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AUTHOR(S): Frank W. Clinard, Jr.

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Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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OVERVIEW OF IRRADIATION EFFECTS RESEARCH ON INSULATING CERAMICS

Frank W. Clinard, Jr.
Los Alamos National Laboratory
Los Alamos, NM 87545, USA

SUMMARY

Insulating ceramics have many uses in fusion reactors. Although various environmental conditions can degrade these materials, the most severe problems lie in the area of irradiation damage. Such damage can be detrimental to dimensional stability, strength, thermal conductivity, and various electrical properties; failure of an insulator can result from deleterious changes in any of these areas. Degradation of electrical properties falls into two categories: permanent effects, and transient effects that occur only when irradiation fluxes are actually impinging on the material. Consequences of irradiation damage can be severe not only for power reactors but for nearer-term machines such as ITER.

INTRODUCTION

Fusion reactors will require electrical ceramics to serve as insulators in RF heating systems and neutral beam injectors, diagnostic components, lightly-shielded magnetic coils, and current breaks between metallic structural elements. When these insulators are subjected to radiation fields (neutron, gamma, or ion bombardment) various physical properties can be degraded; these are discussed in the next section.

PHYSICAL PROPERTY DEGRADATION AND RESULTANT EFFECTS ON CERAMIC INSULATORS FOR FUSION REACTOR APPLICATIONS

Density

When atoms are displaced in a ceramic, options for materials response include recombination of vacancies and interstitials, aggregation of defects, or retention of the nascent atomic-level defects. The latter two processes can result in significant swelling. Retention of vacancies and interstitials may play an important role in ceramics, apparently because space charges and/or directional bonding can present a barrier to the dominant process of recombination.

Swelling may or may not present a difficulty for fusion ceramics, depending on the application. Free-standing materials can often tolerate dimensional changes without a problem, but most insulating ceramics are either structurally confined or are bonded to other materials. In either case, swelling can lead to structural failure. Another source of swelling-induced strength loss is anisotropic dimensional changes. In this case a polycrystalline ceramic can suffer severe cracking as a result of random directional swelling among the grains of the solid.

One of the most swelling-resistant ceramics is spinel ($MgAl_2O_4$). Alumina (Al_2O_3) has severe problems, as this material both undergoes large dimensional changes and is non-cubic (thus prone to strength losses from anisotropic swelling).

It should be pointed out that the data base for swelling and other irradiation effects in ceramics is primarily from fission reactor tests (E_n=1 MeV), whereas damage in a fusion reactor will result from a softened 14 MeV neutron spectrum. Differences in damage response may result from differing details of displacement events or from the much greater generation of transmutation products that accompanies 14 MeV neutron damage. The latter effect could have a major influence on defect aggregation, and requires extensive study.

Strength

Displacive damage has an intrinsic strengthening effect on ceramics. For example, bend strength of spinel can be doubled by elevated-temperature neutron damage, while fracture toughness of single-crystal Al_2O_3 can double as a result of the same irradiation exposure. In both cases the apparent cause is interference with crack propagation by the defect microstructure.

Unfortunately, many other circumstances can lead to loss of mechanical integrity. Among these are anisotropic swelling in polycrystalline ceramics (described above), differential swelling in multiphase materials, and preferential damage to grain boundary phases.

Two extremes of behavior are the severe degradation of strength in alumina and beryllia at doses between 10^{20} and 10^{22} n/cm^2, and the increase of strength observed for spinel even above 10^{22} n/cm^2. Results are strongly dependent on irradiation temperature, and so that variable must always be taken into account. It is important to note that these doses are equal to or less than those expected at the first wall of ITER, indicating that damage-resistant ceramics will be required even for that machine.

Thermal Conductivity

Thermal conductance in insulating ceramics takes place by lattice vibrations (phonon effects). Phonons are scattered by lattice defects, with point defects being the most effective at or above room temperature. Since irradiated ceramics often contain large concentrations of point defects (1 vol% or more), degradation of this property can be severe. It is not unusual to observe a halving of thermal conductivity after neutron irradiation to 10^{22} n/cm^2. Fractional degradation is less for ceramics operating at elevated temperatures, since intrinsic phonon scattering becomes dominant under those conditions.

The least-easily degraded ceramic is single-crystal spinel, which retains almost all of its starting thermal conductivity after elevated-temperature neutron irradiation. This is evidence that most of the point defects in this material recombine harmlessly under those conditions.

Electrical Properties

As a rule, DC electrical properties of insulating ceramics are not significantly degraded after large damage doses unless structural failure occurs. This general observation applies to both electrical conductivity and dielectric strength. Problems with electrical behavior lie primarily with transient degradation during irradiation, as absorption of ionizing energy excites charge carriers into conducting states.

This problem area has not been thoroughly studied, and so it is not possible to say which materials are most resistant to radiation-induced conductivity (RIC). However, it has been shown that the presence of chemical or structural defects reduces RIC, apparently as a result of enhanced charge carrier scattering, trapping, and/or recombination.

Radiation-induced conductivity is flux rather than dose-dependent, and so presents the greatest problems for insulators in high-flux areas near the first wall. It is known that in Al_2O_3 a flux of $\approx 10^5$ rad/s can reduce resistivity by several orders of magnitude; this flux is actually lower than that expected at the first wall of ITER. Reactor designers must decide whether large reductions of resistivity are sufficient to present problems in a highly-resistive ceramic.

High-frequency dielectric properties of insulating ceramics, which are relevant to RF applications, can be degraded by prior displacement damage. For example alumina and beryllia irradiated to 10^{22} n/cm^2 at 385°C suffer a doubling of loss tangent, that being sufficient to catastrophically reduce the lifetime of an ECRH window. There is insufficient data available to say whether flux-dependent ionization effects are significant at the frequencies relevant to RF heating systems.

SUGGESTIONS FOR FURTHER READING

Most of the scientific issues discussed here are addressed, and appropriate references given, in the chapter "Radiation Effects in Non-Metals" by F. W. Clinard, Jr. and L. W. Hobbs from the book Physics of Radiation Effects in Crystals edited by R. A. Johnson and A. N. Orlov, Elsevier Science Publishers (1986).