A major purpose of the Technical Information Center is to provide the broadest dissemination possible of information contained in DOE's Research and Development Reports to business, industry, the academic community, and federal, state and local governments.

Although a small portion of this report is not reproducible, it is being made available to expedite the availability of information on the research discussed herein.

1

LA-UR -86-1276
CONF-860608--1

RECEIVED BY OSTI MAY 1 2 1986

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--86-1276

DE86 010181

TITLE: CERAMICS FOR FUSION APPLICATIONS

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

SUBMITTED TO: World Congress on High Tech Ceramics
Milan, Italy June 23-28, 1986

CERAMICS FOR FUSION APPLICATIONS

F. W. Clinard, Jr.
Materials Science and Technology Division, Los Alamos National Laboratory,
Los Alamos, New Mexico 87545 (USA)

ABSTRACT

Ceramics are required for a variety of uses in both near-term fusion devices and in commercial powerplants. These materials must retain adequate structural and electrical properties under conditions of neutron, particle, and ionizing irradiation; thermal and applied stresses; and physical and chemical sputtering. Ceramics such as Al_2O_3, $MgAl_2O_4$, BeO, Si_3N_4 and SiC are currently under study for fusion applications, and results to date show widely-varying response to the fusion environment. Materials can be identified today which will meet initial operating requirements, but improvements in physical properties are needed to achieve satisfactory lifetimes for critical applications.

INTRODUCTION

As designs for fusion devices become more detailed, requirements and operating conditions for ceramics are specified with greater precision. Although applications vary with the nature of the device, the following three can be considered generic to most designs of advanced fusion machines:

- ceramics for high heat flux applications at the first wall
- dielectrics for RF heating systems
- insulators for lightly-shielded or unshielded magnets

Additional requirements include insulators for neutral beam injectors and direct converters, for suppression of magnetohydrodynamic effects, and for diagnostic systems. It has also been suggested that large portions of the reactor structure itself could be made from ceramics, to reduce residual radioactivity of the facility (ref. 1).

The subject of ceramics for fusion devices has been reviewed earlier (refs. 2-10). Examination of these works reveals an interesting history of perceived ceramics needs and understanding of their operating environment, as well as a record of the slowly but steadily evolving data base. This review is intended to bring the reader up-to-date with respect to these considerations (with focus on the three major ceramics applications cited above), and to draw the reader's attention to likely areas for future work. It is hoped that the latter will prove useful to researchers seeking to develop new or improved ceramics for fusion applications.

CERAMICS FOR HIGH HEAT FLUX APPLICATIONS

Ceramics are in competition with metals and with laminated (perhaps ceramic/metal) systems for use as first wall armor, limiters, divertors, and heat sinks. Ceramics typically offer the following advantages for these applications:

- low activation
- low atomic number for minimal plasma contamination
- high operating temperature
- resistance to chemical sputtering
- absence of problems with toxicity
- low cost of starting materials
- immunity to magnetic forces (if an insulator or semiconductor).

This list represents an impressive argument for the use of ceramics for high heat flux components. However, it must be recognized that the intrinsic brittleness of these materials presents severe problems in a high thermal flux environment, that must be addressed by careful selection of candidate materials and application of brittle materials design techniques.

High heat flux materials can be subjected to heat loads ranging from 30 W/cm^2 (first wall, normal operation) through 100-200 W/cm^2 (shine-through from neutral beam injection or flux to the divertor plate) to 50 kW/cm^2 during brief plasma disruptions. The last value presents severe problems of survivability for most materials, but it is hoped that improvements in instrumentation and feedback systems on advanced machines will allow the worst consequences of disruptions to be avoided.

Requirements for high heat flux ceramics are dominated by the need for good performance under thermal stress conditions, so it is apparent that a candidate material should have high thermal conductivity and a low coefficient of thermal expansion. If prevention of crack initiation is of prime importance, then strength should be high and elastic modulus low; if on the other hand crack propagation is the most important consideration, the needs with respect to the last two parameters are reversed. Since prevention of propagation often implies intentional formation of a dense array of fine cracks that would reduce thermal conductivity, it appears that prevention of crack initiation is the more useful consideration here.

Candidate single-phase ceramics for this application include SiC, Si_3N_4, Al_2O_3, BeO, and $MgAl_2O_4$. The first two are noted for good performance under conditions of high thermal and mechanical stress; alumina is reasonably good under these conditions, and can serve as a standard of comparison for competing materials. $MgAl_2O_4$ is generally considered somewhat inferior to Al_2O_3 as a structural ceramic, but recent work by Smyth et al. (ref. 11) has shown that careful control of impurity content can result in a spinel with strength comparable to that of alumina. BeO is probably the least attractive of these materials because of its toxicity.

One of the most promising materials for high heat flux applications is a new form of SiC, Hitaceram SC-101 (ref. 12). Reduction of impurity content in this sintered product has resulted in a value of thermal conductivity equal to that of aluminum and four times that of conventional polycrystalline SiC (Table 1). Thermal shock studies of SC-101 (ref. 13) show expectedly good performance, equivalent to that of fine-grained graphite.

TABLE 1
Comparison of physical and electrical properties of high-purity polycrystalline SiC with those of other materials (ref. 12).

Material	Thermal Conductivity W/mK, at RT	Electrical Resistivity Ω-cm, at RT	Thermal Expansion Coeff., $\times 10^{-6}$ K
Hitaceram SC-101	270	10^{13}	3.[illegible]
Structural SiC	[illegible]	$<10^{3}$	[illegible]
[illegible]	260	$>10^{14}$	[illegible]
Aluminum	239	2.7×10^{-6}	[illegible]

Lifetime of plasma-facing components may be relatively short because of sputtering erosion, but it is nevertheless envisaged that neutron fluences will be sufficient to cause significant structural changes. Ceramics vary widely in their response to irradiation damage, with some being badly degraded by doses as low as 10^{24} n/m^2 and others demonstrating little change (or an improvement) in properties at 200 times that dose (ref. 10). SiC falls in the middle range, with moderate swelling, little strength change, and (along with most insulating ceramics) a reduction in thermal conductivity (ref. 1). Swelling of this ceramic at temperatures below 1300 K appears to saturate at low doses, implying resistance to gross damage at very high fluences.

Laminar structures (e.g., ceramic bonded to a water-cooled metal substrate) offer an attractive combination of properties, and are under study for use in near-term fusion devices. However, problems resulting from differential swelling of the two materials, plus damage associated with the interface, mitigate against use of such systems where neutron fluxes are high. An example of the consequences of differential swelling for an otherwise attractive pair of materials (SiC on graphite) is shown in Fig. 1. Here the SiC layer swelled to a saturation value of 1.5 vol% early in the irradiation test, while the graphite progressively densified to a value ≈7 vol% greater than that of the as-fabricated material. The result was almost complete delamination, which in a fusion device could lead to further destruction of the protective layer and consequent exposure of the graphite to chemical attack from the hydrogen isotopes of the fuel.

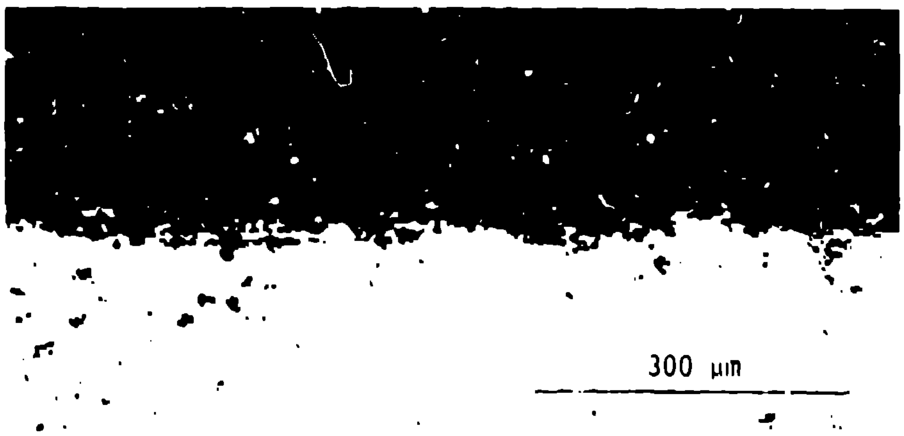

Fig. 1. Microcracking at the interface between SiC (top) and isotropic graphite after irradiation to $2(10)^{25}$ n m^{-2} at 530 K (ref. 14).

Composite ceramics can offer improved structural properties for high heat flux applications, but are subject to irradiation-induced degradation from another source, namely, differential swelling between additive phase and matrix. The consequence can be high internal stresses, and ultimately, separation along phase boundaries. A similar problem affects ceramics with non-cubic crystal structures (e.g., Al_2O_3 and BeO). Here, anisotropic swelling within each grain can generate damaging levels of stress (ref. 15) and limit materials lifetime. Since anisotropy can be strongly temperature-dependent (ref. 16), it is necessary to specify irradiation temperature before the extent of this problem can be judged. In both composite and anisotropic ceramics some relief should be available by using fine particle or grain sizes.

If it becomes possible to reduce sputtering (for example, by reduction of plasma edge temperature), then it will be desirable to have ceramics capable of sustaining very high damage levels. Unfortunately, there are essentially no data available for these materials beyond about 20 displacements per atom (dpa), which is equivalent to a year's exposure at the first wall of a 2 MW/m^2 reactor, whereas lifetime of the facility might be twenty years or more. This is an area where further studies are clearly needed.

Development of ceramics that can withstand intense damage levels will require both a fundamental understanding of damage effects and innovative materials selection. An example of the latter is the use of materials that can periodically be restored to their undamaged condition by thermal cycling. One possibility is to allow first wall materials to operate at very high temperatures (utilizing cooling by radiative means only), but defect aggregates such as voids are notoriously difficult to remove by annealing.

An intriguing idea is to use materials that can exist in either crystalline or amorphous forms, and to vary the operating temperature so that damage acquired at elevated temperatures can be erased by periodic operation at lower temperatures where damage causes conversion to the amorphous condition. This suggestion has recently been proposed for metallic systems (ref. 17), but since ceramics can also undergo such temperature-dependent transitions (e.g., ref. 18), the principle can also be applied here. The cyclic nature of operating temperatures for high heat flux components makes this approach particularly appropriate, but accommodation would have to be made for the characteristic poor thermal conductivity of ceramics in the disordered state.

DIELECTRICS FOR RF HEATING SYSTEMS

Most conceptual designs for fusion devices call for the use of RF beams to heat the plasma. Possible coupling modes and their operating frequencies include ion cyclotron (about 10^8 Hz), lower hybrid (10^9-10^{10} Hz), and electron cyclotron (10^{11} Hz). Corresponding methods for transmitting the energy to the first wall and plasma might involve coaxial cables, waveguides, antennas, and/or windows. Applications for ceramics might therefore include spacers for coaxial cables, a high dielectric constant filler for waveguides, antenna standoffs, and windows.

The most difficult of these applications appears to be windows for use at millimeter wave frequencies ($\approx 10^{11}$ Hz). The failure mode is likely to be thermal stress-induced fracture resulting from absorption of energy from the beam; thus materials requirements are high strength, good dimensional stability, high thermal conductivity and good transmissivity. A compliant mounting system for the window could significantly reduce thermomechanical stresses.

The function of the window is to separate the first wall environment (including residual D-T fuel) from the RF source and the other remote systems of the facility. The portion of the waveguide from the source to the window may be filled with SF_6 gas to improve transmissivity. Location of the window with respect to the plasma has not yet been determined, but since best waveguide performance will be attained if the window is located near or at the first wall, severe neutron and other fluxes must be anticipated.

The window itself will probably be of laminar design, with a flowing coolant between the two elements. Candidate materials include BeO (primarily because of its high thermal conductivity), Al_2O_3 (presently used for gyrotron windows), $MgAl_2O_4$ (because of its generally good radiation resistance), and Si_3N_4 (an insulator known for its high strength and thermal shock resistance). Conventional SiC is a semiconductor, but the high-purity form discussed earlier demonstrates good insulating properties (Table 1) and is therefore also considered a candidate material for this application.

Little is known about the effect of neutron damage on dielectric losses, which are proportional to the product of loss tangent ($\tan\delta$) and dielectric constant (K). First results at mm wave frequencies for heavily-damaged ceramics, recently obtained by Frost (ref. 19), are shown in Table 2. It may be seen that both Al_2O_3 and BeO suffered a doubling of lossiness at room temperature as a result of this exposure. This work also identified a potential problem not heretofore considered: the consequences of reflection of a portion of the intense beam back to the source, as a result of detuning of the window introduced by changes in dimensions and dielectric properties.

Calculations by Fowler (ref. 20) have shown that under realistic conditions a doubling of $K\tan\delta$ leads to an increase of a factor of two in energy absorbed, and that in turn results in a doubling of stress. The consequences to window lifetime can be serious: Frost used results from Ferber et al. (ref. 21) to show that the lifetime for a BeO window can be reduced from one year to less than a day by such a doubling of stress.

Additional significant degradation will result from the reduction of thermal conductivity that accompanies irradiation damage in most ceramics. This can be partially offset by the increase in strength that often accompanies formation of defect aggregates such as dislocation loops and voids (ref. 14). However, in polycrystalline forms of materials such as Al_2O_3 and BeO with non-cubic crystal structures, this strengthening can be more than offset by stresses resulting from anisotropic swelling.

Even if it is possible to locate RF windows in areas where neutron doses are low, a considerable increase in lossiness may result. Working in the range of approximately 10^4-10^6 Hz, Fowler (ref. 20) found increases of as much as an order of magnitude in Al_2O_3 at 10^{22} n/m^2, and a dependence on neutron energy. More recently, Pells et al. (ref. 22) assessed the behavior of two forms of alumina plus aluminum oxynitride at doses up to 10^{24} n/m^2 between 1 and 65 MHz and reported complex and sometimes large dependencies on dose, frequency, and nature of the starting material.

TABLE 2
Room-temperature dielectric properties of alumina and beryllia at 95 GHz after irradiation to 8×10^{21} n/m^2 at 660 K (ref. 19).

Material and Condition*	Dielectric Constant (K)	Loss Tangent ($\tan\delta$), $\times 10^{-4}$	$K\tan\delta$, $\times 10^{-3}$
Al_2O_3:			
control	10.28	4.5	4.6
irradiated	10.10	9.7	9.8
BeO:			
control	6.65	8.0	5.3
irradiated	5.34	17.4	10.2

It can be seen from this discussion that many facets of radiation response come into play when considering the window application. Changes in strength, density, and thermal conductivity are fairly well understood (refs. 14 and 23); however, a fundamental understanding of loss mechanisms in irradiated ceramics is needed, both with respect to post-irradiation effects and to temporary changes concurrent with generation of structural damage and absorption of ionizing energy. Once that is in hand, it should be possible to develop improved forms of candidate materials for this application.

If it is necessary to locate RF windows at the first wall of a fusion device, then irradiation by other than neutrons must be considered. Ion bombardment may have deleterious effects both from implantation (perhaps leading to blistering) and from physical erosion (sputtering). Chemical erosion, although much less than that for elemental materials such as graphite, might present a problem at elevated temperatures. Finally, deposition of impurity layers could reduce transmissivity or increase reflectivity. It may be desirable to provide localized shielding for the window (by either physical barriers or magnetic fields) in order to reduce the deleterious consequences of the first wall environment.

INSULATORS FOR LIGHTLY-SHIELDED MAGNETS

The intense magnetic fields required for containment and shaping of the plasma are generated by either cryogenic or normal (near-room temperature) coils. The former have damage-sensitive components such as the superconductor, its stabilizer, and polymeric insulators, so that shielding is required. The latter type of magnet uses a copper alloy conductor, water cooling, and ceramic insulators, so that reasonably good radiation resistance can be anticipated. In principle the ceramic insulator could be either in bulk or powder form; however, concerns about electrical resistivity and thermal conductivity of the latter (ref. 24) indicate that only the bulk form should be used. Coils of both types are massive, difficult to repair, and represent half the cost of an advanced fusion device; thus the materials chosen for this application should if possible last the lifetime of the machine.

There is a trend toward compact reactors, which implies less shielding and greater use of normal coils. In some designs the inner conductor is just behind the first wall, so that neutron fluxes are high. However, the first wall serves as a shield for particulate and electromagnetic radiation. A lifetime dose of 100 dpa or more is likely for the inboard ceramic insulators of such magnets.

Candidate materials for this application include Al_2O_3, $MgAl_2O_4$, SiC and Si_3N_4. Alumina suffers from anisotropic swelling (refs. 15 and 16), so that high grain boundary stresses and ultimately a catastrophic loss of strength restrict lifetime for this ceramic to doses on the order of 10 dpa. Nevertheless, its high state of development and good starting strength (necessary to resist large magnet forces) makes this material a likely choice for intermediate-term machines.

Tests of spinel to a damage level of ≈20 dpa show excellent resistance to neutron irradiation. At temperatures of 660 K and greater, swelling of single-crystal material is near zero and strength is actually enhanced by irradiation damage. This behavior is attributable to the fact that most irradiation-induced defects recombine harmlessly, while the remainder precipitate into dislocation loops whose strain fields apparently strengthen the material by crack deflection (refs. 14 and 15).

Polycrystalline spinel also performs well, but shows a low level of swelling and less strength enhancement than does its single-crystal counterpart (ref. 14). Transmission electron microscopic (TEM) examination reveals the presence of small voids formed near (but not in) grain boundaries after irradiation at elevated temperatures, apparently as a result of preferential annihilation of nearby interstitial atoms at grain boundaries (ref. 25). This unusual microstructure is shown in Fig. 2. At lower irradiation temperatures, areas near boundaries are denuded of the interstitial dislocation loops that are formed within the grains (ref. 26). It is not clear whether these grain boundary effects are intrinsic to polycrystalline spinel or whether adjustments in composition could mitigate the problem.

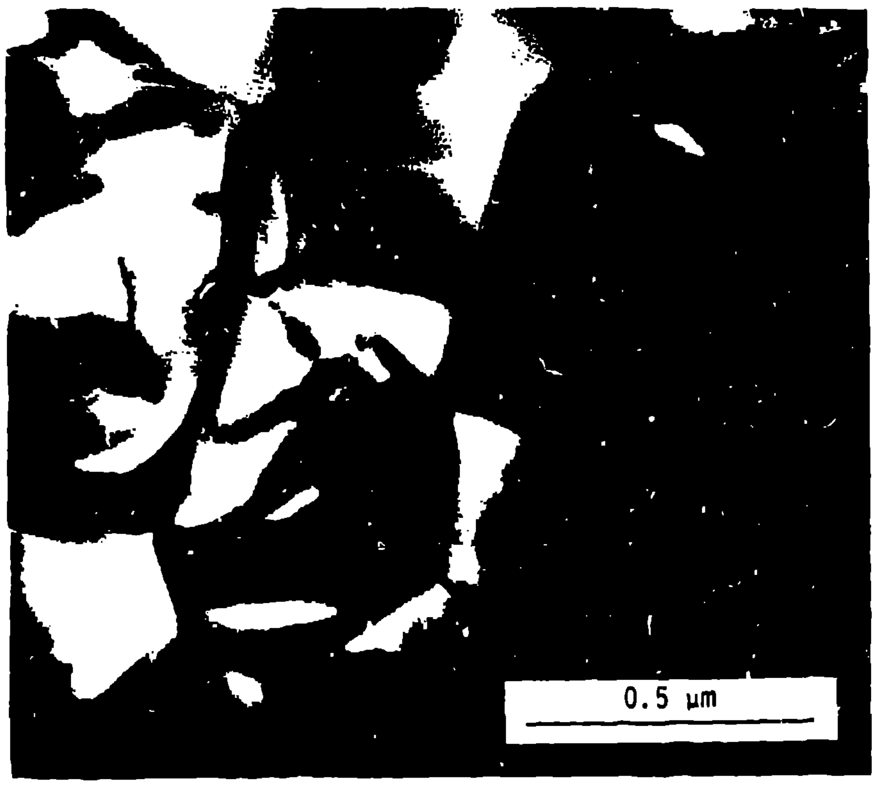

Fig. 2. Voids arrayed near grain boundaries in $MgAl_2O_4$ after irradiation to 2×10^{26} n/m^2 at 1100 K.

The improvement of strength or fracture toughness that accompanies accumulation of neutron irradiation damage in cubic polycrystalline ceramics or single-crystal materials is a phenomenon of great importance to all fusion applications. Examples of results obtained, for several single-crystal materials and test temperatures, are shown in Table 3 along with a description of the dominant damage microstructures observed by TEM. One of two mechanisms is thought to be responsible for the observed enhancement of mechanical properties: either crack deflection by strain fields around dislocation loops, or crack pinning, blunting, branching, and jogging as a result of passage through an array of fine voids (ref. 27). Considering that these improvements in mechanical properties are observed in unoptimized materials, there appears to be ample opportunity for further exploitation of these strengthening phenomena.

TABLE 3

Changes in strength and fracture toughness, along with characteristic damage microstructures, resulting from elevated-temperature irradiation to a dose of 2×10^{26} n/m^2.

Ceramic (ref.)	Irradiation Temp., K	Change in Strength	Change in Fracture Toughness	Damage Microstructure
Al_2O_3 (ref. 27)	925	--	+20%	36Å dia voids
Al_2O_3 (ref. 27)	1100	--	+110%	90Å dia voids
$MgAl_2O_4$ (ref. 14)	680	+92%	--	200Å dia interstitial dislocation loops
$MgAl_2O_4$ (ref. 14)	815	+75%	--	300Å dia interstitial dislocation loops

It is difficult to conduct neutron irradiation tests at temperatures close to that of a magnet's water coolant, using a sodium-cooled fission reactor as a test facility. (For example, the sodium in the EBR-II reactor operates at about 650 K.) Nevertheless, in one instance it was possible to carry out a long-term test at 430 K in a water-cooled reactor, to a damage level of 20 dpa (ref. 26). This work showed that while spinel was strengthened, a small amount of swelling (0.3 vol%) did occur. If tolerable swelling is taken to be 3 vol% (ref. 24), a relatively short lifetime of 4.3 y is calculated for a 2MW/m^2 machine (ref. 10). It is apparent that materials must be developed with even greater dimensional stability than that of conventional spinel, in order to meet the needs of lightly-shielded magnets.

FISSION VS. FUSION NEUTRON DAMAGE

It is important to consider differences between fission neutron (≈1 MeV) and fusion (14 MeV) neutron damage, since the high-dose data base is totally from fission reactor studies yet the environment of a D-T reactor is dominated by a softened fusion neutron energy spectrum.

Higher-energy neutrons have the potential for creating damage cascades different from those formed by fast fission neutrons, and also generate much greater quantities of transmutation products. The former topic is currently being assessed by Kinoshita (ref. 28) who has irradiated a large number of ceramics in the RTNS-II 14 MeV neutron source. Early results have shown the presence of contrast effects in Cr_2O_3 that represent the first reported observations of cascades in ceramics.

Transmutation products are generated relatively rapidly in the environment of high-energy fusion neutrons. Of particular concern are the transmutation gases H and He, which could significantly affect damage microstructures. However, metallic products may also play an important role in altering electrical properties of insulators. Calculated concentrations of several transmutation products for four ceramics (ref. 3) after exposure for a year at the first wall of a $2MW/m^2$ machine are shown in Table 4.

TABLE 4
Transmutation products (in atomic parts per million) for four candidate fusion reactor ceramics (ref. 3).

	SiC	BeO	Si_3N_4	Al_2O_3
Hydrogen	880	206	1334	912
Helium	3190	5840	1516	1574
Carbon	--	1138	656	1248
Magnesium	916	--	510	368

It is of critical importance to carry out simulation tests of transmutation effects in ceramics, both to obtain experimental data for a fusion environment and to establish correlation parameters for the present fission reactor-generated data base. One approach (ref. 10) is to introduce the transmutation products H, He and C by irradiating isotopically-tailored ceramics in a mixed-spectrum fission reactor. In this scheme displacement damage would be generated by the fast neutrons, and transmutations by the thermal neutrons. The key reactions to be utilized are $^{14}N(n,p)^{14}C$ and $^{17}O(n,\alpha)^{14}C$. A study of this type may require special fabrication techniques to assure that adequate concentrations of the special isotopes are retained in the oxides, nitrides, and/or oxynitrides chosed for evaluation.

REFERENCES

1 G. R. Hopkins and R. J. Price, Fusion reactor design with ceramics, Nucl. Eng. and Design/Fusion, 2 (1985) 111-143.

2 A. Holmes-Siedle, Radiation effects in the fusion power programme, Nature, 251 (1974) 191-196.

3 L. H. Rovner and G. R. Hopkins, Ceramic materials for fusion, Nuclear Technol., 29 (1976) 274-302.

4 F. W. Clinard, Jr., Electrical insulators for magnetically-confined fusion reactors, in: C. Stein (Ed.), Critical Materials Problems in Energy Production, Academic Press, New York, 1976, pp. 141-163.

5 F. W. Clinard, Jr., Ceramics for applications in fusion systems, J. Nucl. Mater., 85-86 (1979) 393-404.

6 F. W. Clinard, Jr. and G. F. Hurley, Ceramic and organic insulators for fusion applications, J. Nucl. Mater., 103-104 (1981) 705-716.

7 Y. Suzuki, T. Iseki and T. Maruyama, Ceramics for nuclear reactors, Bull. Res. Lab. for Nucl. Reactors, 7 (1982) 239-255.

8 F. W. Clinard, Jr., G. F. Hurley and R. W. Klaffky, Ceramics for fusion reactor applications, Res Mechanica, 8 (1983) 207-234.

9 L. P. Pells, Radiation effects in ceramic materials for fusion reactors, J Nucl. Mater., 122-123 (1984) 1338-1351.

10 F. W. Clinard, Jr., Ceramics for fusion devices, J. Mater. for Energy Systems, 6 (1984) 100-106.

11 I. R. Smyth, O. Moreno and W. C. Seymour, Engineering ceramics of magnesium aluminum oxide, work presented at the Annual Meeting of the American Ceramic Society, Chicago, IL, April 30, 1986.

12 Y. Ura and O. Asai, Development of SiC ceramics having high thermal conductivity and electrical resistivity, Japan Fineceramics Association Report Vol. 1 No.4; see also Y. Takeda, K. Usami, K. Nakamura, S. Ogihara, M. Maeda, T. Miyoshi, S. Shinozaki and M. Ura, Grain-boundary structure of highly resistive SiC ceramics with high thermal conductivity, Advances in Ceramics, 7 (1984) 253-259.

13 . Gotoh, Hitachi Research Laboratory, in preparation.

14 F. W. Clinard, Jr., G. F. Hurley, L. W. Hobbs, D. L. Rohr and R. A. Youngman, Structural performance of ceramics in a high-fluence fusion environment, J. Nucl. Mater. 122-123 (1984) 1386-1392.

15 F. W. Clinard, Jr. and L. W. Hobbs, Radiation effects in non-metals, in: R. A. Johnson and A. N. Orlov (Eds.), Physics of Radiation Effects in Crystals, North-Holland, Amsterdam, 1985, pp. 387-471.

16 F. W. Clinard, Jr., J. M. Bunch and W. A. Rankin, Neutron irradiation damage in Al_2O_3 and Y_2O_3, in: J. S. Watson and F. W. Wiffen (Eds.) Proc. Int. Conf on Radiation Effects and Tritium Technology for Fusion Reactors, Gatlinburg, TN, USA, October 1-3, 1975, USERDA Report CONF-750989, pp. II-498--II-516.

17 J. Megusar, O. K. Harling and N. J. Grant, Possible in situ regeneration of irradiated structural materials and a possible approach to their development, J. Nucl. Mater. 125 (1984) 346-348.

18 F. W. Clinard, Jr., D. E. Peterson, D. L. Rohr and L. W. Hobbs, Self-irradiation effects in ^{238}Pu-substituted zirconolite: I. Temperature dependence of damage, J. Nucl. Mater. 126 (1984) 245-254.

19 H. M. Frost, Millimeter-wave properties of neutron-irradiated ceramics for RF-window MFE applications, Eighth Annual Progress Report on Special Purpose Materials for Magnetically-Confined Fusion Reactors, DOE/ER-0113/5, in press.

20 J. D. Fowler, Jr., Radiation-induced loss measurements and thermal stress calculations for ceramic windows, J. Nucl. Mater. 122-123 (1984) 1359-1364.

21 M. K. Ferber, H. D. Kimrey and P. F. Becher, Analysis of the temperature and stress distributions in ceramic window materials subjected to microwave heating, Oak Ridge National Laboratory Report ORNL/TM-8713 (1983).

22 G. P. Pells, S. N. Buckley, G. J. Hill and M. J. Murphy, Radiation effects in electrically insulating ceramics, Harwell Laboratory Report AEPE R 11715 (1985).

23 P. G. Klemens, G. F. Hurley and F. W. Clinard, Jr., Reductions in thermal conductivity of ceramics due to radiation damage, in: G. L. Kulcinski (Ed.), Proc. 2nd Topical Meeting on the Technology of Controlled Nuclear Fusion, Richland, WA, USA, September 21-23, 1976, USERDA Report CONF-760935-P3, pp. 957-964.

24 L. J. Perkins, Radiation dose-rate resistivity degradation in ceramic insulators and assessment of the consequences in fusion reactor applications, University of Wisconsin Report UWFDM-469 (1982).

25 F. W. Clinard, Jr., G. F. Hurley and L. W. Hobbs, Neutron irradiation damage in MgO, Al_2O_3 and $MgAl_2O_4$ ceramics, J. Nucl. Mater. 108-109 (1982) 655-670.

26 G. F. Hurley, J. C. Kennedy, F. W. Clinard, Jr., R. A. Youngman and W. R. McDonell, Structural properties of MgO and $MgAl_2O_4$ after fission neutron irradiation near room temperature, J. Nucl. Mater. 103-104 (1981) 761-766.

27 F. W. Clinard, Jr., G. F. Hurley, R. A. Youngman and L. W. Hobbs, The effect of elevated-temperature neutron irradiation on fracture toughness of ceramics, J. Nucl. Mater. 133-134 (1985) 701-704.

28 C. Kinoshita, Radiation damage in oxide and carbide ceramics, in: T. Uchida (Ed.), Summaries of Special Research Project on Nuclear Fusion; The Ministry of Education, Science and Culture, Japan (1984).