactions; but there are many other materials problems that must be solved if commercial fusion power is to succeed. Originally, the classification "Special Purpose Materials" included breeding materials, coolants, materials for tritium service, graphite and silicon carbide, ceramics, heat-sink materials, and magnet materials. More recently in the United States, other groups have been set up to study solid breeder materials, high heat-flux materials, and magnet structural materials. In addition, materials for tritium service now come under the purview of the Tritium Systems Test Assembly (TSTA) program. The result is that Special Purpose Materials now encompass superconductors, stabilizers and insulators for superconducting magnets, and ceramics of all kinds. Even with more limited scope, a broad spectrum of components and materials are included.

Until recently Special Purpose Materials have suffered because service requirements were poorly defined, and the possibility existed for design solutions to many of the materials problems. In current designs more

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attention has been given to components requiring special purpose materials, so that operating conditions have become better defined. This paper addresses these materials, their operating conditions, and the present understanding of the lifetimes of favored candidates.

2.0 Superconducting magnet materials

Superconducting magnets will be required for magnetically confined commercial fusion reactors. These magnets will be subjected to neutron and gamma radiation damage to the highest levels allowed by the lifetimes of the component materials. The reason is that the reactor cost and performance are very sensitive to the size of the superconducting coils and the thickness of the blanket and shield between the plasma and the coils. As an example, cost trends from the ORNL DEMO Systems Code suggest that the cost of increasing the inboard shielding of the Fusion Engineering Device (FED) is \$5 million/cm. The exact costs vary from design to design, but all reactor studies to date have shown similar trends. Therefore, to minimize reactor costs, the magnet components in the reactor-inboard zone will be as lightly shielded as possible, and exposed to the highest allowable doses.

For cost-effective design, the relative sensitivities of the various magnet components to radiation must be known accurately, especially those that set exposure limits. The approximate ranking is given in Table 1. Present magnets are made with glass-reinforced epoxy resins, contain a 25% excess of copper, and might be annealed five times over their lifetime. For this reason, the irradiation behavior of the epoxies and copper with intermediate anneals to room temperature or perhaps 100°C needs to be

Table 1. Approximate radiation lifetimes of
superconducting magnet materials

Material	Lifetime fluence ^a (neutrons/m ²)
Epoxies (G-11)	$\sim 1 \times 10^{22}$
Copper (25% ρ increase - 5 cycles)	$\sim 1 \times 10^{22}$
Nb ₃ Sn	$\sim 1 \times 10^{22}$

Polyimides	$\sim 2 \times 10^{23}$
Copper (100% ρ increase - 10 cycles)	$\sim 2 \times 10^{23}$
(Heat load limit)	$\sim 2 \times 10^{23}$

Nb-Ti	$> 1 \times 10^{24}$
Inorganic insulators	$> 5 \times 10^{25}$
Structural metals	$> 1 \times 10^{26}$

^a 1×10^{22} neutrons/m² (E > 0.1 MeV) $\approx 1 \times 10^{-3}$ dpa in copper. In EPR, 1×10^{22} neutrons/m² will deposit $\sim 10^7$ Gy of ionizing energy in a typical polymeric insulator.

known very accurately. A second type of magnet could be designed with a 100% excess of copper and with polyimide insulation. This magnet would be more difficult to fabricate, but would have a much greater lifetime, and might be limited by the ability to remove heat deposited by the irradiation. The limit on average might be equivalent to that associated with 10 kW of total heat generation in the magnet coils, i.e., about 10 MW of electrical energy to drive the refrigeration system. However, it should be noted that unirradiated strength of polyimides is considerably less than that of epoxies. There is also the possibility of keeping 25% excess copper and using a cable-in-conduit concept or superfluid helium to maintain stability with higher resistivity.

The limits on organic insulation shown in Table 1 are derived from the work of Coltman and Klabunde [1] and Hurley and Coltman [2], who measured the bend strength of samples in liquid nitrogen after ~ 4 K irradiation and warm-up to room temperature. (These properties were found to be more affected by irradiation than were electrical properties.) More recently Schmunk et al. [3] found that composites of epoxy resins with S-glass cloth (boron-free) showed good cyclic compressive strength after irradiation at 50°C to a gamma dose of 3.2×10^9 Gy and a fast-neutron fluence of 3.5×10^{23} neutrons/m² ($E > 1.0$ MeV), and tested at room temperature. It is difficult to make comparisons between these two sets of data, since temperature and stress state are greatly different; however, it appears that the lifetime limits are much higher in "unbonded" applications when stresses are purely compressive than in "bonded" applications where multiaxial stresses occur. The limits shown in Table 1 apply to the more restrictive "bonded" application.

If aluminum were used instead of copper as the magnet stabilizer material, there would be no lifetime radiation limit, because intermediate anneals to room temperature will restore the unirradiated conductivity. However, its resistivity rises about 2.5 times faster than copper, and the frequent anneals might create an operating burden. Furthermore, the very pure aluminum required has low strength, so that the fabrication of the superconducting composite would be difficult.

The irradiation behavior of superconductors is somewhat better understood than that of organic insulators or stabilizers. Conventional NbTi conductor is not sensitive to irradiation, and damage effects in this material can be ignored. High-field superconductors such as Nb₃Sn are much more sensitive to irradiation. Fluences in the range $1-4 \times 10^{22}$ neutrons/m² cause significant disordering of the compound lattice with a loss of critical current and a reduction of the critical temperature. This damage is not annealed out near room temperature, so the damage must be considered to be permanent. Until recently most irradiations of Nb₃Sn were done at room temperature. Data to end-of-life fluences at 4 K are badly needed.

In view of the great economic importance of the radiation lifetimes of superconducting magnet materials, much more work is needed to more accurately define performance limits. A new National Low Temperature Neutron Irradiation Facility (NLTNIF) is being built in the Bulk Shielding Reactor (BSR) at the Oak Ridge National Laboratory [4]. It will be used for the study of irradiation effects in magnet component materials and will provide the data needed for more accurate assessments of the lifetime fluence capabilities of superconducting magnets.

3.0 Ceramic applications in fusion reactors

Ceramics are required in a variety of fusion-reactor components either as a dielectric of some type or as a structural material. Their operating conditions vary widely, ranging from near room temperature to very high temperatures and from first-wall fluxes to low or no flux. Table 2 gives a listing of potential ceramic components in toroidal and mirror reactors. It also gives an indication of the environment and lists some of the candidate materials. In some cases components containing ceramics in high-flux regions are designed to be easily replaceable, so that required lifetimes may be only one to two years, to correspond to scheduled routine maintenance time intervals. Space does not permit a full discussion of all components listed in Table 2; the most difficult components, that is, magnet insulation, RF windows and feed-throughs, dielectric breaks, and structural ceramics, will be discussed. Applications, candidate materials, and anticipated performance of fusion ceramics have been recently reviewed elsewhere [5].

3.1 Magnet insulation

Many magnets for fusion application consist basically of water-cooled copper. While it would be desirable to insulate all such magnets with glass-fiber-reinforced organic insulators, neutron fluxes and fluences are often too high. In particular, magnets for compact reactors, end-cell coils in mirrors, and plasma shaping and control coils may have little or no shielding and require the use of ceramic insulators. It should be noted that magnet insulators will probably have to retain acceptable properties for the lifetime of the fusion device.

Some of the design options for TFEX [6] and the recently completed FED-R design rely on copper TF coils. The FED-R window-frame toroidal field coils are shown in Fig 1. In these cases, thinner shields

Table 2. Qualitative descriptions for ceramic components of fusion reactors

Component	Primary required property	Temperature^a (°C)	Neutron flux range^b	Typical candidate ceramics
Magnet insulation	Electrical resistance	50	Moderate to high	MgAl ₂ O ₄ , Al ₂ O ₃
RF-launcher windows -feedthrough	Loss tangent; thermal conductivity	20-150 20-50	High Low to moderate	BeO, Al ₂ O ₃ , MgAl ₂ O ₄ , Si ₃ N ₄
Drift pump coil insulator	Semiconductor; neutron shielding	20-50	Moderate	PbO
Dielectric break, tokamaks	Mechanical strength	50-500	Moderate to high	Al ₂ O ₃ , MgAl ₂ O ₄
Beam-line insulators	Dielectric strength	50-?	Moderate to low	Not yet specified
Direct converter insulator, mirrors	Mechanical strength; dielectric strength	50	Low	Al ₂ O ₃ , MACOR
Structural ceramics	Strength; leak-free structures	300-1000	High to moderate	SiC, C, Si ₃ N ₄
Divertors, limiters, armor	Low sputtering; thermal conductivity; strength	50-m.pt.	High	C, SiC, BeO
Low-Z coatings	Low atomic number; low sputtering	50-500	High	C, TiC, BeO, SiC, Si ₃ N ₄

Table 2 (continued)

Component	Primary required property	Temperature ^a (°C)	Neutron flux range ^b	Typical candidate ceramics
Diagnostic systems	Various — dielectric strength — transmission coefficient	50+	High	Not yet specified
HHO channel insulation	Compatibility with liquid metal and structural alloy	300–500	High	Y ₂ O ₃
Tritium breeder	Lithium atom density	200–600	High to moderate	Li ₂ O
Neutron multiplier	Neutronic properties	200–600	High	PbO, BeO
Neutron reflector	Neutronic properties	50–500	Low	C
Neutron shield	Neutronic properties	50–500	Moderate to low	B ₄ C, TiH ₂

^aTemperature range of many components will be higher in power reactors.

^bQualitative ranking of neutron flux taken as "high" for first wall, "low" for deep in the shield zone. "Moderate" is used for the blanket region of power reactors or front of the shield in experimental reactors without tritium breeding blankets. The first-wall flux may be up to 5 MW/m^2 (2×10^{19} neutrons/m²·s); "moderate" values are lower by at least one order of magnitude; "low" values, lower by at least two orders of magnitude.

(ALL DIMENSIONS IN METERS)

may yield lower capital cost; and the magnets demand less of technology than would superconducting coils. Ceramic insulators are specified for high radiation resistance, but the question of the feasibility of this approach includes the need for data on the rate of loss of critical properties with irradiation and the adherence of the ceramic to the copper conductor under cyclic operation and neutron bombardment. Should this option prove viable, the potential simplicity of applying the insulator as a thin, flame-sprayed coating is attractive.

One demanding application for an electrical insulator is in the copper insert coils of the choke coils of recently designed tandem mirror reactors (TMR). These coils must operate without significant shielding from the plasma. In the MARS design, shown in Fig. 2 [7], the diameter of the innermost conductor of this coil is 0.6 m. The temperature is 125°C; the neutron flux is 1×10^{19} neutrons/m²·s, and the deposited energy rate is 1×10^4 Gy/s. Only ceramic insulation can provide an adequate service life in this environment. Irradiation tests of MgAl₂O₄ have shown a swelling of 0.8% after a dose of 2×10^{26} n/m² at 430 K [8]. On the basis of this result, the MARS study selected spinel as the insulator of choice. With a limit of 3 vol % swelling, a linear extrapolation of swelling with dose indicates a projected lifetime of 5 to 8 MW·year/m² for this application. The compressive strength of spinel before irradiation is adequate to transfer the hoop stress from the coil to the support structure. Since bend strength is increased about 20% after exposure to the above fluence [7], degradation of mechanical properties does not appear likely.

Some reactor designs based on alternative plasma-confinement concepts use major magnets unshielded or lightly shielded from the plasma. Normal conducting coils of the Compact Reverse Field Pinch

reactor are separated from the first wall by a blanket but without an additional magnet shield. The neutron flux is then about 1% of the first-wall flux, and ceramic insulation is indicated. In the Riggatron concept the normal coils do not even have the advantage of the blanket shielding, but they must bear essentially the unshielded first-wall flux.

The requirements of the insulation for the choke-coil normal insert in the TMR are the best defined requirements for the development of ceramic insulation. Furthermore, the degradation of this insulator probably will limit the lifetime of the coil insert. These conditions set a worthy goal for the more thorough characterization of the effects of irradiation on a ceramic insulation and define the need to develop a more irradiation-resistant ceramic.

3.2 Ceramic components for RF systems

The use of rf power has been proposed for plasma heating, conditioning, and current drive. There are three frequency ranges of interest, ion cyclotron (ICRF), lower hybrid (LHRF), and electron cyclotron (ECRH). Their approximate frequency ranges are:

ICRF	10^7 – 10^8 Hz
LHRF	10^9 – 10^{10} Hz
ECRH	10^{11} – 10^{12} Hz

The power sources come from conventional radio technology (ICRF), radar (LHRF), and from recently developed gyrotrons (ECRH). In all cases, the power is produced some distance from the reactor, is conducted via coaxial cables or waveguides to the reactor, and must be transmitted through one or more feed-throughs or windows before being launched into the plasma.

In general, the ceramic window nearest the plasma is also a boundary between an SF₆-insulated portion of the rf transmission system and the "empty" cavity of the plasma side. The feed-through or window must maintain adequate properties to transmit rf power without leaking. Properties of concern are the loss tangent and dielectric constant (which together determine the absorption of energy from the transmitted beam), thermal conductivity, and strength of the window material.

Because it operates at the highest frequency, the gyrotron feed-through is perhaps the most demanding rf application. As shown in Fig. 3 [9], the gyrotron window consists of an edge-cooled plate or two parallel circular plates with coolant gas passing in-between. Polycrystalline BeO and Al₂O₃ have been used successfully as windows at 28 GHz, but some breakage problems have been experienced at 60 GHz [10]. The failures apparently resulted from the thermal stresses generated during operation. The magnitude of the stresses depends upon the amount of energy deposited, the ability of the material to conduct heat away, and the strength of the material. Al 995 Al₂O₃^{*} is stronger than Thermolux 995 standard BeO,^{**} but the thermal conductivity of BeO is an order of magnitude greater than Al₂O₃, so that thermal gradients and stress are higher in the latter material (see Fig. 4 [9]). In their studies of this problem, Becher and Ferber showed that both Al₂O₃ and BeO suffer environmentally assisted static fatigue behavior in FC 75 fluorocarbon fluid^{***} containing about 7 ppm H₂O (see Fig. 5).

^{*}A product of Wesgo, Bellevue, California.

^{**}A product of Brush-Wellman Corporation, Elmore, Ohio.

^{***}A product of 3M Corporation, St. Paul, Minnesota.

(a)

(b)

Becher and Ferber proposed a development program for improved gyrotron window materials. There is a need for a material with a loss tangent at least an order of magnitude lower than those of materials studied. Properties such as grain size, porosity, impurities, and phase distribution can affect the dielectric constant or loss tangent. Strength might be improved via second-phase additions. For a low loss tangent, single-crystal Al_2O_3 (sapphire) and magnesium aluminate (spinel) were recommended.

Becher and Ferber's work was done on unirradiated materials. In addition to irradiation-induced changes in thermal conductivity and loss tangent, neutron irradiation can cause swelling and a loss of strength via anisotropic crystal growth and grain-boundary separation in both Al_2O_3 and BeO . The irradiation limit near room temperature for polycrystalline BeO is about $5 \times 10^{24} \text{ n/m}^2$ ($E > 0.1 \text{ MeV}$) and for polycrystalline Al_2O_3 is about $3 \times 10^{25} \text{ neutrons/m}^2$ ($E > 0.1 \text{ MeV}$). The above limits are set by visible microcracking, so that it would be expected that a reduction of the static fatigue life would occur at even lower fluences. The loss of thermal conductivity caused by neutron irradiation may be the most important effect of all in window lifetime. It is clear that either BeO or Al_2O_3 must be well shielded from the plasma. Single-crystal windows would have longer lifetimes; but, in cases where design requirements dictate window placement near the first wall, these lifetimes may be inadequate. One concludes that better rf window materials must be developed.

Irradiation-induced degradation of transmissivity is also of concern, since absorption of microwave energy is the source of thermal stresses.

Fowler [11] measured the loss tangent of single-crystal Al_2O_3 after low-dose irradiation with spallation (fission-like) and 14 MeV neutrons, with the results shown in Fig. 6. It is apparent that degradation can be significant at some frequencies even at low damage levels, and is neutron energy-dependent. Clearly, further work is needed to extend such measurements to higher doses and frequencies.

3.3 Dielectric breaks

In the design of tokamak structures, mechanical load paths frequently contain electrical insulators. This is because eddy-current paths must be broken in the machine support structure and because large currents must be safely contained within conductors subjected to large mechanical loads. Occasionally there are other factors involved such as vacuum compatibility and resistance to wear. A need exists to develop and qualify structural electrical insulators for these applications.

These insulator components must serve near the first wall and must be ceramic insulators able to withstand the high neutron exposures. Properties of concern include mechanical strength and failure mode, electrical properties, friction and wear characteristics, and compatibility with the environment at temperature. Design options may include monolithic components or thin insulating coatings on mating metal surfaces — detailed requirements have not been identified. Conceptual designs have considered Al_2O_3 for this application. Other candidates may include MgO , MgAl_2O_4 , or numerous other structural ceramics.

3.4 Structural ceramics

Ceramics have often been proposed for structural applications for one or more of the following reasons.

- a) low neutron activation, which can reduce maintenance and waste-disposal problems, and thus enhance the public acceptance of fusion power;
- b) abundant, low-cost starting materials, which will aid the economy of fusion power;
- c) low-atomic-number constituents, which reduce plasma-contamination effects, and thus simplify reactor operation; and
- d) high operating temperatures, which increase thermodynamic efficiency of heat engines derived from these systems.

Perhaps the most attractive of the above features is the potential for low-neutron activation, which would result in a significantly reduced environmental impact of fusion reactors. To achieve this goal would require very high-purity raw materials and perhaps even isotopic enrichment. While these requirements would increase fabrication costs, it appears feasible to develop cost-effective, low-activation products.

The most difficult aspect of structural ceramics is the design of components using brittle materials. Materials are needed with high rupture strength, good thermal shock resistance, and good resistance to irradiation damage. New design methods and designs tailored to ceramic properties are also required. Much more effort in these areas is required before ceramic structural materials will be considered seriously by the design community.

The lifetime fluence required for the blanket structural material is as high as that for any ceramic components planned for fusion application. The goal fluence should be in the range of 20 Mw-years/m² or greater, or at least 2.5×10^{27} neutrons/m². Unlike other ceramic components in the first wall-region, which are designed for easy replacement,

the blanket structure cannot be designed for frequent replacement, so that lifetimes below 5 MW-years/m² would not be acceptable.

The favored materials for ceramic structures are silicon carbide and silicon nitride. Pells [12] recently reviewed silicon carbide. Silicon carbide has been shown to exhibit good strength retention after irradiation beyond 1×10^{26} neutrons/m² ($E > 0.1$ MeV) at several temperatures. Swelling below $\sim 1000^\circ\text{C}$ shows a temperature-sensitive saturation between 3% at 25°C and 0 at 1000°C . At higher temperatures void swelling is observed. Thermal conductivity is reduced by irradiation, but may still retain acceptable values. Higher fluence data are needed to assess SiC as a structural material.

Silicon nitride has a trigonal crystal structure, suggesting that anisotropic dilation during irradiation might limit the lifetime. Nevertheless, strength is little degraded after irradiation to 2×10^{26} n/m² ($E > 0.1$ MeV) at 410 and 540°C [13]. This good behavior may be the result of low swelling (~ 1 vol %) or low anisotropy during swelling. A possible important restriction on the use of Si₃N₄ is the high production rate of ¹⁴C from nitrogen during irradiation. Like SiC, Si₃N₄ has been irradiated to a fluence only one-tenth that required for fusion structural application.

4.0 In situ electrical properties

Electrical as well as structural properties of ceramics can be degraded by irradiation. Klaffky et al. [14] investigated increases in electrical conductivity during electron irradiation of several forms of Al₂O₃, and found the magnitude of changes to be dependent on rate of absorption of ionizing energy, temperature, and purity of starting material.

These results indicate that changes in properties of ceramics at the start of irradiation can be as important as properties of heavily damaged material.

5.0 Discussion

The category of Special Purpose Materials is now limited to the materials for superconducting magnets and ceramics. For the former area, it appears that materials are available that will withstand limits set by allowable heat loads, so that the major need is a complete data base under the conditions appropriate to a fusion reactor. These data can be obtained in the new National Low Temperature Neutron Irradiation Facility being built in the Bulk Shielding Reactor at ORNL. It should be pointed out that development of more radiation-resistant materials (especially polymers) would offer considerable economic benefit. The ceramics area presents greater difficulties. Ceramics have application in a wide variety of fusion-reactor components. For many components the design requirements are just now being defined. In at least four areas, irradiation-resistant ceramics will be required, some for service in the first-wall fluxes and fluences of the reactor and others for service in lower damage levels. For those applications where electrical resistivity and radiation resistance are the main requirements, MgAl_2O_4 is the present material of choice; but BeO and Al_2O_3 may be used in shielded locations. Perhaps the most demanding requirement is for structural ceramics, especially those with low-activation capability. Results to date on SiC and Si_3N_4 look promising, but total fluences achieved in irradiation of these materials are only about one-tenth that required for the blanket application.

Funding for the development of Special Purpose Materials has been low, because there usually appeared to be design solutions to materials problems or the materials requirements were poorly defined. Now the urgent need for a variety of radiation-resistant ceramics is clear, and a world-wide increase in the level of effort on these materials can be anticipated.

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