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CERAMICS IN CONTROLLED THERMONUCLEAR DEVICES*

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Introduction

Studies in the development of fusion power have progressed in recent years to the point where conceptual electric power generating plants could be proposed and evaluated. Three approaches to magnetically-confined fusion are under active consideration: theta pinch,[1] Tokamak,[2] and mirror[3] concepts.** The theta-pinch reactor would confine the plasma in a toroidal chamber and burn the D-T fuel in intense pulses (a 0.1-sec pulse every 10 sec). The Tokamak concept also utilizes a torus, but would burn almost continuously (hundreds or thousands of seconds per pulse). The mirror reactor would partially confine the continuously-burning plasma in a roughly spherical configuration, and reduce fuel losses by the use of a magnetic well. All concepts utilize conventional power plant technology to convert heat from the fusion reaction into electric power. The mirror reactor would in addition use a direct convertor to recover energy from the particles which escape magnetic confinement.

Ceramic Applications

Ceramics are essential materials in all fusion reactor concepts. Proposed uses in each reactor are as follows:

THETA PINCH

<u>first-wall liner</u> -- to stand off voltages generated during implosion heating of the plasma

<u>blanket intersegment insulator</u> -- to provide paths for magnetic flux penetration to the plasma and to divide the implosion voltage

<u>graphite-encapsulating insulator</u> -- to electrically isolate the graphite moderator in the blanket in order to reduce eddy-current losses

<u>insulators for magnetic coils</u> -- to electrically separate magnet windings

*Work performed under the auspices of the USERDA.
**Technological requirements for these reactors are described in reference 4.

TOKAMAK

torus-segmenting insulator -- to enhance ohmic heating by breaking the electrical continuity of the torus

neutral beam insulators -- to allow injection of neutral beams for plasma heating and refueling

insulators for magnetic coils -- as for theta-pinch

low-Z first-wall liner -- to reduce first-wall plasma contamination problems

MIRROR

direct convertor insulator -- to allow recovery of the energy of escaping plasma particles

neutral beam insulators -- as for Tokamak

lithium ceramic -- to serve as a vehicle for breeding tritium fuel in the blanket

insulators for magnetic coils -- as for theta-pinch

lithium channel insulator -- to reduce power losses in the blanket.

Operating Conditions

The operating environment for fusion reactor insulators varies with each application, but can be severe. Representative conditions for some of the more-difficult applications are:

temperature------------	up to 1500 K (Si_3N_4 theta-pinch first wall)
stress-----------------	up to 3.8×10^8 Pa tensile, pulsed (Si_3N_4 theta-pinch first wall)
voltage----------------	100 kV/cm, pulsed, at 1000 K (theta-pinch first-wall)
fusion neutrons--------	$\sim 10^{15}$ n/cm^2 sec (all reactors)
photons----------------	72 J/cm^2 pulse (theta-pinch first wall)
D-T ions---------------	1×10^{14}/cm^2 sec, 23 keV (Tokamak first wall)
He ions----------------	5×10^{12}/cm^2 sec, $<$100 keV (Tokamak first wall)
wall impurity ions-----	3×10^{12}/cm^2 sec, 23 keV (Tokamak first wall)

Because some of the environmental conditions in fusion reactors have never before been encountered (e.g., intense 14 MeV neutron irradiation), it is not always possible to predict with assurance the magnitude of expected problems. Indeed, simulation of not-yet-achieved operating conditions is in itself a challenging requirement.

Problem Areas

Problems for fusion reactor ceramics can be divided into electrical, structural, and chemical effects; such a division is utilized here. Discussion of magnet insulators is deferred until the end of this section.*

Electrical Effects

high temperature -- Thermal degradation of resistivity by activiation of charge carriers into conducting states can be significant. A typical refractory insulator such as Al_2O_3 has a resistivity of $\sim 10^{15}$ Ω-cm at room temperature; this is reduced to $\sim 10^9$ at 1000 K. However, even the latter value is sufficiently high for most reactor applications.

Temperature dependence of dielectric strength is a function of duration of applied voltage. Under DC conditions, Al_2O_3 shows a reduction in this parameter by a factor of 5 when heated from room temperature to 1000 K. On the other hand, when voltage is pulsed on a microsecond time scale, dielectric strength is not degraded over this temperature range.[6] The reason for such behavior is that DC breakdown occurs by a thermal mechanism involving electrical resistivity, whereas for short times a relatively temperature-independent electronic breakdown mechanism prevails. Thus the importance of high-temperature effects depends on whether high-voltage applications involve short pulses (as for the theta-pinch first-wall insulator) or long-pulse/DC voltages (e.g., neutral beam injectors).

ionizing radiation -- The consequence of absorption of ionizing radiation in an insulator is the excitation of charge carriers into conducting states with a resulting decrease in resistivity. Radiation-induced conductivity is roughly proportional to the rate of absorption of ionizing energy. It has been calculated that even intense levels of fusion reactor radiation (e.g., 10^6 rad/sec) can reduce resistivity of a typical insulator only to the level of thermal degradation at 1000 K.[7] Thus an adequately high resistivity can probably be retained even under ionizing radiation conditions.

The consequences of such irradiation to dielectric breakdown behavior depend on whether the voltage is applied in short pulses or under quasi-DC conditions, through the effect of ionizing radiation on resistivity. For low-temperature DC applications, degradation of dielectric strength by this mechanism could be significant.

structural degradation -- The major problem in the area of electrical effects appears to be structural degradation of the insulator under long-term fusion neutron irradiation. The effect of such irradiation in ceramics is to create point defects, clusters, dislocation loops, and other agglomerated defects. The principal electrical effects will probably be associated with defect aggregates such as voids, cation metal colloids, and anion gas bubbles, all of which can enhance dielectric breakdown. Major structural changes

*A more extensive discussion of problem areas is given in reference 5.

such as transformation from crystalline to amorphous state could occur; however, this is not likely, especially at elevated temperatures.[8]

Lack of knowledge of the consequences of long-term structural degradation is currently hampering ceramic research. Irradiated materials *in which such damage has been properly simulated* must be in hand before definitive studies can be carried out.

Structural Effects

fatigue and fracture -- Ceramics fracture when stresses around a crack tip become excessive. If time-dependent crack propogation to a critical size precedes fracture, the process is called static fatigue. Significant progress has been made in recent years in the development of high-temperature, high-strength ceramics (i.e., materials resistant to crack-induced failure). If such materials are used in high-stress fusion reactor applications and proper attention is paid to component design, quality control, and nondestructive testing, it appears that structural requirements can initially be met. However, as was the case for electrical effects, a major area of concern is structural degradation resulting from long-term neutron irradiation. Strength can be expected to be degraded by radiation-induced internal strains and stress concentration effects associated with defect aggregates. However, strength may also be enhanced by the presence of a fine dispersion of radiation-induced defects.

swelling -- An important consequence of the formation of defects in solids by irradiation is a reduction of density, or swelling. The significance of this phenomenon to fusion reactor ceramics depends on the application, i.e., whether dimensional changes can be tolerated. Where swelling will be a problem, control of composition and microstructure might be utilized to induce dimensional stability, as has been done with metals.[9] Another alternative is to use ceramics outside of their swelling temperature range (e.g., 650 to 1025 K, for fission reactor-irradiated ZrO_2[10]).

reduction in thermal conductivity -- The presence of a high concentration ($\sim$1%) of radiation-induced point defects in ceramics will significantly increase phonon scattering and thus decrease thermal conductivity.[11] The result can be higher operating temperatures and thermal stresses. Al_2O_3 has been found to suffer such a reduction.[12] However, the extent of this effect in other ceramics is not known.

physical sputtering -- The impact of irradiating particles on solid surfaces causes atom ejection, or sputtering. The consequences may be thinning of the bombarded component, changes in surface condition, and (for first-wall applications) contamination of the plasma with impurities.

Ceramics and metals sputter at about the same rate,[13] but the effect of plasma contamination is much lower with low-Z atoms such as those which commonly make up a ceramic. A low-Z first-wall liner may be required for Tokamaks in order to achieve sufficiently long burn times. The insulated first wall of the theta-pinch reactor would be protected by a D-T gas blanket, so that the high-energy fuel particles whic' are so effective in causing sputtering[14] do not reach the wall.

blistering -- Gas ions which penetrate solid surfaces may, if solubility and diffusivity are low, produce a near-surface gas layer and cause blisters to form. The consequences are similar to those from physical sputtering. Such an effect can be reduced by using materials which exhibit high gas diffusivity,[15] or in which diffusivity can be enhanced by compositional changes.[16]

Chemical Effects

chemical erosion -- Hydrogen isotope fuels in a fusion reactor are to some extent chemically reactive with most ceramics. High-energy fuel particles can, if they penetrate the surface, cause near-surface degradation.[17] Low-energy atomic hydrogen isotopes are more reactive than is the same gas in molecular form, and can thus significantly erode or degrade the surface.

Little information is available on chemical attack of ceramics by atomic hydrogen. Data on graphite[18] suggest that such effects may be tolerable for a theta-pinch first-wall insulator, but may be severe for a ceramic Tokamak first wall unless a protective gas blanket is used.

corrosion by liquid lithium -- Most ceramics are vigorously attacked by liquid lithium; exceptions are Y_2O_3, ThO_2, and alloys of the two.[19,20,21] At present, all reactor designs using both liquid lithium and ceramics in the blanket call for a protective metallic cladding for the latter.

indirect reduction by liquid lithium -- The metal layer between ceramic and liquid lithium must be chosen with care, to avoid transport of ceramic anions through the layer to the lithium with consequent ceramic degradation. It has been shown[22] that the system Al_2O_3/Nb/Li can be thus degraded. However, other metals and ceramics should prove more resistant to this effect, and a diffusion barrier such as tungsten can be used between metal and lithium if necessary.

Insulators for Magnetic Coils

Organic insulators are usually used in magnetic coils. However, such materials degrade much more rapidly in a radiation environment than do ceramics.[23] Thus for unshielded coils in fusion reactors, ceramic insulators must be used. Superconducting magnets such as are called for in Tokamak and mirror reactors have radiation shields, but organic insulators may still not be usable in the resulting radiation fields (roughly 10^{18} n/cm^2 and 10^9 rad in 10 yrs).

Stresses resulting from generation of intense magnetic fields will be large, so that high-strength insulators and good design practices must be used to assure satisfactory performance.

Summary

With proper choice of materials and fusion reactor design and operating parameters, ceramics can be specified now which will initially meet requirements for reactor operation. However, major long-term problems are expected, primarily because of anticipated radiation-induced structural degradation. Such long-term effects must be thoroughly evaluated so that ceramics with optimum properties for fusion reactor applications can be selected or developed.

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