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CALCULATIONS FOR CERAMIC WINDOWS

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RADIATION-INDUCED RF LOSS MEASUREMENTS AND THERMAL-STRESS CALCULATIONS FOR CERAMIC WINDOWS*

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Irradiation with high energy neutrons can cause increases in loss tangent and thermal resistivity for some ceramics. Loss tangents over the range 0.02 to several MHz have been measured for single and polycrystalline aluminum oxide and polycrystalline beryllium oxide, after irradiation with a spallation neutron source. Some samples of single crystal aluminum oxide were also irradiated with 14-MeV neutrons at RTNS-II to compare spectral effects. Significant increases in loss tangent were observed at the higher frequencies for the RTNS-II irradiated material. Numerical calculations of thermal stresses in RF windows, based on heating from dielectric losses and thermal conductivities, show that stresses can exceed measured fracture strengths in these materials.

1. INTRODUCTION

Most proposed magnetic fusion devices provide for radio frequency (RF) heating of the plasma.¹ Three distinct heating modes occupy corresponding frequency regimes, as shown in Table 1.

Table 1

Approximate frequency ranges for RF heating	
Mode	Frequency Range
Ion Cyclotron Resonance (ICRH)	10 - 300 MHz
Lower Hybrid Resonance (LHRH)	1 - 10 GHz
Electron Cyclotron Resonance (ECRH)	10 - 300 GHz

To contain the fuel and for impurity control, it is desirable to have a window separating the plasma region from the RF transmission system. Also, some designs require a high-dielectric-strength gas (usually sulfur hexafluoride) in the transmission system to prevent voltage breakdown in the waveguide.

Ceramics are prime candidate materials for RF windows in fusion devices, due to their low loss characteristics, mechanical strength, and good ability to contain tritium. In addition, some ceramics offer high thermal conductivity compared to other insulators.

In this study, we report measurements of dielectric loss (loss tangent) on three candidate window materials which have been irradiated with fast neutrons. Also, some numerical calculations of stresses due to RF heating are shown for these materials in standard window configurations.

2. MEASUREMENTS

Samples of single crystal Al_2O_3 (1 degree cut Linde), polycrystalline Al_2O_3 (Colors AD995), and BeO (National Beryllia Corporation) were irradiated in the spallation neutron source at the Los Alamos Meson Physics Facility (LAMPF). Irradiation temperatures were around 130° C. The neutron energy spectrum in this facility is similar to a fission spectrum but with only a very small thermal component.²

Loss tangents for these samples and for unirradiated controls were measured with a Hewlett Packard 4342A Q-Meter. Most of the irradiated measurements were done on single samples; therefore, the measurement uncertainty is fairly large.

Although the Q-Meter is capable of measuring loss tangents to a frequency of 70 MHz, meaningful data were obtainable only to a few MHz

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for the alumina samples and about a factor of ten higher for beryllia. Above these frequencies, measured loss tangents appeared to go as the square of the frequency. This behavior could be indicative of a surface contact mechanism which dominates at sufficiently high frequency.³ These high frequency discrepancies were not noticed in some other materials (for instance, polyethylene).

Results for the single crystal Al_2O_3 are shown in Figure 1. The curve for the lowest neutron fluence, which was identical to that for controls, was very near the limit of resolution of the Q-meter. It is possible that the loss tangent is lower than indicated for this curve. The other curves show a marked increase in loss tangent with dose at the lower frequencies, but this effect disappears at around one MHz.

Results for the AD995 polycrystalline alumina appear in Figure 2. This material had a higher unirradiated loss tangent than the single crystals. An increase in loss tangent becomes apparent at a small dose, but higher doses bring smaller increases. As with the single crystals, the neutron-induced effect appears to decrease at high frequencies, but remains apparent above one MHz.

FIGURE 1
Loss tangents for single crystal Al_2O_3 irradiated with high-energy neutrons.

FIGURE 2
Loss tangents for polycrystalline Al_2O_3 irradiated with fast neutrons.

The beryllia samples showed a wider sample-to-sample variation in loss tangent among the controls than did either of the alumina types. The results of neutron irradiation on two samples are shown in Figure 3. There was considerable overlap between the standard-deviation error bars for controls and the lower-fluence measurement. Additional samples are being irradiated in order to obtain more conclusive data.

The LAMPF neutron energy spectrum is more like that of a fission reactor than a monoenergetic 14-MeV source. To compare possible

FIGURE 3
Loss tangents for polycrystalline beryllium oxide irradiated with fast neutrons.

spectral effects on loss tangent, two samples of sapphire were irradiated at RTNS-II to a fluence of $5 \times 10^{21} \text{ n/m}^2$. Results of measurement of these samples are shown in Figure 4.

Comparison of this curve with those in Figure 1 shows a significant difference, especially at the higher frequencies. This supports evidence that, for a given fluence, 14-MeV neutrons cause significantly more damage than do fission-spectrum neutrons.⁴

3. CALCULATIONS

RF windows fail due to cracking from environmental stresses. Among these are:

1. Heating stresses due to energy absorption from RF fields.
2. Heating from the nuclear environment.
3. Differential swelling from neutron damage and the temperature gradient in the window.

Calculations have been performed to assess effects from the first of these, using finite difference techniques to generate the temperatures in the window, and a finite-element stress code (SAP V) to solve for the stresses.

RF energy absorption can arise from two different, but related, conditions: inherent

losses in the material (which may be fluence-dependent) and radiation-induced conductivity (RIC) losses, which presumably are flux-dependent. The latter will be discussed in greater detail, below.

Inherent losses in the material depend on the power flux through the material, the free-space wavelength of the field, the loss tangent, and the dielectric constant of the material. The attenuation factor serves as an indicator of the relation among the last three of these quantities. For sufficiently small values of the loss tangent, this quantity may be given approximately as⁵

$$(1) \quad \alpha = (\pi/\lambda_0) \sqrt{\epsilon} \tan \delta.$$

The material-dependent quantity in this expression which is most subject to change is the loss tangent.

Since the attenuation factor goes as the reciprocal of the free-space wavelength, it is apparent that, all other quantities being equal, heating will be most severe at the highest frequencies, in the ECRH region.

Many ECRH designs specify a reference power flux of 5 kW/cm^2 at frequencies in the range of 100 GHz in a face-cooled window. This value was used in the calculations which follow, for a circular window 32mm in diameter and 3mm thick. The cylindrical TE_{02} mode was used for a circular waveguide.

The coolant, which flows in a channel between a pair of windows, exerts an outward pressure on each window. On the waveguide side, this pressure may be balanced by pressurized gas, but on the plasma side no such effect exists. Thus stresses should be higher on the plasma-side window, with tensile stresses highest on the outer (uncooled) surface. The bowing force decreases tensile stresses over most of the inner (cooled) surface.

FIGURE 4
Loss tangent of single crystal Al_2O_3 irradiated with 14-MeV neutrons.

Figure 5 shows the stresses generated on the outer face of a BeO window under the conditions described above. Axial stresses were quite small for all of these calculations and are not shown. The window is clamped against axial motion but is free to expand radially. The peak tensile stress, near the clamp, is a calculational artifact caused by the rigidity of the clamp. The most realistic peak tensile stress occurs at a radial distance of 2.4 cm. Becher and Ferber have calculated time-to-failure as a function of applied tensile stress, for various failure probabilities.⁶ According to their results, for a failure probability of 0.1, this window would fail in a few minutes.

FIGURE 5
Tangential and radial stresses calculated for a beryllium oxide window.

The effect of a uniform outward pressure of 5×10^5 Pa (5 atmospheres) is shown in Figure 6. This causes a 20 percent increase in tensile stress on the outer face, but reduces the peak tensile stress on the inner face.

Beryllium oxide is usually selected as the candidate of choice for RF windows because of its high thermal conductivity. The value of this feature may be diminished in a neutron environment. Almost all ceramics suffer

FIGURE 6
Tangential and radial stresses for the window of Figure 5, under a uniform load of 5×10^5 Pa.

serious degradation of thermal conductivity at low-to-moderate fast neutron doses.⁷ Thermal conductivity for BeO has been shown to fall by a factor of two at a fast neutron fluence of 4×10^{22} n/m².⁸ Figure 7 shows that this would cause the peak tensile stress to rise by about 50 percent.

Calculated stresses for an alumina window under the conditions of Table 2 are shown in

FIGURE 7
Tangential and radial stresses for the window of Figure 5, but with thermal conductivity reduced by half.

Figure 8. Because of its lower thermal conductivity, the peak tensile stress is considerably greater than for beryllium oxide. This window would fail in a few seconds.

Calculations can be a useful design tool. Window configurations can be designed to withstand stresses by thickening at locations of peak stress and by designing a clamp which reduces tensile stresses. As an example, the window of Figure 8, if clamped rigidly against both axial and radial motion, shows a quite different stress configuration (Figure 9). In this case, the clamping puts the window under compression everywhere.

4. EFFECTS OF IRRADIATION

It can be seen from data presented in Section 1 that even a moderate fast neutron dose can cause large increases in loss tangent at sufficiently low frequencies. However, the frequency region of interest is five orders of magnitude higher. Irradiation effects in this region are unknown. Since the calculations shown here indicate serious heating problems even in unirradiated material, even small increases in dielectric loss would be serious.

FIGURE 8
Calculated tangential and radial stresses for an alumina window.

FIGURE 9
Tangential and radial stresses calculated for the window of Figure 8, but clamped at the edge against radial motion.

Another unknown factor is the response of ceramics to radiation-induced conductivity at these frequencies. Based on low-frequency (1-100 Hz) data,⁹ there is some indication that this may not be a problem. The dielectric conductivity for a ceramic is given by

$$(2) \quad \sigma = \omega \epsilon' \tan \delta.$$

For an alumina window at 10^{11} Hz with a loss tangent of 10^{-3} , this works out to an inherent conductivity of about $3.3 \times 10^{-2} (\text{ohm-meter})^{-1}$. Based on experimental data for near-DC measurements, the radiation-induced conductivity is given by the formula

$$(3) \quad \sigma = 2 \times 10^{-9} R^{.8} (\text{ohm-m})^{-1},$$

where R is the dose rate in Gy/s. The dose rate required to equal the inherent conductivity would be about 10^9 Gy/s. This is several orders of magnitude above predicted first-wall doses.¹⁰

The foregoing is based on the assumption that RIC is frequency-independent and additive to the inherent conductivity at a given frequency. If the RIC is found to be frequency-dependent also (through, for instance, the loss tangent), the above analysis would be invalid.

5. CONCLUSIONS

Dielectric losses in candidate RF window materials have been found to increase subsequent to moderate exposure to fast neutrons. Evidence indicates that these increases depend on the energy spectrum of the source. Calculations of stresses due to heating show that current window designs under anticipated operating conditions are marginal. At ECRF frequencies, radiation-induced conductivity is unlikely to be an important factor in window stresses.

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