Material Considerations for ICRH Ceramic-Filled Waveguide Launchers

Laila A. El-Guebaly

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FUSION TECHNOLOGY INSTITUTE

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1. Introduction

Ceramic electrical insulators are widely used in fusion reactors particularly in neutral beam injectors, normal magnets, insulating first walls (in theta pinch reactors), direct convertors, magnetic divertors, and radio frequency (RF) plasma heating systems. In the latter, the ceramics are required for coaxial feed-through insulation, antenna radomes, windows, and ceramic-filled waveguides. These applications require dielectric materials which can maintain electrical and structural integrity in a severe radiation and thermal environment.

The intent of this paper is to review the performance of ceramics in a fusion reactor operating environment, evaluate mechanisms of radiation damage, summarize briefly the work which was done with emphasis on recent developments, establish limits for the use of the ceramics in fusion reactors, and propose a number of ceramics to be used in the ICRH waveguide systems.

Candidate materials for fusion reactor applications are alumina (Al_2O_3), beryllia (BeO), magnesia (MgO), spinel ($MgO \cdot Al_2O_3$), silicon carbide (SiC), silicon nitride (Si_3N_4), silicon oxide (SiO_2), MACOR, titania (TiO_2), and yttria (Y_2O_3). It is of importance to study the performance of such ceramics in a fusion reactor-relevant environment and to assess the combined effects of radiation (neutrons, gamma rays, ions, electrons, etc.) damage, pressure and temperature gradients with accompanying stresses on the properties for which they are selected.

Yet, the radiation effects on ceramics have not been widely studied over the wide range of fluence and temperature. Some excellent data have been gathered by few investigators.[1,2,3] However, much of the work has been confined to relatively low irradiation levels, basic classes of ceramic materials (MgO, Al_2O_3, BeO), simulation irradiation techniques (electron and fission neutron spectra), specific irradiation temperature range, particular crystal structure, and/or tests of certain responses under limited irradiation conditions.

A partial list of requirements for ceramics in fusion reactor applications follows:

- low loss tangent, high dielectric constant, low electrical conductivity, and high dielectric strength.
- mechanical integrity.
- high radiation resistance.
- adequate thermal conductivity.
- thermal stress-strain cycling resistance.
- compatability, fabricability, joinability, and system integrability.

Some of the basic physical properties of ceramics are given in Table 1. The extremely low thermal expansion of silicates is responsible for their unsurpassed resistance to thermal shock. The value of the dielectric constant is independent of frequency[5] over the frequency range of interest for ICRH heating (10-300 MHz). The electrical resistivity and thermal conductivity have a strong temperature dependence as demonstrated by Fig. 1. As will be seen later, even a moderate radiation environment can cause significant changes in the data presented in Table 1 which might lead to serious problems especially where structural and electrical requirements are stringent.

Ceramic property degradation during irradiation may result in significant shortening of component lifetimes. It is not known yet how the physical properties will be simultaneously affected by fusion spectrum irradiation, but individual tests on ceramic properties indicate that it will be adverse.

Table 1. Characteristics of Ceramics

Material	Type of Conductor	DC Electrical Resistivity (Ω-cm) at RT*	Dielectric Constant at RT*	Dielectric Strength (kV/mm)	Loss Tangent (at 100 MHz)	Thermal Conductivity (cal/cm s °C) at 100°C	Thermal Stress Resistance (10)	Limitations
Al_2O_3	Non-conductor	5×10^{13} (4)	8.8 (5)	40-160 (6)	0.0003 (5)	0.069 (7)	Very Good	
BeO	Non-conductor	10^{16} (4)	6.6 (4)	10 (4)		0.5 (7)	Excellent	Toxicity Hydration
MgO	Non-conductor	10^{15} (4)	9.65 (5)		< 0.0003 (5)	0.082 (7)	Fair - Poor	
$MgO \cdot Al_2O_3$	Non-conductor	$> 10^{14}$ (10)				0.033 (7)	Fair	
SiC	Semiconductor	10^5 (10)				0.133 (10)	Excellent	
Si_3N_4		10^{13} (7)	9.4 (7)			0.045 at RT(7)	Excellent	
SiO_2	Non-conductor	10^{15} (4)	3.8 (9)	0.35 (10)	0.0002 (10)	0.0033 (9)	Excellent	
MACOR[8]	Non-conductor	$> 10^{14}$	6.0	1	0.003^{+}	0.0031	Excellent	
TiO_2	Semiconductor	10^{11} (4)	100 (5)	100-210 (5)	0.00025 (5)	0.015 (4)	Excellent	Reduction
Y_2O_3	Non-conductor					0.02 (4)	Fair - Poor	Price

* room temperature

( ) Reference

\+ at 0.1 MHz

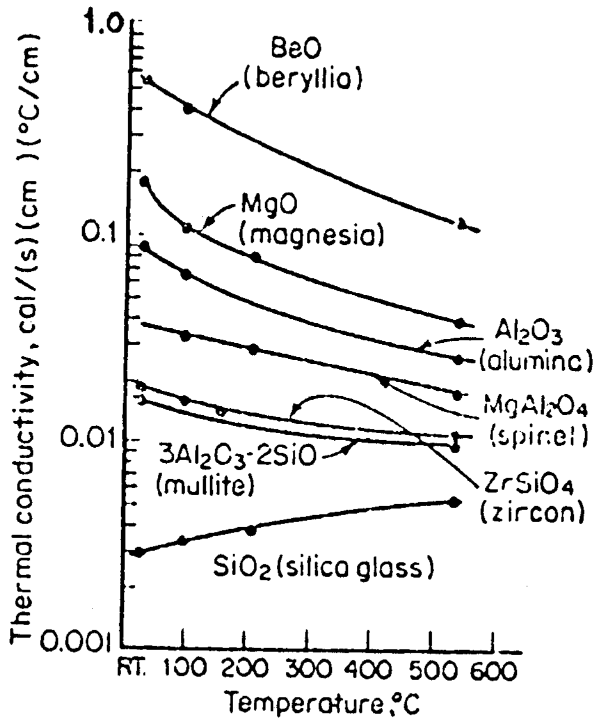

Fig. 1-a. Effect of temperature on thermal conductivity of ceramics (Ref. 10).

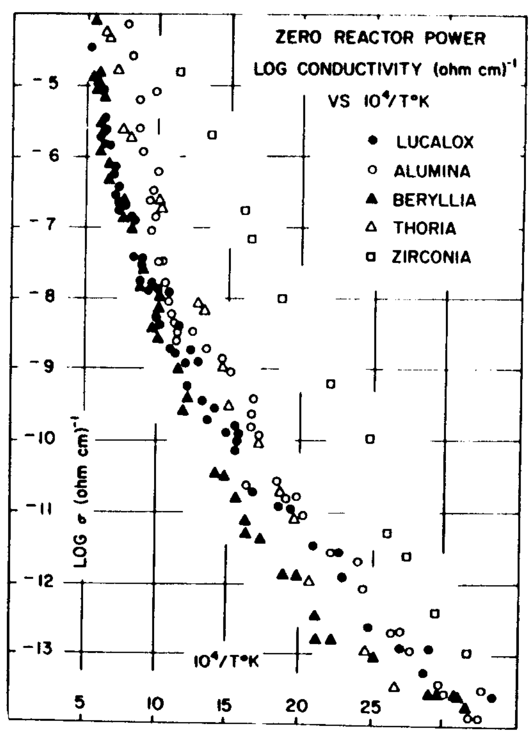

Fig. 1-b. Effect of temperature on electrical conductivity of ceramics (Ref. 21).

Since most ceramics have adequate electrical properties for ICRH systems, it seems that irradiation tests are likely to eliminate some candidate materials from the above list. On the other hand, further studies using high fusion flux levels may add other high performance, radiation resistant materials for fusion reactor applications.

2. Irradiation Effects on Ceramic Properties

The design and operating conditions of ceramic-filled waveguide plasma heating systems for fusion power reactors have not yet been fully identified. They are located close enough to the plasma and required to operate in a first wall-like neutron flux level, i.e., fluxes of ~ 3 x 10^{14} n/cm^2 s and 1.5 x 10^{14} γ/cm^2 s, a fast neutron fluence (E_n > 0.1 MeV) of ~ 6 x 10^{21} n/cm^2 per full power year (FPY), and an ionizing dose rate of 10^5 - 10^6 rad/s for a unit neutron wall loading (1 MW/m^2) reactor.(11) Most of the current power reactors are designed for 3-10 MW/m^2 and operate for ~ 25 FPY's. Moderate electric fields (< 1 kV/mm) are expected. Material problems from the highly energetic neutrons and plasma particles are anticipated to be severe. Operating temperature for ceramics is likely to be 100-300°C, but nuclear heating and RF power losses may result in higher operating temperatures and thus accelerate the thermal stress-induced failure. Therefore, a radiation resistant material with moderate electrical properties might be preferable if it possesses good thermal and strength properties.

In the following sections, the effects of radiation on the electrical properties (loss tangent, electrical conductivity, electrolysis, and dielectric breakdown), thermal conductivity, and structural properties are discussed.

2.1 Loss Tangent

When an electromagnetic wave propagates through a material it becomes partially attenuated. The metals drastically attenuate the waves and the insulators allow large penetration. Power losses in any material depend mainly on the frequency of the wave (ω), the loss tangent ($\tan \delta$) and the dielectric constant (ε) of the material. The attenution coefficient (α) of the wave relates these three quantities and for small values of $\tan \delta$ ($<< 1$), α is proportional to $\omega\sqrt{\varepsilon} \tan \delta$ (Ref. 12). Therefore, low loss tangent materials are required for the RF systems to minimize the power losses and alleviate thermal stresses and heating problems. Insulators (nonconductors) tend to have low loss tangents (10^{-4} - 10^{-3}) in the ICRH frequency range and low AC electrical conductivity (σ). The equality $\tan \delta = \frac{\sigma}{\omega\varepsilon}$ (Ref. 12) indicates the relation between them. On this basis, semiconductors must be excluded from the candidate material list for ICRH heating systems to avoid excessive heating losses in the ceramics. Recent work[13] has concluded that SiC is not suitable for ICRF applications due to its poor electrical properties. The attenuation coefficient is proportional to ω, which means that RF heating is most severe in the higher frequency range of the LHRH and ECRH systems (1-10 GHz and 10-300 GHz, respectively).

The only factor in the attenuation coefficient expression which is most subject to irradiation change is $\tan \delta$ as radiation-induced lattice disruption leads to an increase in the conductivity of the ceramics. The fundamental mechanism of the power loss is the charge carrier motion[1] in the material and it is expected that the RF losses can arise from the radiation-induced conductivity.

Fowler[14] has recently reported the measurements of loss tangent of alumina samples which have been irradiated at ~ 130°C with a fast fission neutron spectrum. Results for single crystal and polycrystalline Al_2O_3 are shown in Fig. 2. The curves show marked increase in tan δ with neutron fluences in the low frequency range (< 1 MHz) and the neutron-induced effect appears to decrease at higher frequencies. In previous studies,[15,16] a factor of 13 increase in tan δ was found at a frequency of 1 MHz when irradiating Al_2O_3 at room temperature with a fast fission neutron fluence of 6 x 10^{21} n/m^2. Furthermore, high purity alumina was irradiated at 500°C with 8 x 10^{25} thermal n/m^2 and a factor of 25 increase in tan δ was observed. Such changes in tan δ could create serious effects in RF ceramics as thermal gradients for the increased loss tangent exceeds those of the unirradiated values by ~ an order of magnitude. Figure 3 reveals that radiation induced effects in tan δ raise the operating temperature and thus consequently the thermal stresses until structural failure of a 0.5 cm thick ceramic window occurs.[17]

2.2 Electrical Conductivity

There are a number of studies of radiation-induced changes in the conductivity of some ceramics. In addition to the conductivity increase by thermal effects (Fig. 1), irradiation degrades the electrical resistivity of the materials by altering the electronic properties and inducing chemical and structural defects.[1] The former is attributed to the absorption of ionizing energy, as the number of charge carriers increase. At low temperatures, the change in DC conductivity ($\Delta\sigma$) goes as the ionizing dose rate (R). In the

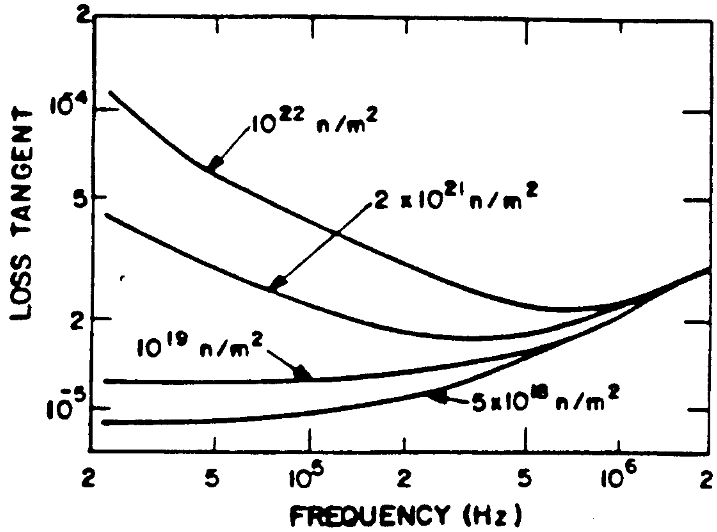

Fig. 2-a. Loss tangents for single crystal Al_2O_3 irradiated with fast fission neutrons (Ref. 14).

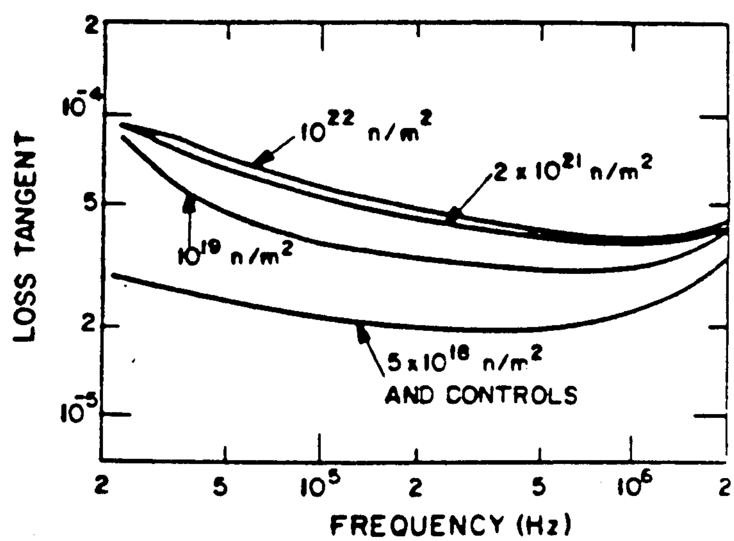

Fig. 2-b. Loss tangents for polycrystalline Al_2O_3 irradiated with fast fission neutrons (Ref. 14).

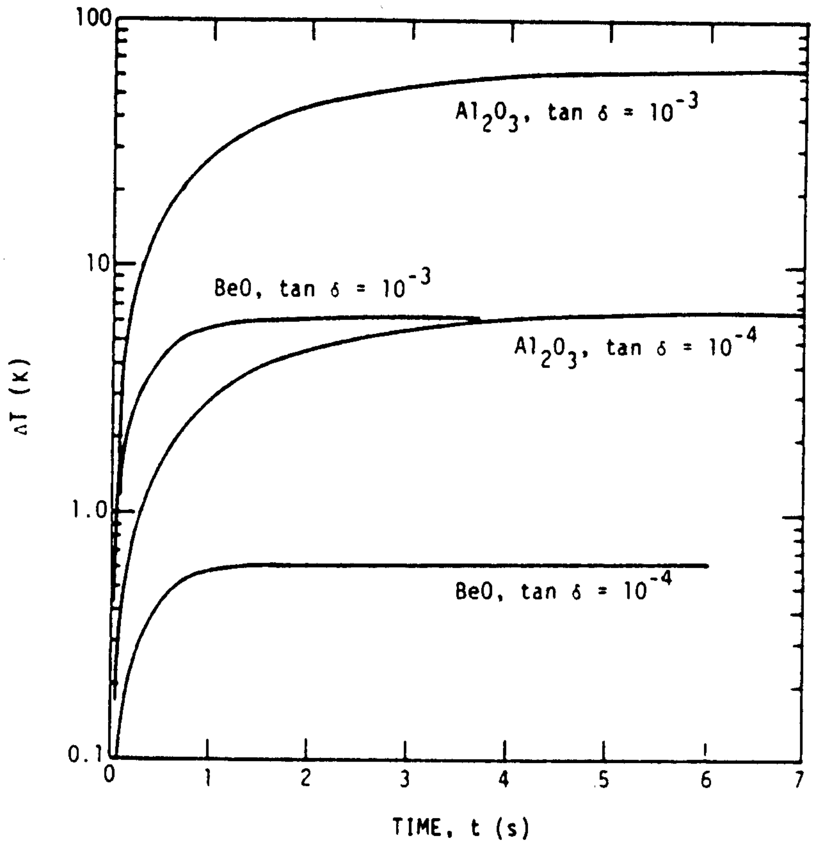

Fig. 3. Temperature rise above 375 K due to RF heating of a 5 mm thick window of Al_2O_3 or BeO; ω = 30 GHz, incident power = 0.5 kW/cm^2 (Ref. 2).

relationship $\Delta\sigma(\Omega\ m)^{-1} = kR(Gy^*/s)$, the material dependent constant K ranges from 10^{-8} to 10^{-13} for insulators.(18,19,20) For instance, a typical first wall dose is 10^4 Gy/s for a unit wall loading reactor. This results in a conductivity change of 10^{-4} - 10^{-9} $(\Omega\ m)^{-1}$ which is comparable to that induced by thermal effects at ~ 1000°C (Fig. 1).

Davis(21) has irradiated Al_2O_3, BeO, and other oxides to a gamma ray dose of ~ 15 Gy/s at different temperatures and the results are reported in Fig. 4. Compared with unirradiated values (Fig. 1), roughly three orders of magnitude increase in conductivity at low temperatures was found while at elevated temperatures the thermal effects dominated. The radiation-induced conductivity of single crystal Al_2O_3 samples has been measured by Klaffky et al.(22) over a wide range of temperatures (300-1300 K) during continuous irradiation with electron beams (6.6-660 Gy/s) and the experimental results are shown in Fig. 5. The authors have developed a theoretical model to describe the major features of the observed change in conductivity. They found that the conductivity of Al_2O_3 rose by two orders of magnitude as the dose rate was increased from 6.6 to 660 Gy/s. This behavior was approximately independent of temperature between 300 and 700 K. A magnesia powder has been irradiated at 475 K with ~ 1 Gy/s gamma ray and the conductivity increased by ~ 3 orders of magnitude.(20) The irradiation effect on the DC and AC conductivity of MACOR was examined by Fowler et al.(23) over a wide range of temperature (30-650°C) and frequency (0-0.1 MHz), and 14 MeV fusion neutron fluence of 10^{18} n/cm^2 (~ 6×10^6 Gy) was used in the experiment. The results of the conductivity measurements (Fig. 6) show remarkable changes in the AC conductivity over the favorite temperature range for fusion reactors.

* 1 gray = 100 rad

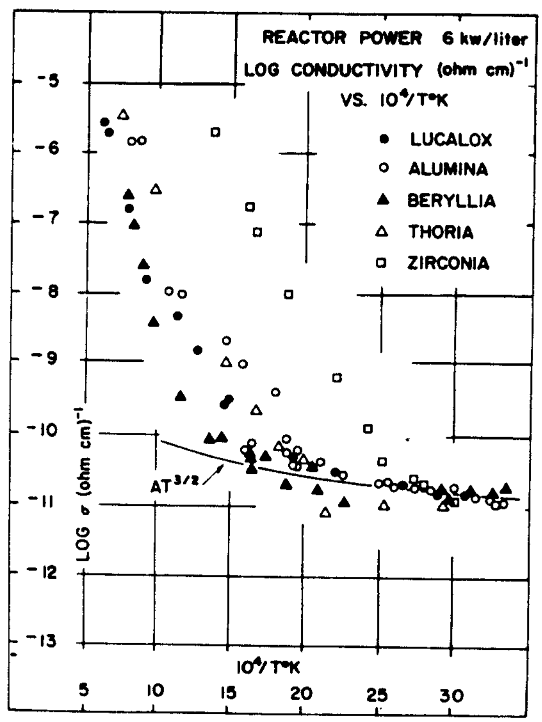

Fig. 4. Electrical conductivity of insulators irradiated in a fission reactor (Ref. 21).

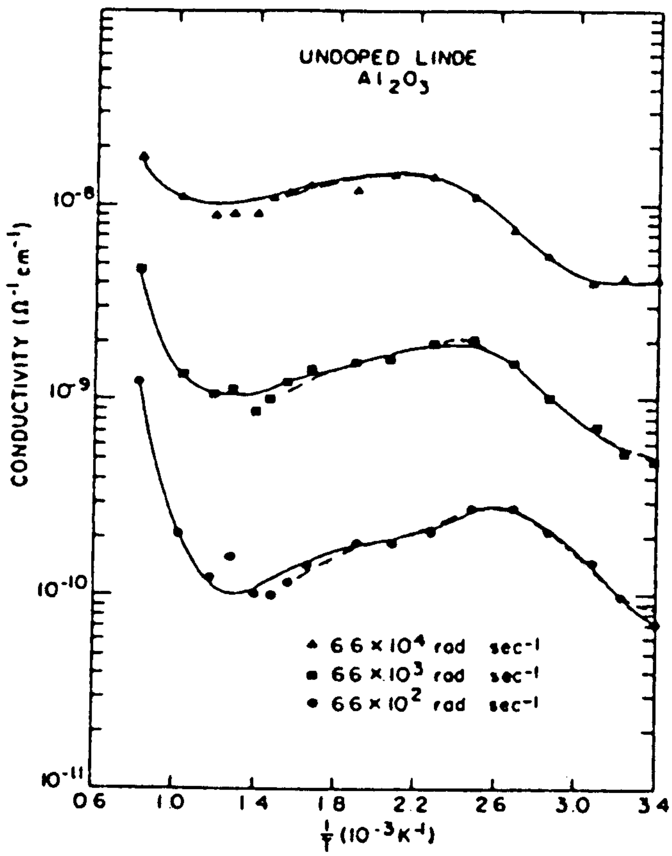

Fig. 5. Temperature dependence of the radiation-induced electrical conductivity for alumina (Ref. 22).

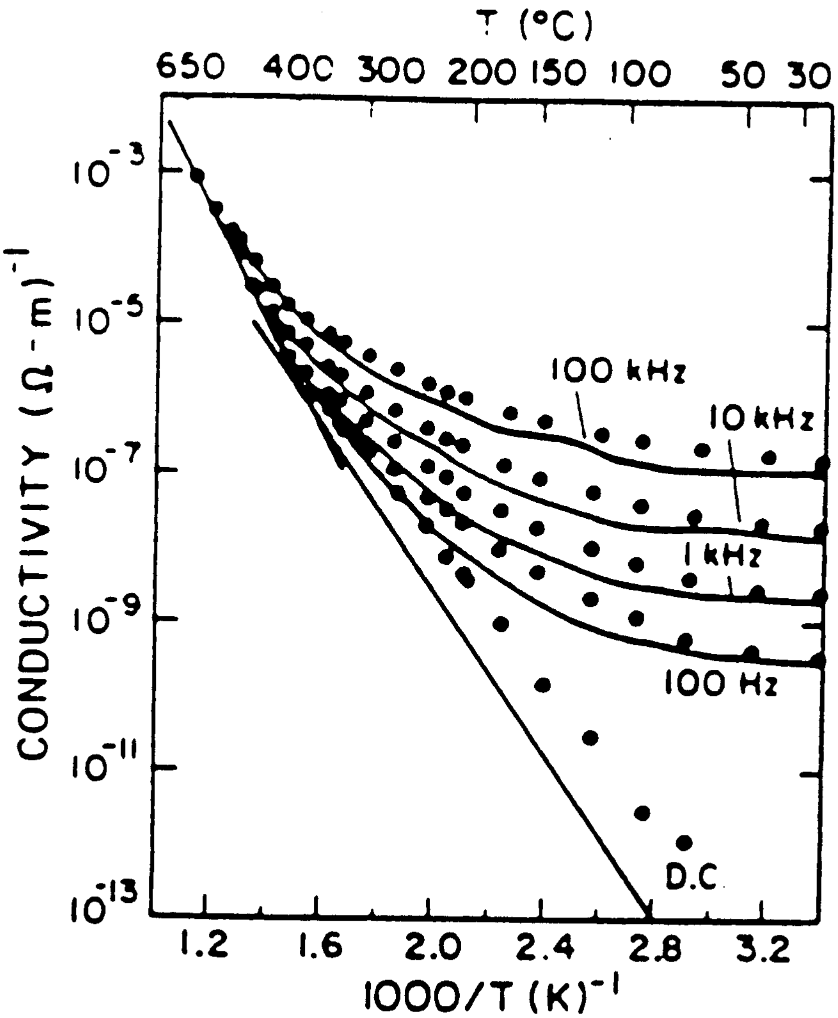

Fig. 6. DC and AC electrical conductivity of MACOR irradiated to 10^{18} 14 MeV n/cm^2 (Ref. 23).

2.3 Electrolysis

By definition, electrolysis is the migration of impurity ions within the insulator. Electrolysis can destroy the ceramics particularly at elevated temperatures and electric fields. Weeks et al.[24] found that single crystal MgO and spinel became conductive and breakdown occurred when subjected for 5 to 150 h to electric fields of 10-1000 V/mm at 1273 K. No evidence of electrolysis damage was found[25] in single crystal Al_2O_3 at temperatures up to 1273 K. However, it is possible that ion migration will be higher along grain boundries in polycrystalline ceramics.

Since diffusivity is enhanced by irradiation, it is anticipated that intense flux will accelerate electrolysis and limit insulator lifetimes. Therefore, ceramics must be avoided in high temperature and electric field applications where electrolysis might be a problem.

2.4 Dielectric Breakdown

Dielectric breakdown of ceramics occurs across the surface or through the bulk of the material. Either the thermal or the avalanche mechanism can lead to the bulk dielectric breakdown.[26] Even small current flow within the material yields Joule heating which accelerates conduction until thermal breakdown occurs. This is enhanced in low resistivity materials and more likely to occur at high temperatures and long times of AC or DC voltage applications. At higher voltages, electron collision ionization and multiplication can cause avalanche breakdown which is not strongly temperature-dependent. There is some evidence that repeated application of sub-breakdown voltage pulses can lead to a decrease in breakdown strength of some insulators.[25]

Insulators used in fusion devices will be exposed to ionizing and displacive radiation. The latter causes structural damage which can supply sites for electron emission and scattering and can alter the charge carrier concentration. The effect of ionizing radiation is to excite the charge carriers. The ionizing radiation rate is considered more important than the total dose since charge carrier concentration at any time is a balance of several kinetic processes.(1) However, the effect of lengthy exposure to ionizing radiation needs further investigation.

Single crystal Al_2O_3 was irradiated at elevated temperature for short pulses at ~ 10^{22} n/cm^2 and no degradation in the dielectric strength was found. However, a slight reduction was observed under an x-ray dose rate of ~ 6 Gy/s in the avalanche temperature range (up to 450 K) and no significant reduction was seen in the higher thermal breakdown temperature region.(27) It should be pointed out that these findings are irrelevant to first wall conditions where far too high dose (~ 10^4 Gy/s per unit wall loading) at moderate temperatures may be encountered.

Dielectric breakdown of insulators often occurs across the surface rather than through the bulk.(1) It is postulated that surface breakdown is caused by electric field accentuation followed by flashover. Surface conditions (impurities, irregularities, and cleanliness) may enhance the electric field and consequently the secondary electron emission. Coatings or glossy insulators are often used to increase the dielectric breakdown strength by offering low secondary electron yield, controlled surface resistivity, and/or improved surface cleanliness. In the RF launchers, the gaps are usually filled with inert gases (such as SF_6, argon, and freon) to further enhance the voltage standoff characteristics of the stystem.

2.5 Thermal Conductivity

The importance of the thermal conductivity of the insulators is that high values result in lower operating temperatures and thermal stresses. Thermal conductivities of some ceramics are listed in Table 1, and Fig. 1 shows the significant reduction in these values at higher temperatures. Due to the superior thermal conductivity of BeO (room temperature value is ~ an order of magnitude higher than most oxides and ~ equal to that of Al metal), it is usually selected as a candidate material for RF systems. Figure 7 demonstrates the effect of the thermal conductivity on the temperature gradient across thin slabs of Al_2O_3, BeO, and SiO_2 in RF heating systems.[9] The temperature differences in Al_2O_3 and SiO_3 are roughly 10 and 100 times that in BeO, respectively, and this is attributed to the large differences in the thermal conductivities. The value of this feature for BeO is diminished in a neutron environment as will be shown later.

Thermal conductivity is significantly reduced by irradiation induced damage, as defects scatter the phonons by which heat is conducted in insulators. Klemens et al.[28] have developed a model for irradiation reduction in thermal conductivity of ceramics at high temperatures and there is a good agreement between the theoretical model and the experimental data. The magnitude of the reduction varies greatly with the ceramic and depends on measurement temperature and irradiation dose. However, all tested specimens showed the same general features:

- a decrease of thermal conductivity with temperature and fluence.
- a more pronounced reduction at lower irradiation temperatures.
- a tendency to saturate at the higher irradiation fluences.

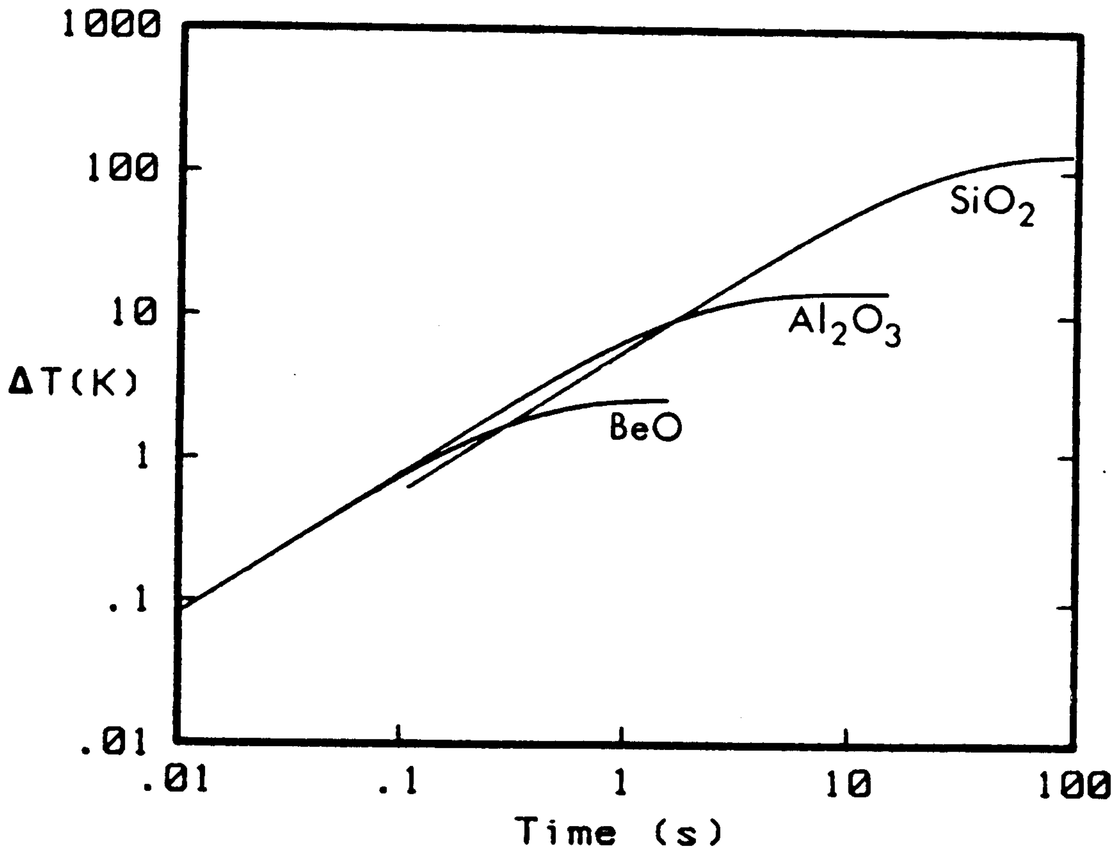

Fig. 7. Temperature rise above 300 K due to RF heating of thin slabs of BeO, Al_2O_3, and SiO_2; ω = 30 GHz, input power = 1 kW/cm^2 (Ref. 9).

This behavior is best presented by Thorne and Howard's[29] results, shown in Fig. 8, where different forms of Al_2O_3 were irradiated to fission neutron fluences up to 8 x 10^{20} n/cm^2 (E_n > 1 MeV) at 250, 475, and 700°C; K and K_o are the irradiated and unirradiated thermal conductivities, respectively. At the lowest temperature and the highest fluence the reduction is ~ 80% (factor of 5).

Irradiation to a fission neutron fluence of ~ 10^{20} n/cm^2 (E_n > 0.1 MeV) reduced the thermal conductivity of MgO measured at 300°C by 44% (Ref. 30). Hickman and Pryor[31] presented the effect of neutron irradiation fluences up to 10^{21} n/cm^2 at temperatures of 75 to 700°C on polycrystalline beryllium oxide. The irradiation-induced defects reduced the thermal conductivity by a factor of 2-3 at the lower temperatures and the reduction is less at higher temperatures. A factor of two reduction in the thermal conductivity caused the thermal stresses to rise by ~ 50% in a thin RF beryllia window[9] and accordingly accelerated the failure probability.

Hurley and Clinard[32] measured the thermal diffusivity, which is proportional to the thermal conductivity, of fourteen oxides and nitrides after irradiation to fission fluences as high as 2.3 x 10^{22} n/cm^2 (E_n > 0.1 MeV) at 925, 1015 and 1100 K. They found decreases of ~ 45, 50, 70, 75 and 95% in polycrystalline $MgO{\cdot}Al_2O_3$, Y_2O_3, Al_2O_3, Si_3N_4, and BeO, respectively, at 925 K and 2.3 x 10^{22} n/cm^2. Single crystal spinel showed the least reduction (< 1%) at every temperature and fluence, and beryllia had the greatest reduction (factor of ~ 20). Similar measurements were done by Hurley and Bunch[33] on fifteen ceramics exposed to a fast fission fluence of ~ 3 x 10^{21} n/cm^2 (E_n > 0.1 MeV) at 740 ± 40°C. Most of the ceramics underwent large thermal diffusivity reductions and single crystal materials displayed less damage than

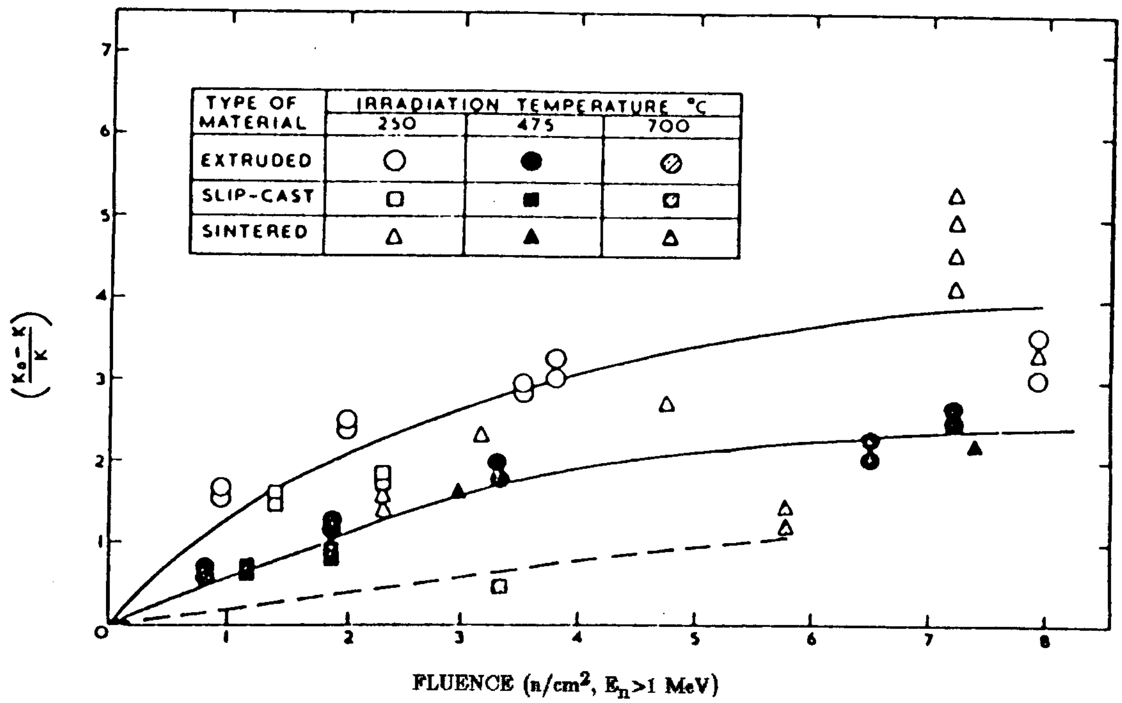

Fig. 8. Thermal conductivity of polycrystalline Al_2O_3 irradiated with fast fission neutrons at three temperatures (Ref. 29).

polycrystals. Reported reductions in thermal diffusivity are 33, 45, 53, and 60% for polycrystals Y_2O_3, $MgO \cdot Al_2O_3$, Si_3N_4, Al_2O_3, and BeO, respectively. Compared to the previous results, the reduction is less for two reasons: the fluence level is ~ an order of magnitude lower, and the higher irradiation temperature yields lesser degradation in thermal diffusivity.

2.6 Structural Properties

Swelling with accompanying stresses and dimensional changes are the major structural problems in insulators. There have been few studies of the more complicated irradiation-induced swelling in ceramics as compared with metals. The structural aspects and mechanism of damage have been discussed in detail elsewhere;[33-42] a brief summary is given here. Specimens were irradiated to neutron fluences up to ~ 10^{22} n/cm^2 at a variety of temperatures (25-1000°C) and subsequent examinations included volume expansion measurements and structural change observations. In general, the degree of swelling increases with fluence and peaks in the temperature range 0.2 to 0.4 of the melting temperature of ceramics (Fig. 9). The non-cubic structure of some ceramics reduces the tolerance for radiation damage because of anisotropic swelling.

Irradiation-induced swelling of some ceramics and the experimental conditions are summarized in Table 2 and the measured results are shown in Figs. 10-12. Only scattered data points are available for Si_3N_4, MACOR, Y_2O_3, and SiO_2. The non-cubic polycrystalline ceramics swell anisotropically and suffer drastic weakening at fluences > 10^{20} n/cm^2 even at low swelling levels. The data presented in Table 2 for non-cubic samples include the volume expansion of some which were definitely fractured, but on which dimensional measurements could be obtained.

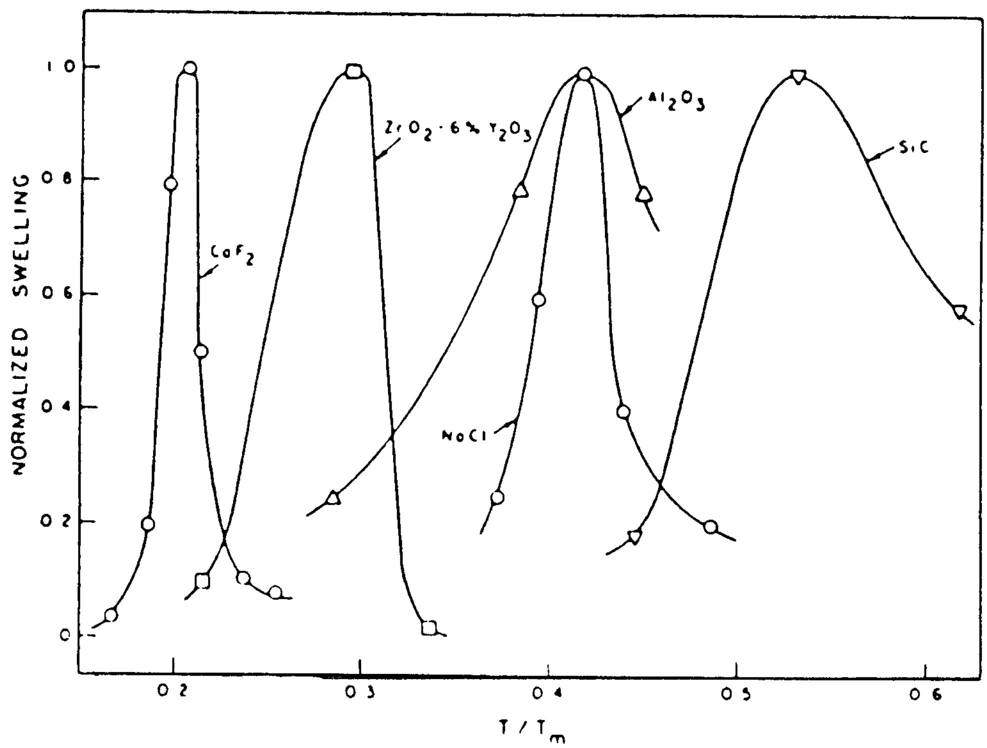

Fig. 9. Swelling peaks in ceramics (Ref. 34).

Table 2. Irradiation Parameters and Measured Swelling in Ceramics

Material	Crystal Structure	Form*	Irradiation Temperature (K)	Fission Neutron Fluence (10^{22} n/cm^2)	Neutron Energy (MeV)	Swelling** (vol %)	Reference	Fig.
Al_2O_3	Non-cubic		425	0.1	> 1	1.25	39	10
		SC	430	0.03	> 0.2+	-	37	
		SC	680	2	> 0.1	3.5	36	
		SC	815	2	> 0.1	3.3	36	
		SC	925	2.3	> 0.1	4.1	37	11
		SC	1015	0.28	> 0.1	1.6	33	
		SC	1015	0.3	> 0.1	1.7	37	
		SC	1100	2.3	> 0.1	4.4	37	11
			650	0.56	> 0.1	2.2	42	
		PC	925	1.2	> 0.1	3	37	
		PC	925	1.9	> 0.1	3.5	37	
		PC	925	2.3	> 0.1	3.5	37	
		PC	1015	0.28	> 0.1	1.9	33	
		PC	1015	0.3	> 0.1	1.9	37	
		PC	1100	1.2	> 0.1	6.0	37	
		PC	1100	1.9	> 0.1	6.5	37	
		PC	1100	2.3	> 0.1	6.5	37	
BeO	Non-cubic		375	0.07	> 1	4	31	12
			385	0.1	> 1	5.8	39	10
		PC	1015	0.28	> 0.1	3.3	33	
MgO	Cubic		300	0.05	> 1	1	38	
			425	0.1	> 1	1	39	10
		PC	430	2.1	> 0.2+	2.6-3	37	
			1075	0.05-0.5	> 1	< 1.8	39	
			1375	0.02-0.48	> 1	< 2.1	39	

* SC = single crystal, PC = polycrystal

** negative means densification

+ and 4.6 x 10^{22} thermal neutrons/cm^2

Table 2. Irradiation Parameters and Measured Swelling in Ceramics (Continued)

Material	Crystal Structure	Form*	Irradiation Temperature (K)	Fission Neutron Fluence (10^{22}n/cm^2)	Neutron Energy (MeV)	Swelling** (vol %)	Reference	Fig.
$MgO \cdot Al_2O_3$	Cubic	SC	680	2	> 0.1	0.05	36	
		SC	815	2	> 0.1	-0.11	36	
		SC	925	0.8	> 0.1	-	37	11
		SC	1015	0.28	> 0.1	0.1	37	
		SC	1100	2.3	> 0.1	-	37	
		PC	430	2.1	> 0.2+	0.8	35	
		PC	680	2	> 0.1	- 0.2	36	
		PC	815	2	> 0.1	- 0.35	36	
		PC	925	2.3	> 0.1	0.2	37	
		PC	1015	0.28	> 0.1	0.3	33	
		PC	1015	~ 0.3	> 0.1	0.4	37	
		PC	1100	2.3	> 0.1	1.6	37	
Si_3N_4	Non-cubic	PC	680	2	> 0.1	~ 1.1	36	
		PC	815	2	> 0.1	~ 1.0	36	
			1015	0.28	> 0.1	0.4	33	
SiO_2	Non-cubic		675	2.4	> 0.1	- 1.4	41	
			825	2.5	> 0.1	- 1.1	41	
MACOR	Non-cubic		825	2.7	> 0.1	1.1	41	
			300	10^{-4}	14++	-	23	
Y_2O_3	Cubic	PC	650	0.6	> 0.1	0.2	42	
		PC	1015	0.28	> 0.1	0.1	33	

* SC = single crystal, PC = polycrystal

** negative means densification

+ and 4.6 x 10^{22} thermal neutrons/cm^2

++ fusion neutrons

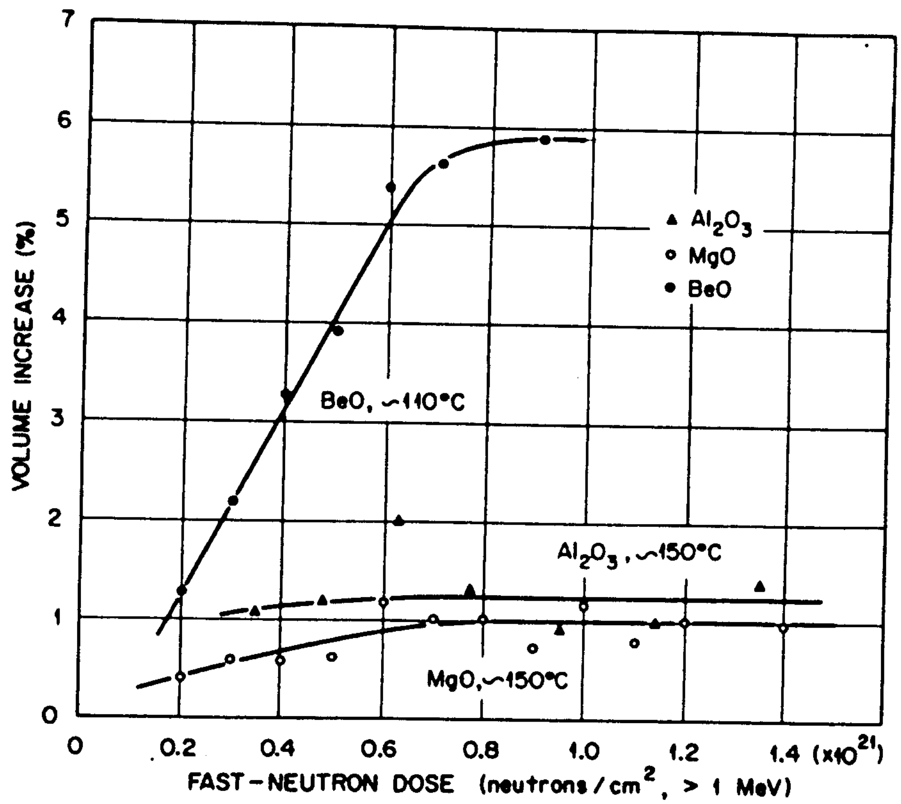

Fig. 10. Volume increases of sintered BeO, MgO, and Al_2O_3 irradiated with fast fission neutrons (Ref. 39).

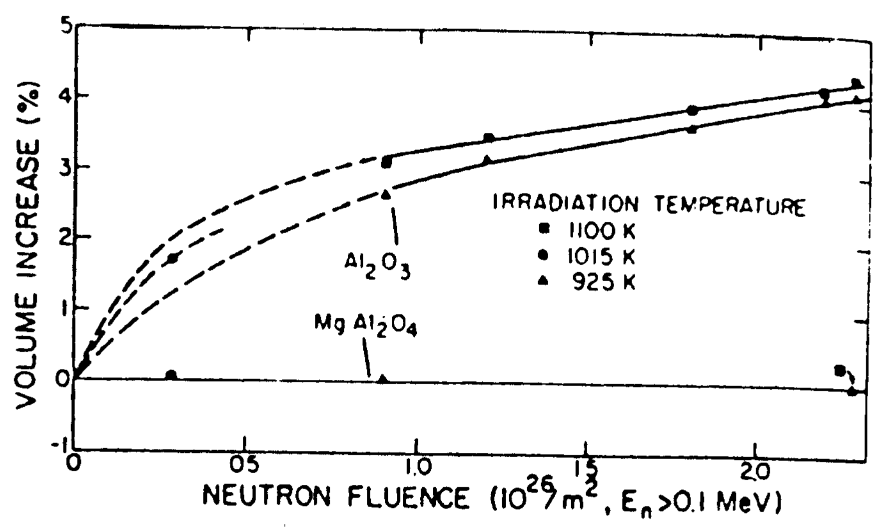

Fig. 11. Swelling in single crystals Al_2O_3 and spinel as a function of fission neutron fluence for three irradiation temperatures (Ref. 37).

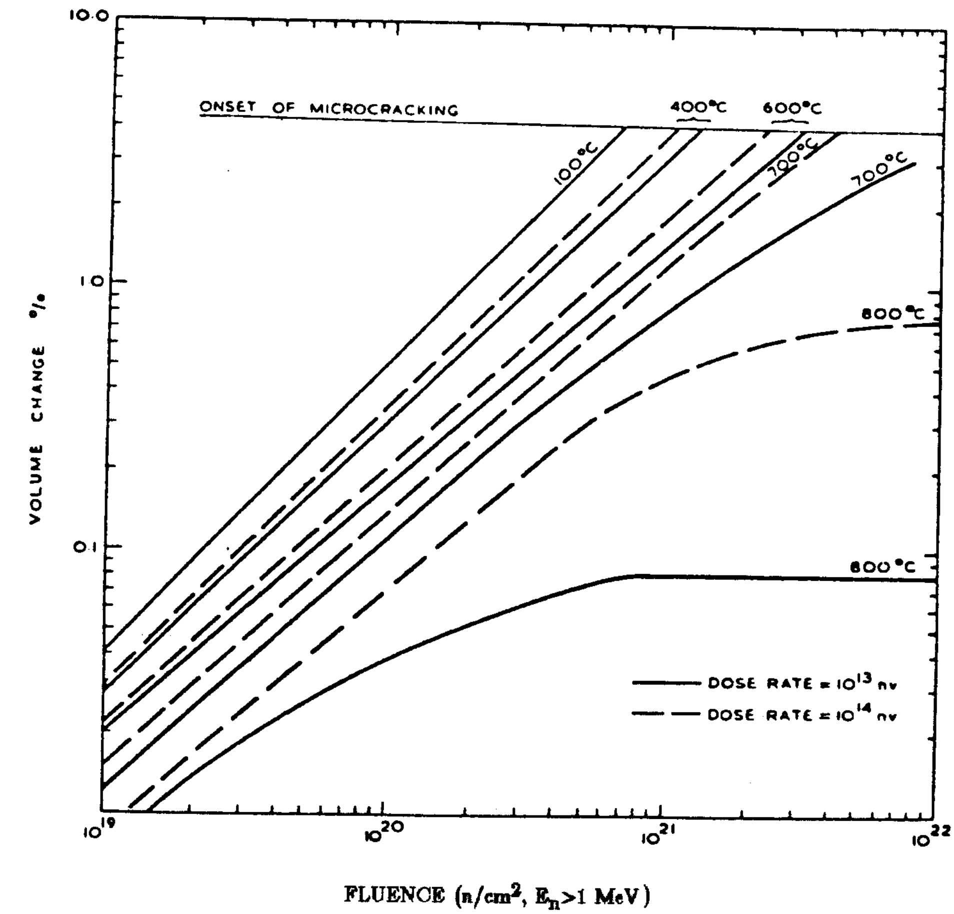

Fig. 12. Predicted volume expansion as a function of fission neutron fluence and irradiation temperature (Ref. 31).

Alumina has been irradiated over a wide range of fluences and temperatures. The single crystal form shows more resistance to structural changes than polycrystals. At high fission neutron fluences > 10^{22} n/cm^2 (E_n > 0.1 MeV), it exhibits several percent swelling, with anisotropic growth of the non-cubic material leading to microcracking.(2) Swelling occurs to a lesser degree near room temperature, and is more isotropic.

Beryllia showed large swelling even at moderate fluences. The primary mode of damage are the grain-boundary cracks, which are caused by anisotropic crystal expansion. Hickman and Pryor(31) suggested 4 vol % swelling as the onset of the microcracking (Fig. 12). This corresponds to a fast fission neutron fluence of ~ 10^{21} n/cm^2 at the temperature range of interest for the ICRH applications (100-300°C).

The grain boundary separation does not account for all of the observed volume increase in BeO. Helium bubbles, lattice expansion, and defect clusters account for the remainder of the expansion. Appreciable quantities of He are formed in BeO material used in fusion reactors (14 MeV neutron source), since Be has a high (n,2n) reaction cross section above 2 MeV and this reaction is immediately followed by a disintegration process in which two alpha particles are emitted. This contributes significantly to the expansion of BeO and promotes microcracking by reducing the contact area between grains. On this basis, the 4 vol % swelling onset for microcracking could be induced by a fast fusion fluence of ~ 10^{20} n/cm^2. This undoubtedly limits the usefulness of this ceramic in high fluence applications.

Magnesia is a cubic structure ceramic with reasonably low irradiation-induced swelling. It exhibits good dimensional stability (3 vol % swelling) to high fission neutron fluences (2 x 10^{22} n/cm^2; E_n > 0.1 MeV).

Spinel is the most desirable material for high irradiation applications. It has a remarkably good radiation resistance to swelling, in particular the single crystal form which exhibits essentially no change in volume after irradiation at elevated temperatures to 2 x 10^{22} n/cm^2 (E_n > 0.1 MeV) while polycrystalline spinel shows slight swelling (0.8 vol %) at 430 K.

Other ceramics such as MACOR, Si_3N_4, and SiO_2 are still under consideration for irradiation tests. However, they are less radiation resistant to swelling because of their non-cubic structure which leads to anisotropic expansion and, eventually, structural failure. Hence, many silicates are subject to radiolysis even at low radiation levels and should be placed in well-shielded locations. MACOR glass-ceramic has been irradiated(23) to 10^{18} 14 MeV n/cm^2 at room temperature with no evidence of structural changes. It is estimated that a factor of five higher neutron fluence,(43) to account for the degraded fusion spectrum (E_n > 0.1 MeV), is the limit for using the MACOR in fusion devices without any structural problems. The irradiated samples of yttria were notable in displaying insignificant swelling due to their cubic structure.

Directly following from the above, the global conclusions are:

- Single crystals are more radiation resistant than polycrystalline forms of most ceramics.
- The cubic structure of ceramics precludes anisotropic expansion.
- Non-cubic ceramics are subject to internal cracking even at low swelling levels.
- At elevated fluences, Al_2O_3 and BeO swelled the most while spinel offered the lowest degree of swelling among its class of cubic ceramics.

- In most cases, the swelling appears to be rising proportionately to the fluence. Hence, the swelling can be extrapolated to lower or higher fluences, if no experimental data are available.

Since no tests are presently conducted in degraded fusion spectrum, the question of the differences between fast fission and fusion neutron damage remains unanswered. Ultimately, fusion neutron irradiation data will be obtained from tests in the planned fusion material test facilities. At this time, it is assumed that fast fusion neutrons ($E_n > 0.1$ MeV) produce roughly twice the damage from fast fission neutrons.[44] This is in reasonable agreement with theoretical estimates based on damage energy calculations and with the difference in damage measured in magnesia[45] and alumina.[14,44] If this holds true at all fluence levels, then the fluence limits for the use of the polycrystalline spinel, magnesia, alumina and beryllia in fusion reactors are 4×10^{22}, 10^{22}, 5×10^{20}, and 5×10^{18} n/cm^2 ($E_n > 0.1$ MeV), respectively, in the temperature range 100-300°C. These are based on 3 vol % radiation-induced swelling (that can be accommodated without causing stress problems[46]) in spinel and MgO, and one tenth (factor of safety) of the fluence for observed microcracking in the Al_2O_3 and BeO.

3. Radiation Effects on Water

The ceramics-filled waveguides will most probably be water-cooled in order to remove the nuclear heating as well as the heating from RF energy absorption. The losses in the water are undoubtedly larger than those in the ceramic. This mandates the use of high coolant velocity and pressure which generate more problems by creating pressure gradients across the ceramic. A pure water of high resistivity is recommended to avoid excessive RF losses. An attractive property of water is that it possesses a relatively high dielectric constant (~ 80 at room temperature) compared to ceramics. This led recently to the feasibility study of water-filled waveguides.[47]

Water, used to fill or cool the waveguide systems, is subject to radiolytic dissociation under irradiation leading to corrosion/erosion product formation. A review of the radiation effects on water is summarized by Schultz.[48] The major conclusions are:

- Radiation decompose pure water through the reactions:

  $$H_2O \rightarrow H + OH$$

  $$2\ H_2O \rightarrow H_2 + H_2O_2$$

- Radiation induced chemical reactions in pure water are reversible. In other words, the back reactions of the reaction products to reform water are highly possible.
- Increased temperature results in reduced decomposition rates and equilibrium concentrations of decomposition products. Above ~ 150°C the recombination rate is high and essentially independent of temperature.
- The presence of radiolytic product in water, particularly hydrogen peroxide (H_2O_2), accelerates the erosion of the container. As a result, the container ionic species increase the conductivity of the water and, consequently, higher RF losses are anticipated.
- The natural contact between the container and the water causes chemical corrosion and forms an oxide layer at the surface of the container. The principal oxidizing agent for corrosion is the oxygen which is formed by the decomposition of hydrogen peroxide and some other reactions. Also, oxygen can enter the cooling circuit through whatever air is absorbed by surfaces in the system and without some sort of degassing apparatus, the corrosion rate of initially gas-free pure water will rise rapidly. If the

corrosion is too severe, a stainless steel cladding, as thin as 5 mils, might be used.

- The water neutron-induced transmutations (^{16}N and ^{17}N formed from ^{16}O and ^{17}O in H_2O, respectively) and the presence of the longer lived radioactive corrosion products are the major sources of water activation. The transport of these products through the cooling system is probably the greatest environmental hazard of the highly irradiated water-cooled/filled waveguide systems.

4. Discussion

Irradiation studies of ceramics for fusion systems are receiving more attention than in the past. It is now apparent that the ceramic materials could be the weak point in the performance of the ICRH system of fusion reactors, unless they are properly chosen. The problems associated with the use of ceramics in radiation environments are now well-recognized. The structural and electrical degradation appears to be lifetime limiting for the ceramics. Therefore, the RF system must be designed to permit periodic replacement of the ceramic components especially those adjacent to the first wall where the radiation level is high.

The RF heating losses are a strong function of the loss tangent, dielectric constant, and the thermal properties of the ceramics. The small amount of data available demonstrates that the loss tangent is highly degraded by fission neutron irradiation, as a result of the marked increase in the electrical conductivity during absorption of ionizing doses. It should be stressed that increased degradation is expected from the more energetic - and thus the more damaging - fusion neutrons as ionizing doses exceed that of fission neutrons by roughly an order of magnitude.[49] The neutron-induced degradation in loss tangent still remains unknown in the mega- and gigahertz frequency ranges, and more importantly the concurrent effect of ionizing (e.g. gamma rays, electrons) and displacive (ions, neutrons, etc.) radiation on loss tangent has not yet been investigated.

Insulators do not possess a unique dielectric strength. There is a strong relation between the design and the material performance of ceramics in RF systems. Size, geometry, surface preparation and temperature environment are as important as material properties in determining the dielectric breakdown strength of the ceramics. Thus, material scientists and designers should work together to develop high-voltage insulators for fusion devices.[50]

Work to date has identified three orders of magnitude increase in the DC electrical conductivity of ceramics exposed to moderate ionizing doses. No data are available on the radiation-induced AC conductivity of ceramics at elevated doses in the MHz frequency range of interest for the ICRH heating systems.

The radiation effect on thermal conductivity, while remaining significant, is less of a problem at high operating temperatures. Single crystal spinel showed almost no degradation in thermal properties at elevated fission neutron fluences, whereas polycrystalline spinel, MgO, and Al_2O_3 suffered 50-70% reduction in thermal conductivities. Accordingly, ceramics in RF systems of fusion reactors exposed to the more damaging 14 MeV neutrons will encounter drastic reduction in the thermal conductivity. However, it should be pointed out that radiation-induced effects anneal out in the high temperature range (900-1100°C). The insulator temperature should be kept low during operation, by active cooling if necessary, to avoid electrolysis and thermal stress-induced failure.

Al_2O_3 is the most fully-developed ceramic and has a fairly complete data base. However, it suffers from microcracking that results from anisotropic swelling and will likely be specified for fusion systems up to its limit of radiation stability. MgO is a well-developed ceramic with good physical properties. It is a candidate for those applications where Al_2O_3 is appropriate, whereas for high irradiation environments MgO is preferable. MgO is the most popular form of powdered insulator being used in high irradiation fields. MgO powder has been used successfully in highly irradiated normal magnets.[48] Available evidence suggests that there are probably no life-limiting mechanisms associated with neutron damage for the powdered insulators (since ceramic powder behaves quite differently[50]), with the possible exception of degradation of the electrical properties.[48] A good deal of research has been carried out on the spinel, much of it in the area of structural changes under irradiation. Spinel is of particular interest in the high neutron irradiation environment because of the superior absence of swelling, particularly in the single crystal form. In contrast with Al_2O_3 and MgO, hardly any degradation was observed in the structural properties. Unfortunately, no data are available on the irradiation effects on the electrical properties of spinel.

MACOR can easily be machined into intricate shapes, a very useful property for ceramics. It exhibits satisfactory radiation resistance at relatively low fluences and higher-flux studies are needed. Yttria exhibits dimensional stability under irradiation and more high-flux tests are required. Titania had not, to our knowledge, been irradiated previously and its behavior under irradiation is still unknown; even though there has recently been more interest in using it to fill the ICRH waveguides because of the notably high dielectric constant.

Several problems have been cited in the water-cooled/filled waveguide system. Among these are radiolysis, transmutations, and decomposition of water under irradiation, and consequently the buildup of erosion/corrosion products. Initially gas-free relatively pure water with high resistivity is recommended to reduce the RF power losses.

5. Conclusions

The mechanical rather than electrical degradation appears to be lifetime limiting for most ceramics. Spinel, magnesia, and alumina are the leading candidate ceramics for fusion applications from the structural standpoint and could be used in RF launchers up to their limits of radiation stability.

Fusion-reactor ceramics are simultaneously subjected to a variety of radiation damage processes. Further studies are required to determine the concurrent effect of ionizing and displacive radiation on candidate materials under fusion reactor-relevant environment (high fluence, degraded fusion spectrum, high ionizing dose, moderate temperature, stress conditions, and MHz frequency range). The effect the structural damage has on the electrical properties of ceramics needs also to be evaluated. Some economical methods should be developed for continuous growth of single crystal ceramics as they offer advantages over polycrystals.

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