LA-UR -86-3123   CONF-8609138--3

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

LA-UR--86-3123

DE87 000144

TITLE: THE EFFECT OF IRRADIATION-INDUCED DEFECTS ON FUSION REACTOR CERAMICS

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SUBMITTED TO The Fifth Europhysical Topical Conference on Lattice Defects in Ionic Crystals

Madrid, Spain   September 8-12, 1986

Los Alamos

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FORM NO 836 R4
ST NO 2629 5/81

THE EFFECT OF IRRADIATION-INDUCED DEFECTS

ON FUSION REACTOR CERAMICS

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ABSTRACT

Structural, thermal, and electrical properties critical to performance of ceramics in a fusion environment can be profoundly altered by irradiation effects. Neutron damage may cause swelling, reduction of thermal conductivity, increase in dielectric loss, and either reduction or enhancement of strength depending on the crystal structure and defect content of the material. Absorption of ionizing energy inevitably leads to degradation of insulating properties, but these changes can be reduced by alterations in structural or compositional makeup. Assessment of the irradiation response of candidate ceramics Al_2O_3, $MgAl_2O_4$, SiC and Si_3N_4 shows that each may find use in advanced fusion devices. The present understanding of irradiation-induced defects in ceramics, while far from complete, nevertheless points the way to methods for developing improved materials for fusion applications.

INTRODUCTION

Ceramics are specified for use in magnetically-confined fusion devices to serve both as structural components and as electrical insulators.* Structural

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* The use of solid, lithium-bearing ceramics as tritium breeding materials will not be discussed here.

applications include first-wall armor and divertors, and possibly large structural components in low-activation designs. Electrical uses include RF windows and standoffs, insulators for lightly-shielded or unshielded magnetic coils, components for neutral beam injectors, and insulating layers or coatings to reduce MHD effects.[1]

The environment for fusion ceramics is complex and severe: depending on the component, the above applications may involve high temperatures, large structural and thermal stresses, intense electromagnetic fields, ion bombardment, and corrosive conditions. However, the dominant problem for all ceramic components appears to be alteration by bulk irradiation. Fusion neutron irradiation, involving a softened 14 MeV spectrum, is the major difficulty for most structural ceramics; but for electrical insulators, absorption of ionizing radiation may lead to temporary yet possibly severe degradation of insulating properties.

This review approaches the subject of irradiation-induced defects by considering four ceramics that are candidates for various fusion applications. The state of knowledge of these defects is reviewed for each material, with emphasis on aggregates such as dislocation loops and voids. Discussion of the defects includes consideration of their role in the three most important categories of materials performance, viz., structural, thermal and electrical properties; however, the data base is sufficient to allow treatment of electrical effects only for the first two ceramics.

The latter part of the paper considers which of the candidate ceramics discussed earlier is appropriate for the three applications considered most critical to the success of fusion power: first wall protection, RF windows, and magnet insulators. The aim here is to show that an understanding of defect behavior is far from an academic exercise, but rather serves as the keystone to selection and development of qualified materials.

The reader will find that in most cases the extent of understanding of defects and their effect on physical properties is inadequate for intelligent materials selection for fusion applications; in fact, one of the goals of this review is to make just that point. Nevertheless the results described here do establish the basis for understanding the importance of defects in fusion ceramics and point the way for future research.

RESPONSE OF CANDIDATE MATERIALS TO IRRADIATION

Alumina (Al_2O_3)

More studies of irradiation effects have been carried out on this material than on any other ceramic (with the possible exception of fission reactor fuels). The relatively extensive data base with respect to defects formed and their effect on physical properties not only allows prediction of the usefulness of this material but also supplies reference points with which the performance of other ceramics can be compared.

Irradiation-induced defects and consequent swelling. When refractory ceramics such as alumina are irradiated near room temperature, defect content and physical property changes are often dominated by point defects and their fine aggregates. This is the case because the low homologous temperature results in low mobility for the defects and therefore their retention in isolated form. Because of the complexity of the subject this review will not attempt to identify the various types of point defects generated in irradiated ceramics; a more thorough discussion of this topic is given in ref. 1. However, the diversity of these defects must be recognized when attempting to understand in depth the physical property changes that occur at room temperature.

Alumina irradiated to 8×10^{20} nvt* at 523K exhibits bulk swelling of 1.2 vol%. Up to that fluence x-ray and macroscopic dilation agree; however, at greater doses x-ray dilation decreases while swelling approaches saturation.. This behavior is attributed first (at low doses) to accumulation of point defects and then to aggregation into interstitial clusters.[2] The corresponding large concentration of point defects, far higher than that attainable in metals[3], implies a barrier to recombination. Such a barrier, which is probably related to electrostatic effects, is an important yet little-understood factor in establishing the defect content of irradiated ceramics.

Neutron irradiation at temperatures high enough for significant defect mobility results in aggregation of interstitial atoms into dislocation loops. These are of character 1/3<0001>{0001} and 1/3<10$\bar{1}$0>{10$\bar{1}$0}, formed respectively on basal and prism planes of this hexagonal ceramic[4]. This process is accompanied by swelling, which is anisotropic (Fig. 1).[5] The bias in favor of c-axis growth at higher temperatures reflects a predominance of basal-plane loops under that condition. Dislocation loops in Al_2O_3 are faulted when small, but can undergo a reduction of energy by unfaulting as partial dislocations sweep across the loops.[6]

Since interstitials are more mobile than are vacancies, it is possible to have the above loops formed while vacancies remain dispersed in the lattice as point defects or fine aggregates. However, at higher temperatures, vacancies can agglomerate to form void-like features. These features might actually be a colloidal dispersion of aluminum metal (by analogy with sodium colloids in NaCl[7]), or oxygen gas bubbles (similar to the iodine inclusions formed in KI[8]). However, Bunch, Hoffman and Zeltman[9] have shown by a process of elimination that the features are indeed voids. Nevertheless, it should be noted that under conditions of in-situ TEM damage Shikama and Pells[10] have reported formation of aluminum particles.

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* This fluence is approximately equivalent to 8×10^{24} n/m^2 (E>1 MeV).

Fig. 2 shows voids in Al_2O_3 along with their complementary interstitial dislocation loops.[11] Voids in this ceramic are typically found aligned in the <0001> direction. Although swelling occurs as a result of the creation of additional atom sites (i.e., the loops) rather than void formation, under conditions of easy void formation their volume fraction corresponds to the magnitude of bulk volume change. Swelling response of Al_2O_3 at three elevated temperatures (Fig. 3)[11] demonstrates that growth does not saturate with increasing damage dose, at least up to 20 displacements per atom (dpa).*

To this point we have mentioned two ways by which a lattice can accommodate displaced atoms: by their retention as isolated defects and by their aggregation. A third way, mutual annihilation, is actually the dominant process. It can be crudely estimated that in Al_2O_3 irradiated to 20 dpa at 1100 K, 0.2% of displaced atoms undergo aggregation (that is, 4 vol% swelling divided by 20 dpa). About 1% are found to have been retained in the lattice as isolated defects upon cooling to room temperature after irradiation.[12] Thus the vast majority of defects in alumina have recombined, but with significant numbers retained in isolated or aggregated form. As will be shown in the next section, some ceramics (notably spinel) are biased even more strongly toward recombination.

The fact that Al_2O_3 undergoes anisotropic swelling means that the

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* The concept of displacements per atom for ceramics is complicated not only by a lack of data on threshold displacement energies[1] but also by the fact that damage rates are typically different for each sublattice. Nevertheless it is a handy approximation to assume one dpa per 10^{25} n/m^2, whether dealing with fast fission neutrons or first wall fusion neutrons (softened 14 MeV spectrum).

polycrystalline form of this material can, at dose levels on the order of a few dpa, suffer high internal stresses and ultimately grain boundary separation. An example of such separation is shown in Fig. 2. This effect, which usually determines the lifetime of Al_2O_3 in a neutron environment, is strongly temperature-dependent (see Fig. 1).

Structural properties. Fracture strength of ceramics is given by the relationship

$$\sigma_f = A(E\Gamma)^{\frac{1}{2}}/(c)^{\frac{1}{2}} \qquad (1)$$

where E is Young's modulus, Γ is fracture energy, c is the characteristic dimension of the critical (failure-inducing) flaw, and A is a constant. The parameter $(E\Gamma)^{\frac{1}{2}}$ is termed the fracture toughness.

In general terms, fracture toughness increases as any mechanism capable of frustrating crack propagation becomes operative. The effect of the damage microstructure in Al_2O_3 (Fig. 4) is to cause a crack introduced by microindentation to undergo deflection, jogging, branching, and presumably blunting by encounters with the voids, with the result that toughness is doubled.[13] By analogy with the behavior of $MgAl_2O_4$ (discussed below), there may also be a contribution to toughening from strain fields around dislocation loops.

Thermal conductivity. In an insulating material heat is conducted at low and moderate temperatures by thermal vibrations (phonons). Phonons are scattered by lattice defects, with the effect being most pronounced for point defects when above cryogenic temperatures. Thus the result of irradiation damage is usually to decrease thermal conductivity.

Reduction of thermal diffusivity (a parameter approximately proportional to thermal conductivity) for Al_2O_3 after neutron irradiation at elevated temperatures is shown in Fig. 5. Analysis of these results by Klemens et al.[12] shows that the decrease is attributable to the presence of both point defects and aggregates, with point defects contributing roughly two-thirds of the total effect. With respect to aggregates, the contribution of voids dominates. A point defect concentration on the order of one percent was estimated; this is a relatively high value, but is not characteristic of all ceramics irradiated at high temperatures (see the discussion of spinel below).

The data of Fig. 5 show that as irradiation temperature is increased the reduction of thermal diffusivity is lessened; this reflects the decreased concentration of point defects at higher temperatures and the formation of coarser aggregates under these conditions. The approach to saturation at higher doses results from the inability of the lattice to sustain higher concentrations of fine defects and the relative ineffectiveness of the increasing concentration of aggregates in scattering phonons.

Electrical properties. The most important change in electrical properties of ceramics is seen during rather than after irradiation. As the rate of absorption of ionizing energy increases, charge carriers are increasingly excited into conducting states and the electrical resistivity decreases; this process is known as radiation-induced conductivity, or RIC.

A thorough assessment of this phenomenon has been carried out in Al_2O_3 up to ionizing dose rates of 6.6×10^2 Gy/s by Klaffky et al.[14,15] These investigators found that dependence of RIC on rate of energy absorption obeyed the relationship

$$\sigma \sim r^n, \qquad (2)$$

with the value of the exponent being dependent on temperature and on concentration of electronic traps and recombination centers. In general, however, a rough proportionality between r and σ was found. The effect of the presence of lattice defects is to increase charge trapping and recombination, thus lowering the conductivity. This was found to be true whether the defects were introduced chemically (by additions of Cr_2O_3)[14] or by prior neutron irradiation.[15]

Pulsed-voltage dielectric breakdown strength (DBS) of Al_2O_3 has been shown by Bunch [16] to be insensitive to the presence of fine voids. DBS was measured by the application of microsecond pulses at room temperature, so that breakdown was electronic rather than thermal. Calculations have shown[17] that although under these conditions voids can reduce DBS, cavity size must be on the order of 100 nm rather than the ≈10 nm size studied by Bunch.

Britt and Davis[18] have investigated dc breakdown in this ceramic at an ionizing dose rate of 6 Gy/s. A slight reduction of DBS was observed in the avalanche temperature range up to 450K, while breakdown strength above that temperature (in the thermal breakdown region) was unaffected. It is likely that dielectric strength will be significantly degraded in the much higher ionizing fluxes expected at the first wall of a fusion reactor.

Dielectric losses have been found to be sensitive to the presence of structural damage. Frost[19] has shown that loss tangent of Al_2O_3 at 10^{11} Hz is approximately doubled by prior irradiation to $8x10^{25}$ n/m^2 at 660K, leading to a proportionate increase of lossiness. Pells et al.[20] have also observed increases at $\approx 10^5$-10^8 Hz, and have shown that the magnitude of changes are strongly dependent on the form of the starting material.

Some results are available in the literature on the relationship of loss factor of ceramics to content of chemical impurities (e.g., see ref. 21), but efforts to correlate increases of lossiness with structural irradiation damage are just beginning. Such work, as well as measurements of degradation during irradiation, is sorely needed so that damage-resistant materials can be developed for RF window applications.

Spinel ($MgAl_2O_4$)

Spinel shows excellent resistance to neutron irradiation and is therefore a prime candidate for fusion applications. However, some starting properties (especially strength) are only moderately good, so that this ceramic is an appropriate subject for optimization studies.

Irradiation-induced defects and consequent swelling. Single-crystal spinel has been irradiated to $2x10^{26}$ n/m^2 at several temperatures and the nature of the resultant defects evaluated by TEM. After irradiation to $2x10^{26}$ n/m^2 at 925K the damage microstructure is dominated by faulted dislocation loops of type 1/4<110>{110} clustered in rosettes (Fig. 6). Smaller 1/6<111>{111} faulted loops are less frequently found[22]. At 1100K only large loops of the former type are generated. Irradiation at 680 and 815K also results in formation of faulted loops of the {110} type.[23] These loops are stoichiometric, whereas the {111} loops are stoichiometric only if partial inversion is present. Calculations based on number and size of loops shows that the percentage of displaced atoms that undergo aggregation is quite small (≈0.01%), with other defects remaining in isolated form or having recombined. (As will be described in the section on thermal conductivity, the latter process is overwhelmingly dominant for this material.) Swelling is near zero, and in some cases is actually negative.[24]

Polycrystalline spinel irradiated at 925 and 1100 K shows in addition to the above loops a concentration of small features (presumably voids) near but not in grain boundaries.[11] These are thought to have formed when interstitials migrated to the boundaries and annihilated there, leaving an excess of vacancies to condense into cavities. Swelling, while still low, is greater than that for single-crystal material.[11] At 680 and 815K voids are not found and swelling is again near zero.[24] Under these conditions polycrystalline spinel exhibits denudation of damage near the grain boundaries, suggesting that interstitials are again lost to the grain boundaries and that the characteristic {110} loops therefore cannot form in such regions.

Irradiation at 430K results in swelling of 0.8 vol%, and again denuded grain boundaries.[25] The larger swelling value at lower temperatures may indicate greater retention of point defects under these conditions; such defects are known to be the source of significant swelling in some ceramics (e.g., Al_2O_3 and SiC).

Structural properties. Four-point bend strength of spinel is dramatically increased by irradiation damage, perhaps by the presence of interstitial dislocation loops.[24] It has been proposed[13,24] that the mechanism of strengthening is crack deflection by the intense strain fields around the loops. An alternate explanation, that preexisting flaws are blunted by irradiation[26], may also be a contributing factor. Since spinel has a cubic crystal structure, mechanisms of weakening involving anisotropic dimensional changes cannot operate in this material.

A lesser amount of strengthening was observed for the polycrystalline form[24], indicating a deleterious effect from the presence of grain boundaries. Two possible sourc for this behavior come to mind: denudation of visible damage along grain boundaries, and impurity effects. In support of the first mechanism it can be argued that inhomogeneous distribution of structural damage could lead to internal stresses that could partially nullify strengthening effects. With respect to the second mechanism, it is known that ≈1000 appm lithium was present in both polycrystalline test materials, so that transmutation-generated helium may have contributed to a relative reduction of strength. This would be especially likely if the lithium were preferentially located in the grain boundaries.

It is apparent that a better understanding of strengthening mechanisms in both single-crystal and polycrystalline ceramics is needed so that this phenomenon can be fully exploited for fusion applications.

Thermal conductivity. Thermal diffusivity of spinel measured at room temperature after irradiation at three elevated temperatures is shown in Fig. 5. It may be seen that the single-crystal form suffers little degradation, indicating that the vast majority of vacancy-interstitial pairs have recombined. Results for the polycrystalline form show greater reduction of thermal diffusivity, probably as a result of the formation of near-grain boundary voids.

Electrical properties. Pells et al.[20] have assessed changes in electrical conductivity of single-crystal spinel as a function of rate of absorption of ionizing energy. It was shown that at 7.5 Gy/s this ceramic exhibits a hundred-fold greater conductivity at room temperature than does Al_2O_3, but that this difference disappears at 700K. Detailed work on spinel remains to be done.

Silicon Carbide (SiC)

This ceramic is noted for its high strength and good thermal conductivity over a wide temperature range. SiC is usually thought of as a semiconductor, but one recently-introduced form[27] offers good electrical resistivity.

Irradiation-induced defects and consequent swelling. A thorough assessment of neutron damage has been carried out by Price[28-30,32] on the beta (cubic) form of SiC fabricated by chemical vapor deposition (CVD). TEM examination has shown that after irradiation to 1.2×10^{26} n/m^2 (E>0.18 MeV) at ~1500K the damage microstructure consists of 5 nm clusters identified as Frank dislocation loops on {111} planes.[28] At lower temperatures and fluences damage aggregates were even smaller, and were not observed below ~775K.

Irradiation at 1523 and 1773K led to the formation of faceted voids, most of which were tetrahedra bounded by {111} planes (Fig. 7).[28] Void distribution was heterogeneous, most notably with respect to denudation near grain boundaries. At the higher temperature there was an occasional tendency for voids to cluster along {111} planes, suggesting that stacking faults are preferential sites for void nucleation.

Silicon carbide exhibits a swelling minimum with increasing irradiation temperature. At 300K growth is 3 vol%, decreasing to near zero at ≈1300K.[29] Over this range swelling reaches saturation (or at least quasi-saturation) at a fluence of 10^{20}-10^{21} nvt; Clinard et al.[24] have shown that after irradiation to $2x10^{26}$ n/m^2 at 680K the swelling value of 1.5 vol% attained at the lower dose range is again observed. It appears that the large growth at room temperature is attributable primarily to retention of a relatively high percentage of point (or at least unresolved) defects, the concentration of which is reduced by recombination at higher temperatures. The observation by Price[29] that up to ≈1300K x-ray lattice expansion is in agreement with bulk swelling supports this interpretation. Above 1300K void formation is accompanied by resumption of swelling, with growth in this regime showing no tendency toward saturation.[28]

<u>Structural properties.</u> Strength of β SiC irradiated to $3x10^{21}$ nvt at 903 and 1293K has been determined at room temperature by four-point bend tests.[28] No significant changes were observed. The absence of strength reduction is understandable in a cubic material; failure of this property to increase indicates that the combination of unresolved damage and dislocation loops present after such treatment is incapable of impeding crack propagation. In other work Price and Hopkins[30] have measured strength of CVD SiC after irradiation to $2x10^{25}$ n/m^2 at 1013K and again found no significant change, consistent with the implication from swelling results that the damage microstructure is similar for the two experiments. No measurements of strength have been made on SiC containing voids.

Matthews[31] and Price and Hopkins[30] have reported a sharp drop in strength of reaction-bonded SiC after neutron irradiation. The mechanism is clear here: differential swelling between the matrix and free silicon leads to internal stresses and cracking that result in the observed weakening. This mechanism is similar to strength reduction from anisotropic swelling, but variations of growth rate in a two-phase material could of course degrade ceramics regardless of their crystal structure.

Thermal conductivity. Price[32] irradiated CVD SiC to $3\text{-}8\times10^{25}$ n/m^2 at 823-1373K, and measured thermal conductivity of the damaged material at room temperature. Decreases of from 87% (after irradiation at the lower temperature) to 67% were noted, with these decreases being consistent with a phonon mean free path determined by point defects in the former case and defect clusters in the latter. The fractional decrease for a given sample was lessened when measurements were carried out at elevated temperatures, reflecting the relatively greater contribution from phonon-phonon scattering (and concommitant lessened contribution from defects) under these conditions.

Silicon Nitride (Si_3N_4)

This ceramic has thermal and strength properties similar to those of silicon carbide, except that Si_3N_4 is less stable thermodynamically at high temperatures. However, silicon nitride is in all forms a good to excellent electrical insulator.

Irradiation-induced defects and consequent swelling. Youngman[33] has shown that sintered beta Si_3N_4 irradiated to 2×10^{26} n/m^2 at 925 and 1100K exhibits two types of defect aggregates: faulted planar defects on $\{10\bar{1}0\}$ planes, and pore-like features in a glassy grain boundary phase. The latter are shown in Fig. 8. These features are probably oxygen bubbles, since such defects are known to form in other irradiated glasses.[34] The observed swelling of ~1 vol. has been attributed to the presence of the planar faults, some of which were identified as faulted interstitial dislocation loops.[33]

Structural properties. Beta silicon nitride has a hexagonal crystal structure, and might therefore be expected to suffer from anisotropic swelling and an accompanying decrease of strength. However, x-ray analysis by Hurley and Cocks [35] showed little or no long-range contribution to the internal strain in this material, indicating that growth is not strongly anisotropic. By contrast, these authors found large anisotropic strains and an 18% strength loss in orthorhombic Si_2ON_2 under the same irradiation conditions.

Measurements of four-point bend strength of silicon nitride after irradiation to 2×10^{26} n/m^2 at 680 and 815K have shown little or no degradation.[24] Since the effect of the easily-damaged grain boundary phase should be to weaken the material, there may be a compensating strengthening effect from the defect content of the matrix phase. Certainly no gross damage of the sort that afflicts anisotropic polycrystalline alumina at this dose was noted for Si_3N_4.

Thermal conductivity. Thermal diffusivity of silicon nitride is significantly degraded by neutron damage, with this parameter being reduced by roughly half.[36] Since the dislocation content alone is unlikely to be responsible for that magnitude of change[12], it would appear that a significant concentration of fine-scale defects remains in the lattice after irradiation.

MATERIALS CHOICES FOR SPECIFIC FUSION APPLICATIONS

In this section prime candidate ceramics are proposed for three engineering applications. These applications, while not completely representative of all fusion needs, involve the most severe conditions likely to be encountered in a fusion device and can therefore serve to guide materials selection for less-demanding uses.

Structural Ceramics for Use at the First Wall

This environment is dominated by fluctuating (sometimes very high) temperatures, severe thermal fluxes, and exposure to physical and chemical sputtering conditions. Lifetime neutron fluences are expected to be low compared with those expected for other applications, because of frequent changeout necessitated by erosion or thermal shock. Nevertheless, doses will be sufficient to cause major changes in physical properties of many ceramics.

The best ceramic for this application is probably beta silicon carbide. Its refractory nature and good thermal shock resistance impart the desired starting properties, and neutron damage should not degrade mechanical properties. Some swelling must be tolerated, so that monolithic material is preferred to a layered structure laminated to a substrate. The major problem will be degradation of thermal conductivity; it may be necessary to rely on recovery of this property during excursions to high temperatures.

RF Windows

The mode of failure for this application is thermal stress-induced fracture. If the window can be protected from the first wall environment by placement or shielding, the major source of thermal energy will be absorption from the beam. Present designs call for a laminated window with flowing coolant, although if coarsening of defects can lead to reduced lossiness it may be desirable to operate the material well above ambient temperature. Ceramics specified for this application must exhibit good strength and thermal conductivity, and a low loss factor. Periodic replacement may be possible, but a long lifetime would offer many benefits.

There is no one prime candidate material for this application. If neutron damage is ignored the high strength and thermal conductivity of silicon nitride and silicon carbide make these ceramics good choices, but uncertainties as to inherent lossiness of silicon carbide and radiation resistance of silicon nitride must be considered negative factors. At the least, damage-sensitive grain boundary phases should be eliminated from these materials.

Spinel offers good radiation resistance, so that this ceramic may be the best choice if its initially lower strength and thermal conductivity can be tolerated. Alumina is somewhat better with respect to these two parameters, and damage-induced degradation of strength can be overcome by use of single-crystal material. Dimensional changes will still be large, however, so that adoption of a compliant window support system may be necessary. Whatever the ceramic selected, it may be possible to control its defect content so as to maximize transmissivity and resistance to irradiation-induced degradation of this important property.

Insulators for Lightly-Shielded Coils

These insulators have modest electrical requirements, so that with careful design radiation-induced conductivity may be tolerable. Structural problems of concern include loss of adequate strength to withstand the large magnetic forces, and dimensional changes. These insulators must last for the lifetime of the reactor itself.

Spinel appears to be the best choice for this application. It may be anticipated that strength will increase with irradiation damage unless the transmutation gases that accompany irradiation with 14 MeV neutrons have a deleterious effect. (The low temperatures present in a water-cooled magnet will mitigate against that by suppressing gas mobility.) Swelling, although low, may prove to be the lifetime-limiting factor; for that reason efforts should be directed toward developing microstructural alterations that enhance recombination of defects.

SUMMARY

The severe irradiation environment of a fusion reactor can lead to significant degradation of critical properties of candidate ceramics. However, an increased understanding of irradiation-induced defects should allow development of a new generation of damage-resistant materials for improved performance and extended lifetimes.

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FIGURE CAPTIONS

1. Dilation along c- and a-axes in single-crystal Al_2O_3 as a function of irradiation temperature.

2. Aligned voids and grain boundary separation in Al_2O_3 irradiated to 1.2×10^{26} n/m^2 at 1100K.

3. Swelling of single-crystal Al_2O_3 and $MgAl_2O_4$ as a function of neutron fluence for three irradiation temperatures.

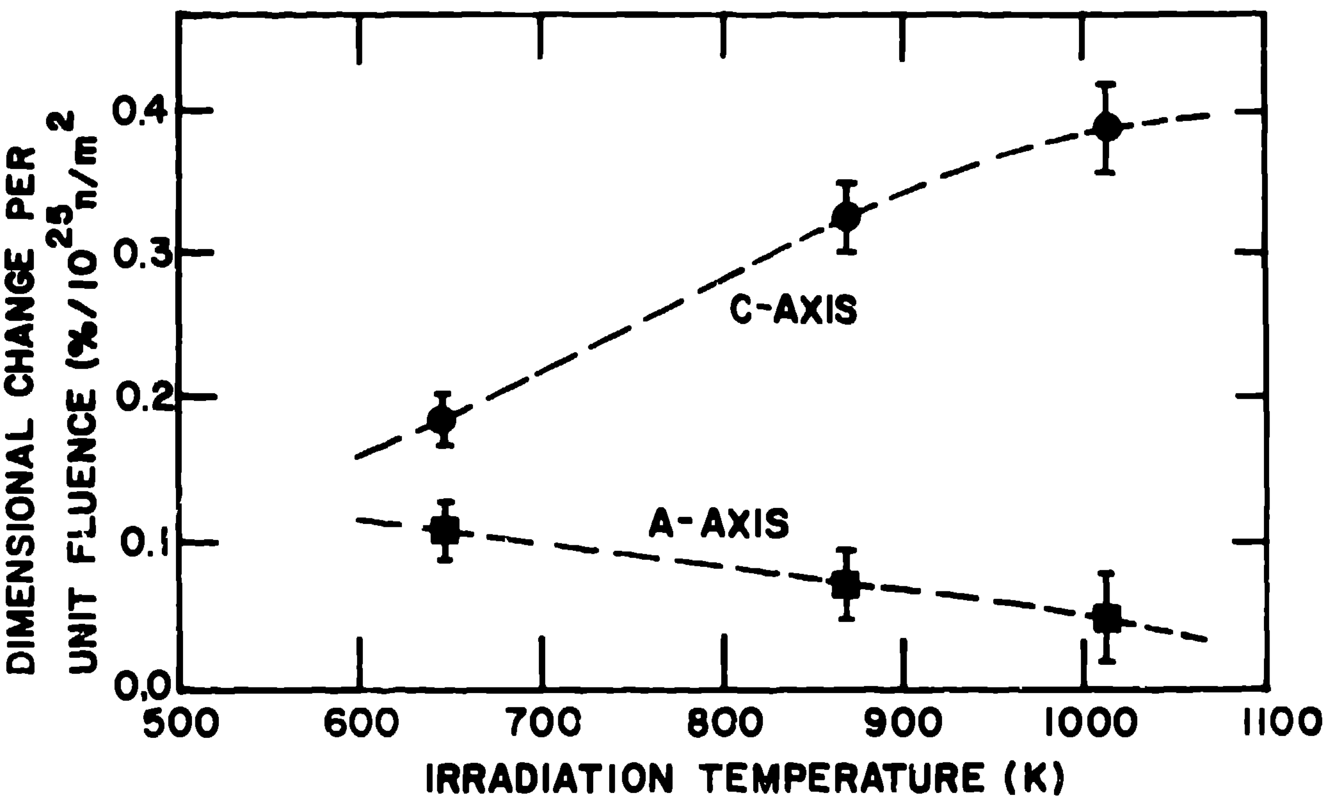
4. Bright-field TEM image of an induced crack in Al_2O_3 after irradiation to 2×10^{26} n/m^2 at 1100K.

5. Reduction of room-temperature thermal conductivity in single-crystal and polycrystalline Al_2O_3 and $MgAl_2O_4$ after neutron irradiation at the indicated temperatures.

6. Weak-beam dark-field TEM micrograph of faulted interstitial dislocation loops in a {111} section of single-crystal $MgAl_2O_4$ after irradiation to 2.3×10^{26} n/m^2 at 925K.

7. Bright-field TEM image of voids in SiC irradiated to 8.8×10^{25} n/m^2 (E>0.18MeV) at 1723K (Price, ref. 28).

8. Damage to the grain boundary phase of Si_3N_4 after irradiation to 2×10^{26} n/m^2 at 1100K (Youngman, ref. 33).



DIMENSIONAL CHANGE PER
UNIT FLUENCE (%/10^25 n/m^2)
0.4
0.3
0.2
0.1
0.0
C-AXIS
A-AXIS
500
600
700
800
900
1000
1100
IRRADIATION TEMPERATURE (K)

Figure 1

Figure 2

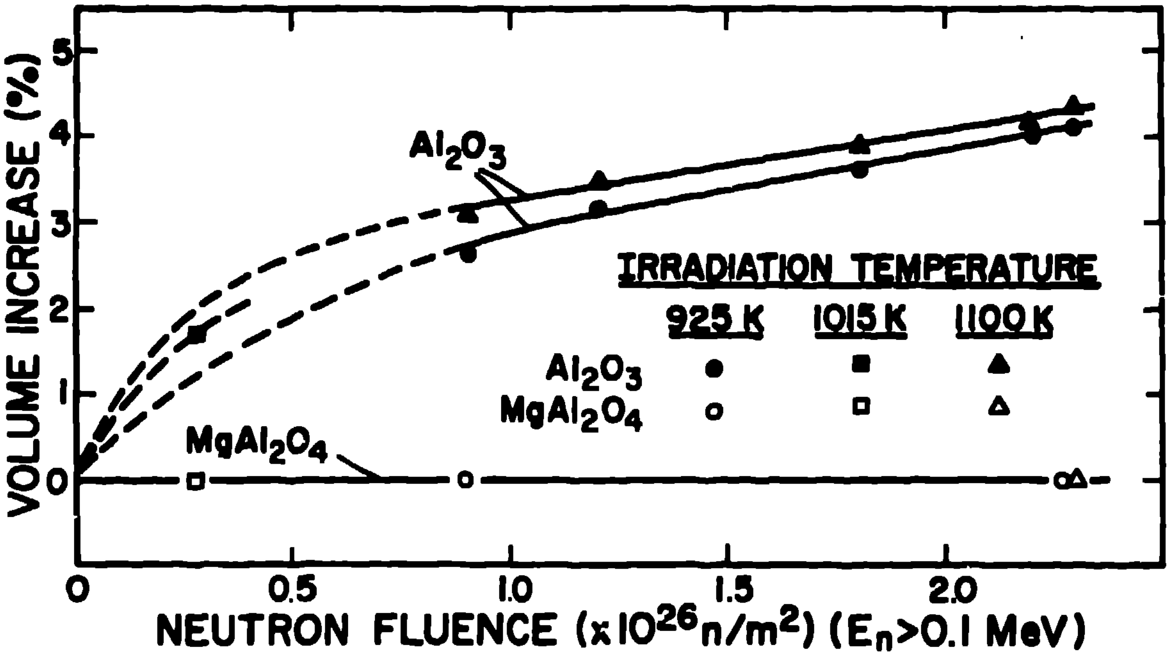

VOLUME INCREASE (%)
NEUTRON FLUENCE (x10^{26}n/m^2) (E_n>0.1 MeV)
Al_2O_3
$MgAl_2O_4$
IRRADIATION TEMPERATURE
925 K
1015 K
1100 K
Al_2O_3
$MgAl_2O_4$
0
1
2
3
4
5
0
0.5
1.0
1.5
2.0

Figure 3

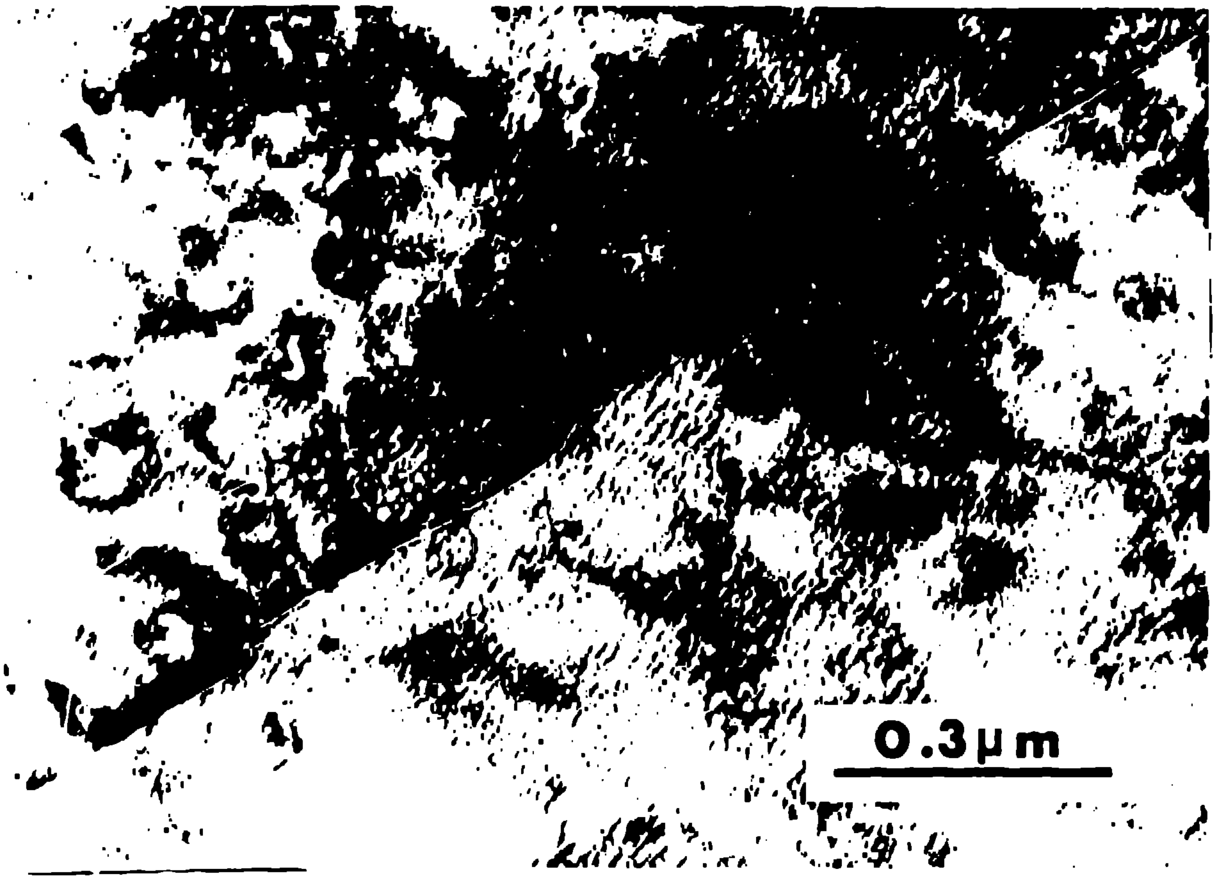
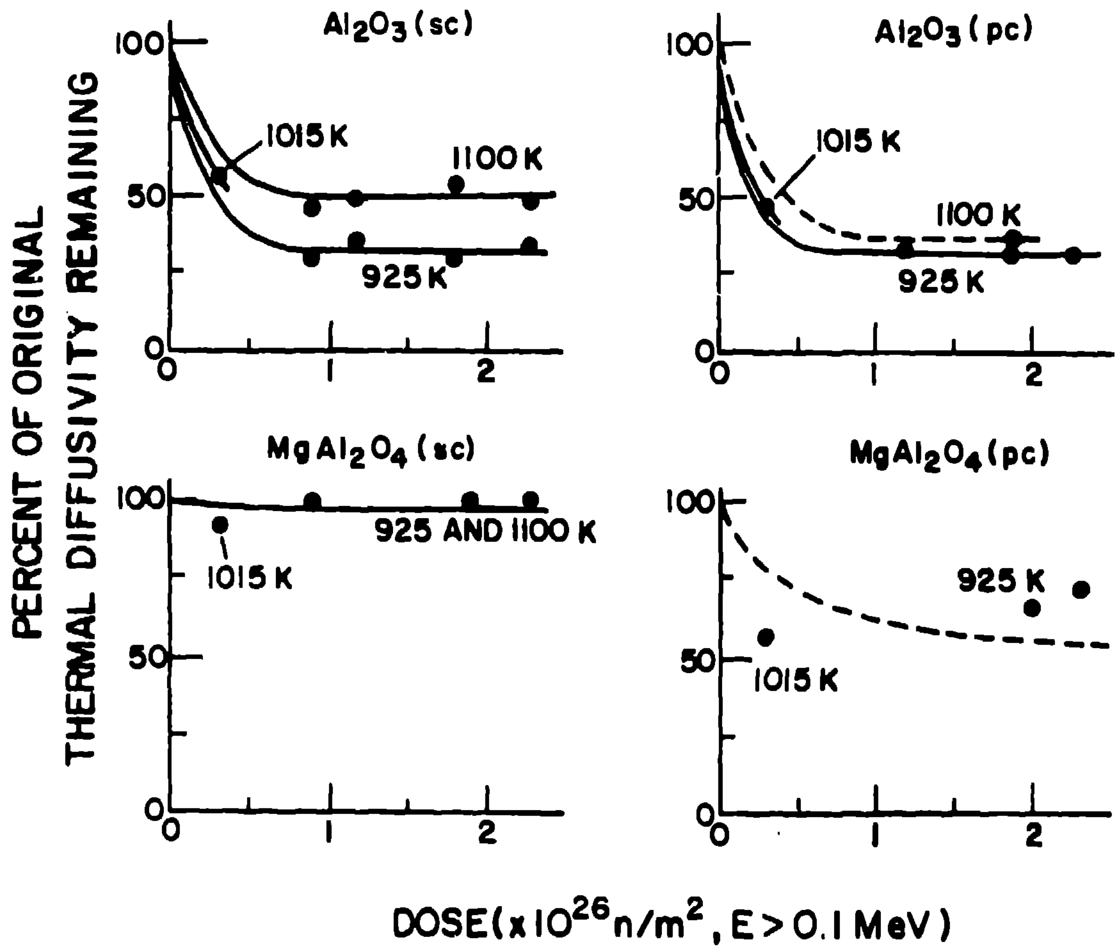


Figure 4



Al_2O_3 (sc)
Al_2O_3 (pc)
$MgAl_2O_4$ (sc)
$MgAl_2O_4$ (pc)
PERCENT OF ORIGINAL
THERMAL DIFFUSIVITY REMAINING
1015 K
1100 K
925 K
925 AND 1100 K
100
50
0
1
2
DOSE($\times 10^{26}$ n/m^2, E > 0.1 MeV)

Figure 5

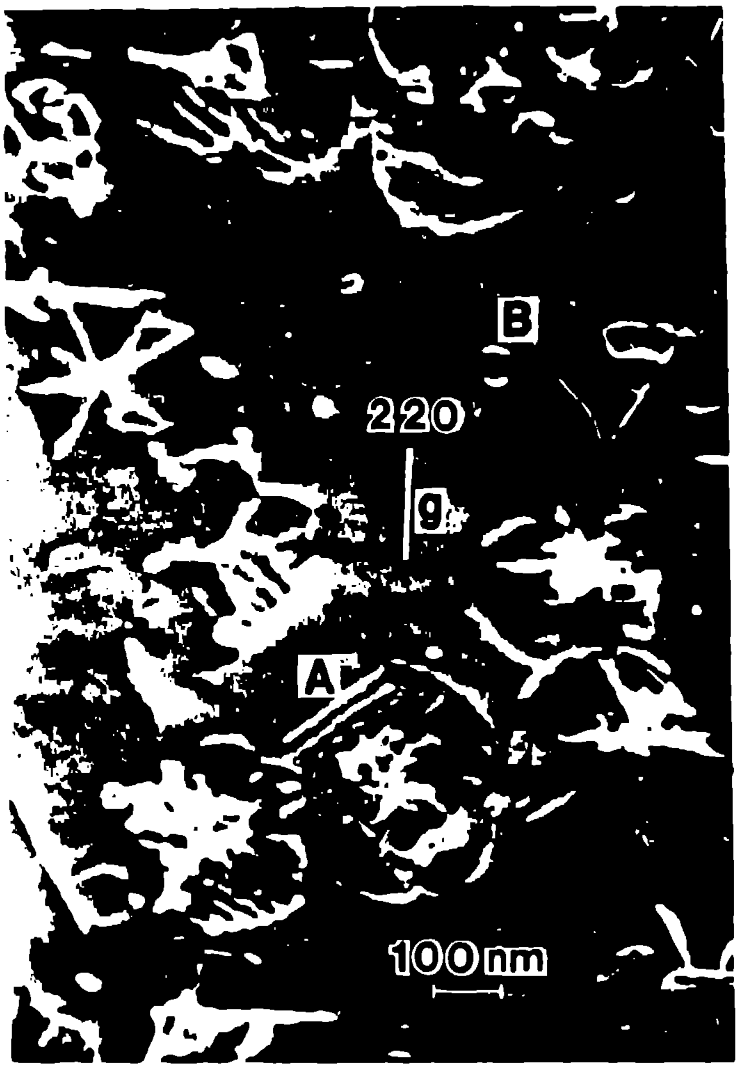


Figure 6

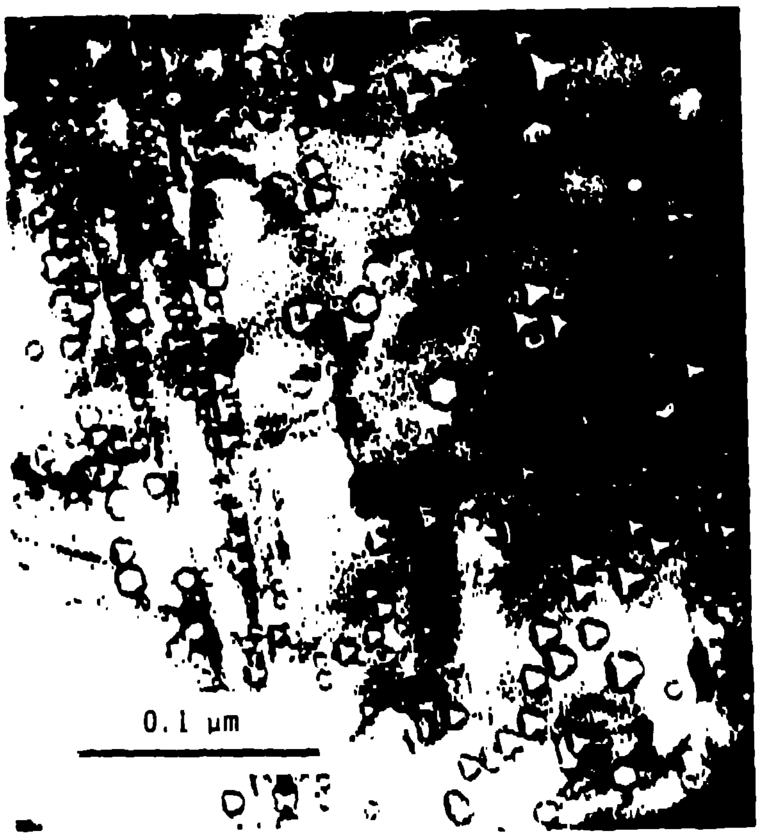


Figure 7

Figure 8