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DATA COMPILATION FOR RADIATION
EFFECTS ON CERAMIC INSULATORS

August 1986

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Data Compilation for Radiation Effects
on Ceramic Insulators

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Data of radiation effects on ceramic insulators were compiled from the literatures and summarized from the viewpoint of fast neutron irradiation effects. The data were classified according to the properties and ceramics. The properties are dimensional stability, mechanical property, thermal property and electrical and dielectric properties. The data sheets for each table or graph in the literatures were made. The characteristic feature of the data base was briefly described.

Keywords: Radiation Effects, Ceramics, Insulators, Data Base,
Swelling, Mechanical Property, Thermal Property,
Electrical Property, Dielectric Property,
Thermonuclear Reactor Materials

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セラミックス絶縁材料の放射線照射効果に関するデータ収集

日本原子力研究所東海研究所物理部

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(1986年8月4日受理)

核融合炉においては各種絶縁材料が使用されるが、その環境は従来の核分裂炉に比較して高線量場であり、極低温から高温までの広い温度範囲にわたる。このため絶縁材料の放射線照射効果に関しては、高速中性子の照射効果の視点にたった現象の解明が目標としてとらえられる必要がある。

本報告では、絶縁材料の中からセラミックスを中心とする無機絶縁材料をとりあげ、それらの放射線照射効果についての文献データの収集を行った。収集したデータは特性で分類した。対象とした特性は、寸法安定性(スエリング)，機械的特性，熱的特性，電気的特性等である。各特性毎にさらにセラミックスの種類で分類した。図表データはデータシート化した。また、各特性毎に、データの特徴と現状について簡単にまとめた。

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本報告書は^株東芝との共同研究の一部をまとめたものである。

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1. Introduction

Studies of radiation effects on insulators have been vigorously performed for the development of fusion devices. In fusion Devices, nonorganic insulators, most of which are ceramic materials, are expected to be used for the components at elevated temperatures. Organic insulators are expected to be used for super-conducting magnet at low temperatures.

The properties of insulators under radiation have not been well understood yet as compared to those of metallic materials. One of this reason is that insulators have not been exposed to high radiation environments so far. However, in a fusion device, insulators are expected to be used in a environment in which the radiation level is much higher than those in a fission reactor and 14 MeV neutrons have the main contribution on damage in insulators. To know the property changes under a fusion radiation environment is of great importance in developing fusion devices.

In the present report, the data of radiation effects on ceramics as organic insulators were collected from the literatures to assess the current data base. This is thought to be useful to clarify the research items and the future directions in studying the radiation effects on insulators and in developing new ceramic insulators.

The environments and properties of ceramic insulators in a fusion device are briefly described in chapter 2. The data base are summarized in chapter 3. The data sheets and the literatures are shown in chapter 4 and chapter 5 respectively.

2. Environment and Properties of Ceramics in Fusion Devices

The environment which ceramics insulators encounter is dependent on the location in fusion devices where they are used. In a Tokamak reactor, insulators of torus structure, limiter and lightly-shielded magnetic coil, which are not expected to be replaced in the half reactor life, should be resistant to the cumulative radiation dose. On the other

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hand, windows of RF heating system and insulators of neutral beam injector are ready to be replaced, which should be resistant to the degradation during service.

An example of radiation environments on insulators is shown in Table 2-1. Almost all insulators are exposed to high dose of radiation, especially to fast neutrons up to a dose above 10^{22} n/cm², at a wide range of temperatures. In these environments, the degradation of ceramics may results in a serious problem. The properties which should be taken into account are:

dimensional stability (swelling),
change of mechanical properties (fracture strength),
and decrease of thermal conductivity (related to
thermal stress),
when ceramics are used as structural materials. In the case
of the application as insulation materials,
change of electrical conductivity,
decrease of dielectric breakdown strength
and increase of dielectric loss
should be assessed.

The effects of 14 MeV neutron irradiation on the above properties in ceramics is one of the most important problems to be clarified. This needs the fundamental knowledges of the elementary process such as ionization and displacement of lattice atoms in ceramics.

3. Data

The data collected from the literatures are summarized in Table 3-1 to Table 3-9. The data were selected from the literatures published in 1970-1985 which contained the data in the form of tables or graphs. The main scope of the survey in the literatures are listed to the application of ceramics to fusion devices, to incore monitor cable insulation in fission reactors and to SiC encapsulation of fuel element in a high temperature gas cooled reactor. The data on ceramic neutron absorber such as B₄C and ceramic fuel such

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as UO_2 were omitted.

The data were classified according to the properties described in chapter 2 and further classified according to the species of ceramics. If the nature or trade name of ceramics are given in the literature, these informations are also shown in the Tables. For each data, radiation particle, radiation dose, irradiation temperature and facility used for irradiation are given in the tables. The data sheets were made for each table or graph in the literatures, shown in chapter 4. The number of the data sheet and the literature are given in the tables. The list of the literatures are shown in chapter 5.

The brief description of the data base on each properties are the following sections.

3.1 Swelling (Table 3-1 to Table 3-3)

Swelling is expressed by the percentage of the volume increase or decrease to the original volume of ceramics. Swelling is measured by the density change or by the calculation from the measured void density and void number density by using a transmission electron microscope. Most of the irradiations were performed by using EBR-II except for those in SiC. Al_2O_3 ceramics have been mostly examined while other ceramics were examined less systematically.

3.2 Mechanical Property (Table 3-4)

Most of the strength data were obtained as fracture strength by using three or four point bend test method after irradiation. In the case of brittle materials, the probability of fracture is usually analyzed by the Weibul statistics. In some literatures, the Weibul modulus was measured on irradiated ceramics. SiC ceramics have been examined while only a few data of other ceramics were found.

3.3 Thermal property (Table 3-5)

Thermal properties of ceramics in the literatures are thermal conductivity (k) and thermal diffusivity (κ). These two values are related to each other by

$$\kappa = \frac{k}{C_p \rho}$$

where ρ is the density and C_p the specific heat of the ceramic. Most of the data are expressed by the ratio of k or κ in irradiated ceramics to those before irradiation.

3.4 Electrical Property (Table 3-6)

The measured values of the electrical property in the literatures are electrical conductivity or electrical resistivity. There are only a few data on the resistivity recovery during annealing after irradiation in SiC and on the radiation induced conductivity on Al_2O_3 .

3.5 Dielectric Property (Table 3-7, Table 3-8)

Several nonsystematical data were found. They are the data of dielectric constant of irradiated Al_2O_3 and SiO_2 and the data of the short pulse dielectric breakdown strength of Al_2O_3 , as shown in Table 3-7.

The measurement of loss tangent has been made on only Al_2O_3 and SiO_2 , as shown in Table 3-8.

3.6 Miscellaneous (Table 3-9)

The change of lattice parameter by irradiation has been reported in several literatures. The data of He reemission from BeO and Al_2O_3 and optical absorption coefficient in Al_2O_3 were found.

Table 2-1 Ceramics in fusion reactors

Component	Operating Conditions				Candidate materials	Special problems
	Neutron flux (n/m ² ·s)	Ionizing dose rate (Gy/s)	Temperature (°C)	Potential gradient (kV/mm)		
First wall Limiters	10 ¹⁹	10 ⁴	<1200	—	High	Sputtering erosion
	10 ¹⁹	10 ⁴	<1200 ^a	—	High	SiO, Si ₃ N ₄ Coated graphite ^b
Armor	10 ¹⁹	10 ⁴	<1200	—	Medium	Coated graphite ^b
Blanket structure	10 ¹⁷ –10 ¹⁹	10 ⁴	<1000	—	High	SiO, Al ₂ O ₃ Activation, swelling
Breeding Materials	10 ¹⁸ –10 ¹⁹	10 ⁴	<1400	—	Low	Li compounds Swelling
Neutral beam injector insulator	10 ¹⁴ –10 ¹⁶	10	<250	1–5	Medium	Al ₂ O ₃ , MgO, MACOR glass ceramic
Toroidal current break	10 ¹⁶ –10 ¹⁸	1–100	~500	<1	High	Al ₂ O ₃ , MgAl ₂ O ₄
Shaping and diverter coil insulators	10 ¹⁸	100	~500	~1	High	Al ₂ O ₃ , MgAl ₂ O ₄
Direct converter Insulators	10 ¹⁴ –10 ¹⁶	>10	~1000	~10	Low	Al ₂ O ₃ , MACOR glass ceramic
Windows for rf heating	<10 ¹⁹	<10 ⁴	~500	0.1–1	High	BeO, Al ₂ O ₃ Loss tangent must be low
Diagnostics & Instrumentation	<10 ¹⁴ –10 ¹⁹	10 ⁴	<700	~1	Low	Wide variety Optics & electronics

G. R. Hopkins et al., Nucl. Eng. Des./Fusion, 2 (1985) 111

Table 3-1 Swelling data

MATERIAL		IRRADIATION			DATA	REF
		DOSE	FACILITY	TEMPERATURE		
β -SiC		$1.2 \times 10^{22} \text{ n/cm}^2$ (E > 0.18 MeV)	ETR	625, 1500°C	A-1	2
α -SiC		$1.2 \times 10^{21} \text{ n/cm}^2$ (E > 1 MeV)	HFBR	200°C	A-2 A-3	1
SiC	NC-430	$1.2 \times 10^{21} \text{ n/cm}^2$ (E > 1 MeV)	HFBR	200°C	A-2 A-3	1
Al_2O_3	sapphire	$5.6 \times 10^{21} \text{ n/cm}^2$ (E > 0.1 MeV)	EBR-II	377, 602, 752°C	A-5 A-6 A-7	4
		$2.8 \times 10^{21} \text{ n/cm}^2$ (E > 0.1 MeV)				
	sc	$2.3 \times 10^{22} \text{ n/cm}^2$ (E > 0.1 MeV)	EBR-II	740°C 652, 827°C	A-15	8
		$2.2 \times 10^{22} \text{ n/cm}^2$ (E > 0.1 MeV)				
Lucalox		$4.1 \times 10^{21} \text{ n/cm}^2$ (E > 0.1 MeV)	EBR-II	377, 602, 752°C	A-5 A-6	4
		$8.2 \times 10^{21} \text{ n/cm}^2$ (E > 0.1 MeV)				
		$8 \times 10^{21} \text{ n/cm}^2$ (E > 0.1 MeV)				
		$8.2 \times 10^{21} \text{ n/cm}^2$ (E > 0.1 MeV)	ETR	70 ~ 325°C	A-12	5
AD-995		$8.2 \times 10^{21} \text{ n/cm}^2$ (E > 0.1 MeV)	EBR-II	690 ~ 1100°C	A-9 A-12	5
		$2.8 \times 10^{21} \text{ n/cm}^2$ (E > 0.1 MeV)				
		$2.3 \times 10^{22} \text{ n/cm}^2$ (E > 0.1 MeV)	EBR-II	740°C 652, 827°C	A-15 A-17	8 10
AL-995		$8.2 \times 10^{21} \text{ n/cm}^2$ (E > 0.1 MeV)	EBR-II	690 ~ 1100°C	A-11	5
AD-999X		$4.8 \times 10^{21} \text{ n/cm}^2$ (E > 0.1 MeV)	EBR-II	337, 602, 752°C	A-5 A-6	4
Avco		$4.8 \times 10^{21} \text{ n/cm}^2$ (E > 0.1 MeV)	EBR-II	337, 602, 752°C	A-5	4

sc: single crystal

Table 3-2 Swelling data

MATERIAL		IRRADIATION			DATA	REF
		DOSE	FACILITY	TEMPERATURE		
MgO		$2.1 \times 10^{22} \text{ n/cm}^2$ (E > 0.2 MeV)	HFIR	157°C	A-16	9
		$4.6 \times 10^{22} \text{ n/cm}^2$ thermal				
		$2.1 \times 10^{22} \text{ n/cm}^2$ (E > 0.1 MeV)	EBR-II	157°C	A-17	10
Y_2O_3		$6 \times 10^{21} \text{ n/cm}^2$ (E > 0.1 MeV)	EBR-II	377, 602, 752°C	A-5 A-8	4
		$2.8 \times 10^{21} \text{ n/cm}^2$ (E > 0.1 MeV)	EBR-II	740°C	A-15	8
$\text{Y}_2\text{O}_3 +$ 1% ZrO_2		$2.8 \times 10^{21} \text{ n/cm}^2$ (E > 0.1 MeV)	EBR-II	740°C	A-15	8
$\text{Y}_2\text{O}_3 +$ 10% ZrO_2		$6 \times 10^{21} \text{ n/cm}^2$ (E > 0.1 MeV)	EBR-II	377, 602, 752°C	A-5 A-8	4
$\text{Y}_3\text{Al}_5\text{O}_{12}$	sc pc	$2.8 \times 10^{21} \text{ n/cm}^2$ (E > 0.1 MeV)	EBR-II	740°C	A-15	8
BeO	Niberlox	$2.8 \times 10^{21} \text{ n/cm}^2$ (E > 0.1 MeV)	EBR-II	740°C	A-15	8
BeO- 5SiC		$2.8 \times 10^{21} \text{ n/cm}^2$ (E > 0.1 MeV)	EBR-II	740°C	A-15	8
$\text{ZrO}_2 -$ Y_2O_3	stabilized	$4.4 \times 10^{21} \text{ n/cm}^2$ (E > 0.1 MeV)	EBR-II	377, 602, 752°C	A-13	6
Si_3N_4	NC-132 pc	$2.8 \times 10^{21} \text{ n/cm}^2$ (E > 0.1 MeV)	EBR-II	740°C	A-15	8

sc: single crystal

pc: polycrystal

Table 3-3 Swelling data

MATERIAL		IRRADIATION			DATA	REF
		DOSE	FACILITY	TEMPERATURE		
MgAl ₂ O ₄	sc pc	2.8 × 10 ²¹ n/cm ² (E > 0.1 MeV)	EBR-II	740°C	A-15	8
	sc pc	2.3 × 10 ²² n/cm ² (E > 0.1 MeV)	EBR-II	652, 827°C	A-17	10
	sc pc	2.2 × 10 ²² n/cm ² (E > 0.1 MeV)	EBR-II	407, 542°C	A-4	3
	pc	2.1 × 10 ²² n/cm ² (E > 0.2 MeV) 4.6 × 10 ²² n/cm ² thermal	HFIR	157°C	A-16	9
Si ₂ ON ₂	pc	2.8 × 10 ²¹ n/cm ² (E > 0.1 MeV)	EBR-II	740°C	A-15	8
Sialon		2.8 × 10 ²¹ n/cm ² (E > 0.1 MeV)	EBR-II	740°C	A-15	8
SiO ₂	sc	2.3 × 10 ²² n/cm ² (E > 0.1 MeV)	EBR-II	400, 550°C	A-14	7
SiO ₂ -based glass ceramic		2.4 × 10 ²² n/cm ² (E > 0.1 MeV)	EBR-II	400, 550°C	A-14	7
MACOR		2.7 × 10 ²² n/cm ² (E > 0.1 MeV)	EBR-II	550°C	A-14	7
		10 ¹⁶ , 10 ¹⁸ n/cm ² (14 MeV)	RTNS-II	RT	A-18	11

sc: single crystal

pc: polycrystal

Table 3-4 Mechanical property data

MATERIAL		IRRADIATION			DATA	REF
		DOSE	FACILITY	TEMPERATURE		
SiC	reaction-bonded	$3 \times 10^{21} \text{ n/cm}^2$ (E > 1 Mev)		400, 650°C	A-19	12
		$8.1 \times 10^{21} \text{ n/cm}^2$ (E > 1 Mev)	HFIR	730°C	A-27	14
	self-bonded	$2.3 \times 10^{13} \text{ e/cm}^2\text{s}$ (52 Mev)	Linac	ambient	A-20	13
		$2 \times 10^{20} \text{ n/cm}^2$ (E > 1 Mev)	HFBR	ambient	A-21	13
	α-SiC	$9.7 \times 10^{21} \text{ n/cm}^2$ (E > 1 Mev)	HFIR	730°C	A-27	14
	NC-430	$1.2 \times 10^{21} \text{ n/cm}^2$ (E > 1 Mev)	HFBR	200°C	A-22 A-23	1
		$1.2 \times 10^{21} \text{ n/cm}^2$ (E > 1 Mev)	HFBR	200~1100°C	A-24 A-25	1
Al ₂ O ₃	sc	$2.2 \times 10^{22} \text{ n/cm}^2$ (E > 0.1 Mev)	EBR-II	407, 542°C	A-4	3
MgO		$2.1 \times 10^{22} \text{ n/cm}^2$ (E > 0.2 Mev)	HFIR	157°C	A-16	9
MgAl ₂ O ₄	sc pc	$2.2 \times 10^{22} \text{ n/cm}^2$ (E > 0.1 Mev)	EBR-II	407, 542°C	A-4	3
		$2.1 \times 10^{22} \text{ n/cm}^2$ (E > 0.2 Mev)	HFIR	157°C	A-16	9
Si ₃ N ₄	pc	$2.2 \times 10^{22} \text{ n/cm}^2$ (E > 0.1 Mev)	EBR-II	407, 542°C	A-4	3
SiO ₂	sc	$2.4 \times 10^{22} \text{ n/cm}^2$ (E > 0.1 Mev)	EBR-II	400, 550°C	A-28	7
SiO ₂ -based glass ceramic		$2.4 \times 10^{22} \text{ n/cm}^2$ (E > 0.1 Mev)	EBR-II	400, 550°C	A-28	7
MACOR		$2.4 \times 10^{22} \text{ n/cm}^2$ (E > 0.1 Mev)	EBR-II	400, 550°C	A-28	7
		$10^{16}, 10^{18} \text{ n/cm}^2$ (14 Mev)	RTNS-II	RT	A-26	11

sc: single crystal pc: polycrystal

Table 3-5 Thermal property data

MATERIAL		IRRADIATION			DATA	REF
		DOSE	FACILITY	TEMPERATURE		
SiC	α -SiC	$1.2 \times 10^{21} \text{ n/cm}^2$ (E > 1 MeV)	HFBR	< 147°C	A-29	1
		$8.1 \times 10^{21} \text{ n/cm}^2$ (E > 1 MeV)	HFIR	730°C	A-30	14
	NC-430	$8.1 \times 10^{21} \text{ n/cm}^2$ (E > 1 MeV)	HFIR	730°C	A-30	14
Al_2O_3	sc	$2.5 \times 10^{22} \text{ n/cm}^2$ (E > 0.1 MeV)	EBR-II	650 ~ 827°C	A-31	15
		$2.8 \times 10^{21} \text{ n/cm}^2$ (E > 0.1 MeV)	EBR-II	740°C	A-15	8
	pc	$2.5 \times 10^{22} \text{ n/cm}^2$ (E > 0.1 MeV)	EBR-II	650 ~ 827°C	A-31	15
	ADD-995	$2.8 \times 10^{21} \text{ n/cm}^2$ (E > 0.1 MeV)	EBR-II	740°C	A-15	8
MgAl_2O_4	sc	$2.5 \times 10^{22} \text{ n/cm}^2$ (E > 0.1 MeV)	EBR-II	650 ~ 827°C	A-31	15
	pc	$2.8 \times 10^{22} \text{ n/cm}^2$ (E > 0.1 MeV)	EBR-II	740°C	A-15	8
$\text{Y}_3\text{Al}_5\text{O}_{15}$	sc pc	$2.5 \times 10^{22} \text{ n/cm}^2$ (E > 0.1 MeV)	EBR-II	650 ~ 827°C	A-31	15
Y_2O_3	pc	$2.8 \times 10^{22} \text{ n/cm}^2$ (E > 0.1 MeV)	EBR-II	740°C	A-15	8
$\text{Y}_2\text{O}_3 + \text{ZrO}_2$	pc	$2.8 \times 10^{22} \text{ n/cm}^2$ (E > 0.1 MeV)	EBR-II	740°C	A-15	8
BeO-5SiC	pc	$2.8 \times 10^{22} \text{ n/cm}^2$ (E > 0.1 MeV)	EBR-II	740°C	A-15	8
MACOR	—	$10^{16}, 10^{18} \text{ n/cm}^2$ (14 MeV)	RTNS-II	RT	A-32	11
SiO_2	Vitreous	$5 \times 10^{19} \text{ n/cm}^2$ (E > 1 MeV)			A-33	16
Porcelain		$2.1 \times 10^{11} \text{ n/cm}^2$ (14.3 MeV)	neutron generator		A-56	28

sc: single crystal pc: polycrystal

Table 3-6 Electrical property data

MATERIAL		IRRADIATION			DATE	REF
		DOSE	FACILITY	TEMPERATURE		
SiC	NC-430	$< 2 \times 10^{20} \text{ n/cm}^2$ (E > 1 MeV)	HFBR	< 200°C	A-34	13
		$< 1.2 \times 10^{21} \text{ n/cm}^2$ (E > 1 MeV)	HFBR	< 200, 1100°C	A-35	1
		$< 4 \times 10^{21} \text{ n/cm}^2$ (E > 1 MeV)	HFBR	147, 1100°C	A-38	14
		$8.1 \times 10^{21} \text{ n/cm}^2$ (E > 1 MeV)	HFIR	730°C	A-38	14
Al_2O_3	sc	$6.6 \times 10^2 \sim 6.6 \times 10^4$ rad/s 1.5 MeV electron	-		A-36 A-37	17
	cable	$< 10^6 \text{ R/h}$	-	ambient	A-39	18
		$< 3 \times 10^{20} \text{ n/cm}^2$ (E > 0.1 MeV)		445°C	A-43	20
MgO	cable	$< 10^6 \text{ R/h}$	-	ambient	A-40	18
Glass-bonded MICA		$1 \times 10^{18} \text{ n/cm}^2$ (E > 0.1 MeV)	ORR		A-41	19
MACOR		$10^{16}, 10^{18} \text{ n/cm}^2$ (14 MeV)	RTNS-II	RT	A-42	11
MgAl ₂ O ₄		$< 3 \times 10^{20} \text{ n/cm}^2$ (E > 0.1 MeV)		445°C	A-43	20

sc: single crystal

Table 3-7 Di-electric property data

sc: single crystal

Table 3-8 Di-electric loss data

MATERIAL		IRRADIATION			DATA	REF
		DOSE	FACILITY	TEMPERATURE		
Al_2O_3	sc	$5 \times 10^{17} \text{ n/cm}^2$ (14 MeV)	RTNS-II	RT	A-46	21
	sc pc	$1 \times 10^{18} \text{ n/cm}^2$ (fast)	LAMPF	RT	A-46	21
	ADD-995	$2.5 \times 10^{19} \text{ n/cm}^2$ (fast)		47, 95°C	A-44	22
SiO_2	Fused	$2.5 \times 10^{19} \text{ n/cm}^2$ (fast)		47, 95°C	A-44	22

sc: single crystal pc: polycrystal

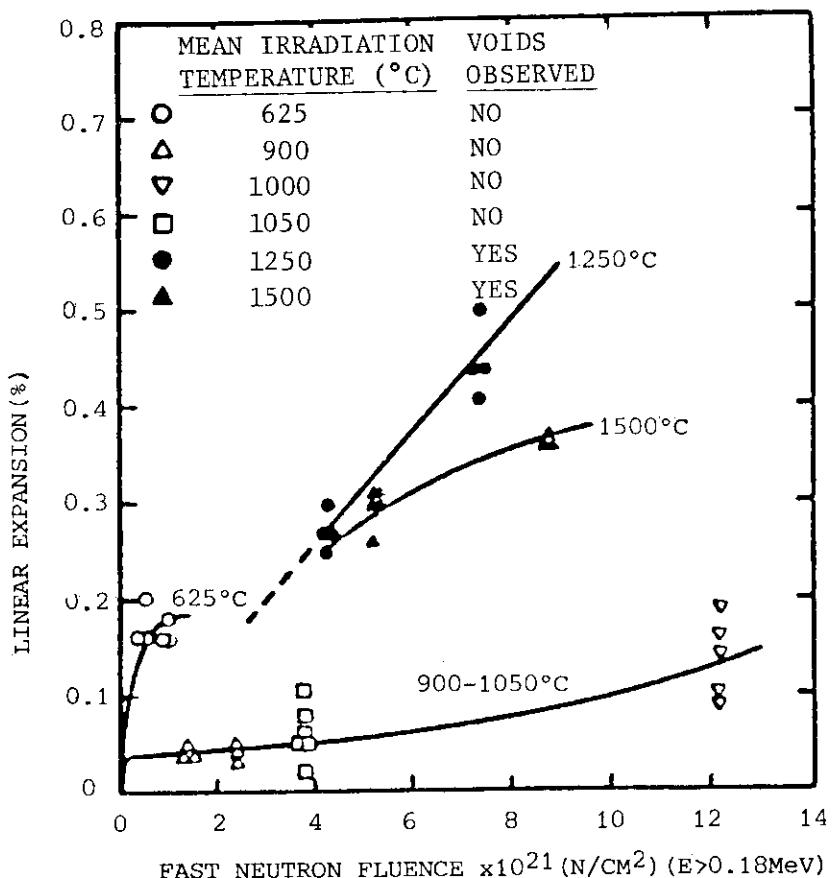
Table 3-9 Miscellaneous

MATERIAL		IRRADIATION			DATA	REF
		DOSE	FACILITY	TEMPERATURE		
α -SiC	reaction-bonded	3×10^{21} n/cm ² (E > 1 MeV)		450, 650°C	A-47	12
BeO	sintered	$< 2 \times 10^{21}$ n/cm ² (E > 1 MeV)	ETR	110 ~ 1100°C	A-48 2 A-50	23
Si_3N_4		3×10^{21} n/cm ² (E > 0.1 MeV)	EBR-II	742°C	A-52	25
$\text{Si}_2\text{N}_2\text{O}$		3×10^{21} n/cm ² (E > 0.1 MeV)	EBR-II	742°C	A-52	25
		$< 3 \times 10^{20}$ n/cm ² (fast)	SILOE	< 327°C	A-51	24
Sialon		3×10^{21} n/cm ² (E > 0.1 MeV)	EBR-II	742°C	A-52	25
BeO		$< 1 \times 10^{21}$ n/cm ² (E > 0.8 MeV)			A-53	27
Al_2O_3						
$\text{Al}_2\text{O}_3-\text{SiO}_2$						
Al_2O_3	sc	$< 5.6 \times 10^{16}$ /cm ² (5~15MeV p)			A-54 A-55	26
Al_2O_3	sc	1×10^{17} n/cm ² (14MeV)	RTNS		A-54 A-55	26

sc: single crystal

4. Data sheets

Material	β -SiC	Property	Swelling	1/1
Irradiation Condition	1.2 $\times 10^{22}$ n/cm ² (E > 0.18 MeV) ETR (Idaho) 626°C, 1500°C			

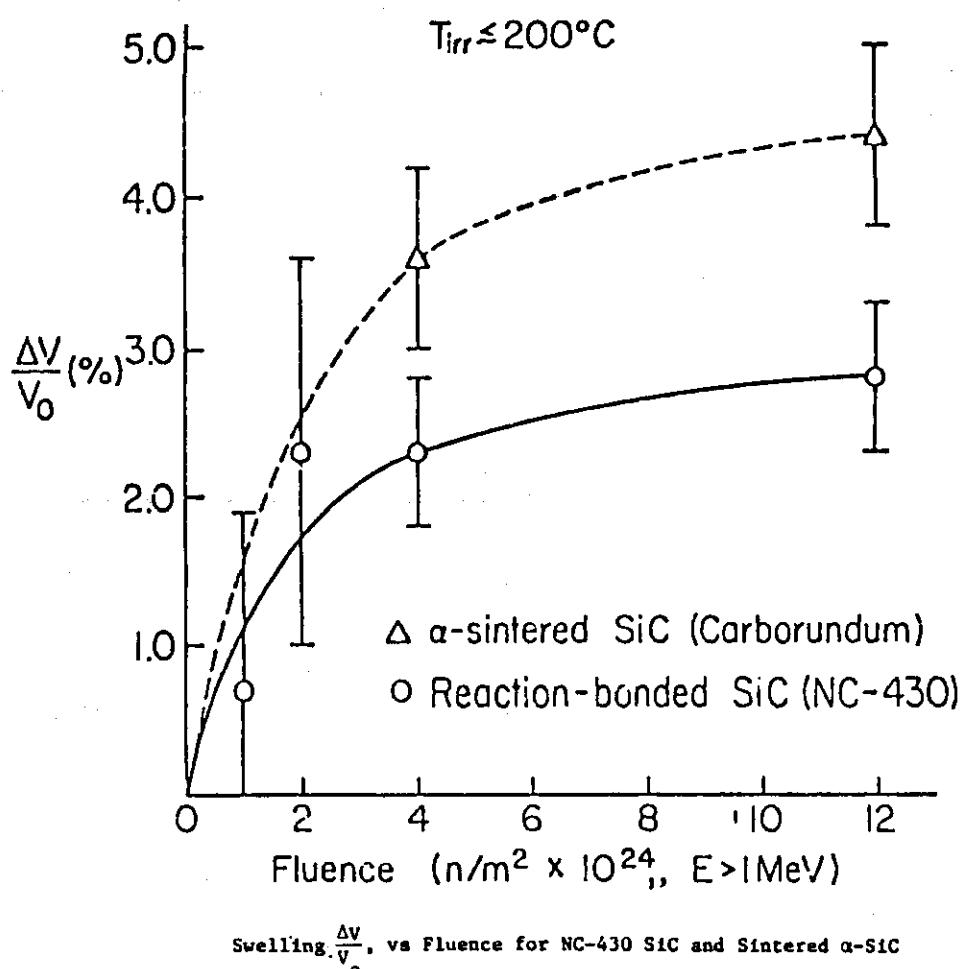


Expansion of β -silicon carbide as a function of fast neutron fluence at 625°C to 1500°C.

Reference	Neutron Irradiation-induced Voids in β -Silicon Carbide
	P. J. Price
	J. Nucl. Mater. 48 (1973) 47

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Material	α -SiC, SiC(NC-430)	Property	Swelling	1/1
Irradiation Condition	$1.2 \times 10^{21} \text{ n/cm}^2 (\text{E} > 1 \text{ MeV})$ HFBR (BNL)			



	Ceramic Materials for Fusion Reactors
Reference	G. Hopkins, G. C. Trantina and J. Corelli
	AP-1702, EPRI Research Project 992, Interim Report, February 1981

Material	α -SiC, SiC(NC-430)	Property	Density	1/1
Irradiation Condition	$1.2 \times 10^{21} \text{ n/cm}^2$ ($E > 1 \text{ MeV}$) HFBR (BNL)			
	<p>Fluence ($\text{n}/\text{m}^2 \times 10^{24}$, $E > 1 \text{ MeV}$)</p> <p>$\Delta \delta / \delta_0$ (%)</p> <p>$\triangle \alpha$-sintered SiC</p> <p>\circ Reaction bonded SiC (NC-430)</p> <p>$T_{irr} \leq 200^\circ\text{C}$</p> <p>Density changes $\frac{\Delta \delta}{\delta_0}$ vs fluence for NC-430 SiC and sintered α-SiC</p>			
Reference	Ceramic Materials for Fusion Reactors G. Hopkins, G. C. Trantina and J. Corelli AP-1702, EPRI Research Project 992, Interim Report, February 1981			

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Material	MgAl ₂ O ₄ , Al ₂ O ₃ , Si ₃ N ₄	Property	Swelling Strength	1/l
Irradiation Condition	2.2 ± 0.4 × 10 ²² n/cm ² (E > 0.1 MeV) 407°C, 542°C		EBR-II	

Swelling and strength changes after irradiation to $2.2 \pm 0.4 \times 10^{26}$ n/m² (E>0.1 MeV) at 680 and 815K

Material	Condition/ Irradiation Temperature, K	Volume Change, % [†]	Number of Bend Bar Samples	Strength, MPa and [Standard Deviation]	Strength Change, %
MgAl ₂ O ₄ (sc) ^{††}	control	--	5	145 [18]	--
	680	0.05	4	279 [28]	+92
	815	-0.11	4	254 [20]	+75
MgAl ₂ O ₄ (pc) ^{††}	control	--	3	129 [2]	--
	680	-0.19	6	178 [14]	+38
	815	-0.35	4	173 [16]	+34
MgAl ₂ O ₄ (pc)	control	--	5	112 [12]	--
	680	-0.39	3	156 [12]	+39
	815	-0.31	3	137 [17]	+22
Al ₂ O ₃ (sc)	control	--	8	273 [80]	--
	680	3.54	4	290 [43]	+6
	815	3.37	4	333 [40]	+22
Al ₂ O ₃ (sc)	control	--	7	302 [68]	--
	680	3.52	4	330 [22]	+9
	815	3.28	4	286 [124]	-5
Si ₃ N ₄ (pc)	control	--	7	234 [20]	--
	680	1.1	4	195 [12]	-17
	815	1.0	4	219 [7]	-6
SiC/graphite ⁷⁾	At 680 K, SiC swelled 1.47 vol% and graphite densified ~7 vol %. resulting in nearly-complete delamination.				

[†] The negative sign represents densification.

^{††} (sc) = single crystal, (pc) = polycrystal.

Sources, impurity contents in wt ppm and other characteristics of test materials are:

1) Linde Division, Union Carbide Corp.; 100 Si, 20 Fe, 8 B.

2) Ceradyne Inc.; 1000 Li, 200 Fe, 70 Ga, 60 Ca; ~99% dense.

3) Coors Porcelain Co.; 1500 Li, 150 Fe, 40 Si, 30 Ca; grain size ~100µm; ~100% dense; ~1% Al₂O₃-rich.

4) Tyco Laboratories Inc.; 100 Nb, 80 Fe, 15 Ni.

5) Linde Division, Union Carbide Corp.; 60 Fe, 50 Nb, 40 Mo.

6) Ceradyne Inc.; 20,000 Mg, 2000 Al, 300 Fe, 200 B, 200 Ca; beta phase, with MgO present. This ceramic was an experimental material made from powders ball-milled with Al₂O₃ balls to reduce residual radioactivity. No attempt was made to optimize strength or control boundary phases.

7) Materials Technology Corp.; chemically vapor-deposited stoichiometric β-phase SiC on isotropic graphite of 18 µm grain size and density 1.80 g/cc.

Reference	Structural Performance of Ceramics in a High-fluence Fusion Environment
	F.W.Clinard,Jr., G.F.Hurley, L.W.Hobbs, D.L.Rohr and R.A.Youngman
	J. Nucl. Mater. <u>122 & 123</u> (1984) 1386

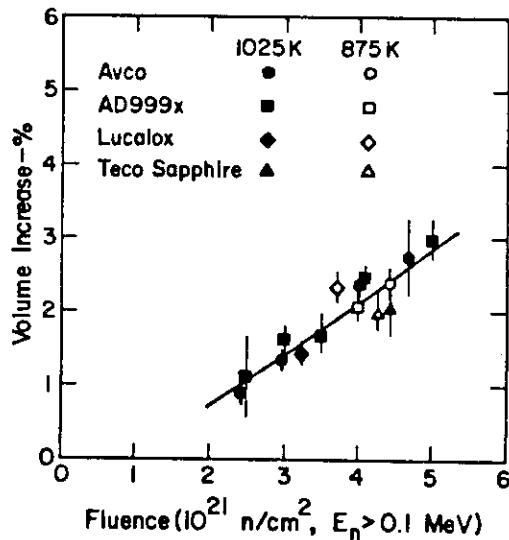
Material	Al_2O_3 , Y_2O_3 $\text{Y}_2\text{O}_3 - 10\% \text{ZrO}_2$	Property	Swelling	1/1
Irradiation Condition	2 $\sim 6 \times 10^{21}$ n/cm ² ($E > 0.1$ MeV) EBR-II 377°C, 602°C, 752°C			

Material	Irradiation Temperature, K	Neutron Fluence, n/cm ² ($E_n > 0.1$ MeV)	Macroscopic Swelling, $\Delta V/V$, %
Al_2O_3 (Sapphire)	650	5.6×10^{21}	2.2
	875	4.3×10^{21}	2.0
	1025	4.4×10^{21}	2.1
Al_2O_3 (Lucalox)	650	4.1×10^{21}	1.5
	875	3.7×10^{21}	2.3
	1025	3.2×10^{21}	1.4
Al_2O_3 (AD-999x)	650	4.8×10^{21}	1.7
	875	4.0×10^{21}	2.1
	1025	4.1×10^{21}	2.4
Y_2O_3	650 (Moly. Corp.)	6.0×10^{21}	0.2
	875 (Moly. Corp.)	5.1×10^{21}	(-0.1) ^a
	1025 (Lindsey)	5.4×10^{21}	-0.3
$\text{Y}_2\text{O}_3 - 10\% \text{ZrO}_2$ (Yttralox)	875	3.3×10^{21}	(0.0) ^a
	1025	3.9×10^{21}	(0.1) ^a

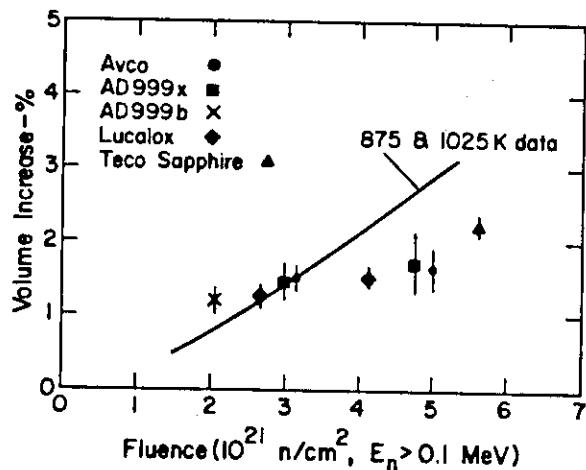
^a Below level of significance.

Reference	Neutron Irradiation Damage in Al_2O_3 and Y_2O_3
	F. W. Clinard, Jr., J. M. Bunch and W. A. Ranken
	Conf. Proc. Radiation Effects and Tritium Technology for Fusion Reactor, CONF-750989, 1976, II-498

Material	Al_2O_3	Property	Swelling	1/1
Irradiation Condition	2 $\sim 6 \times 10^{21} \text{ n/cm}^2$ ($E > 0.1 \text{ MeV}$) EBR-II 377°C, 602°C, 752°C			



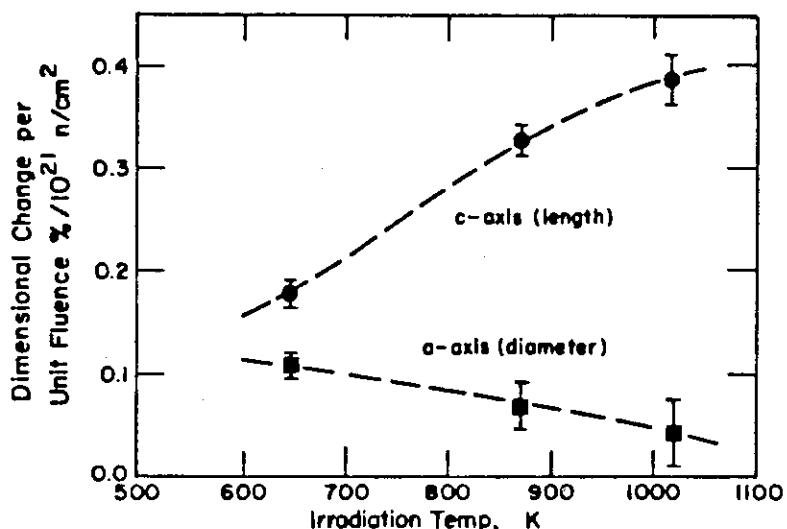
Volumetric Swelling of Al_2O_3 as a Function of Neutron Fluence at 875 and 1025K.



Volumetric Swelling of Al_2O_3 as a Function of Neutron Fluence at 650K. Data from Fig. 1 are Shown for Comparison.

Reference	Neutron Irradiation Damage in Al_2O_3 and Y_2O_3
	F. W. Clinard, Jr., J. M. Bunch and W. A. Ranken
	Conf. Proc. Radiation Effects and Tritium Technology for Fusion Reactor, CONF-750989, 1976, II-498

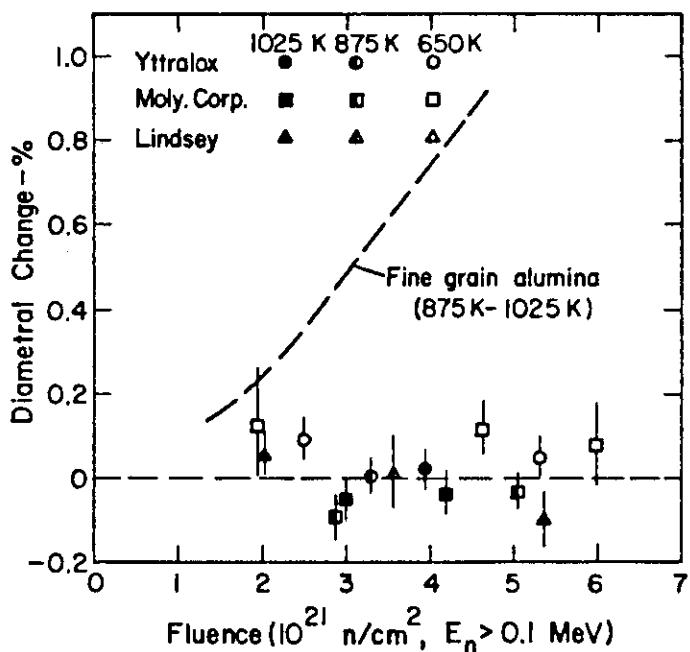
Material	Al_2O_3	Property	Swelling	1/1
Irradiation Condition	2 \sim 6×10^{21} n/cm ² ($E > 0.1$ MeV) EBR-II 377°C, 602°C, 752°C			



Dimensional Change per Unit Fluence versus Irradiation Temperature for Sapphire Irradiated to Neutron Fluences from 4.3 to 5.6×10^{21} n/cm² ($E_n > 0.1$ MeV).

Reference	Neutron Irradiation Damage in Al_2O_3 and Y_2O_3
	F. W. Clinard, Jr., J. M. Bunch and W. A. Ranken
	Conf. Proc. Radiation Effects and Tritium Technology for Fusion Reactor, CONF-750989, 1976, II-498

Material	Y_2O_3 $\text{Y}_2\text{O}_3 - 10\% \text{ZrO}_2$	Property	Swelling	1/1
Irradiation Condition	2 \sim 6 $\times 10^{21} \text{n/cm}^2$ ($E > 0.1 \text{ MeV}$) EBR-II 377°C, 602°C, 752°C			

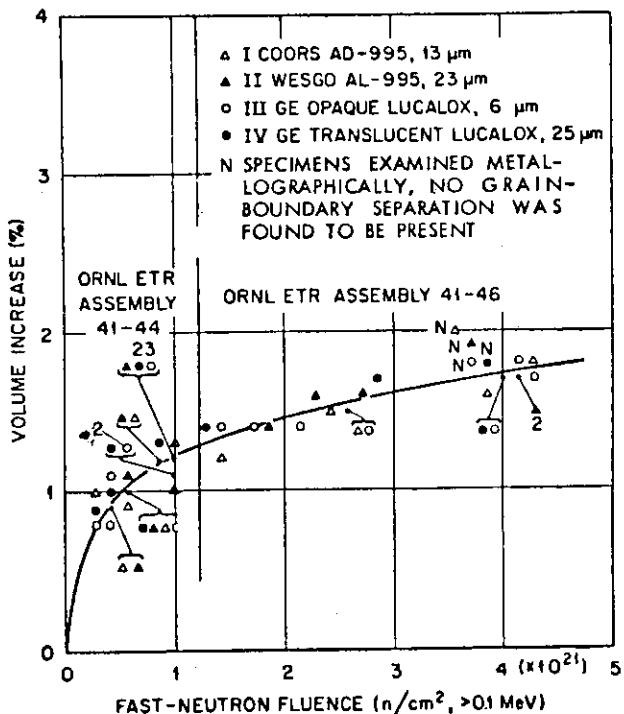


Diametral Change of Y_2O_3 Made from Moly. Corp. and Lindsey Powders and $\text{Y}_2\text{O}_3 - 10\% \text{ ZrO}_2$ (Yttralox) versus Neutron Fluence. Data from Fig. 1 are Shown for Comparison.

Reference	Neutron Irradiation Damage in Al_2O_3 and Y_2O_3
	F. W. Clinard, Jr., J. M. Bunch and W. A. Ranken
	Conf. Proc. Radiation Effects and Tritium Technology for Fusion Reactor, CONF-780989, 1976, II-498

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Material	Al_2O_3	Property	Swelling	1/1
Irradiation Condition	$4.4 \times 10^{21} \text{ n/cm}^2 (\text{E} > 0.1 \text{ MeV})$ ETR 60 - 90°C			



Volume increase of four commercial types of alumina irradiated at low temperature (60 to 90°C) in the ETR in two identical assemblies.

Characteristics of Commercial Alumina Products

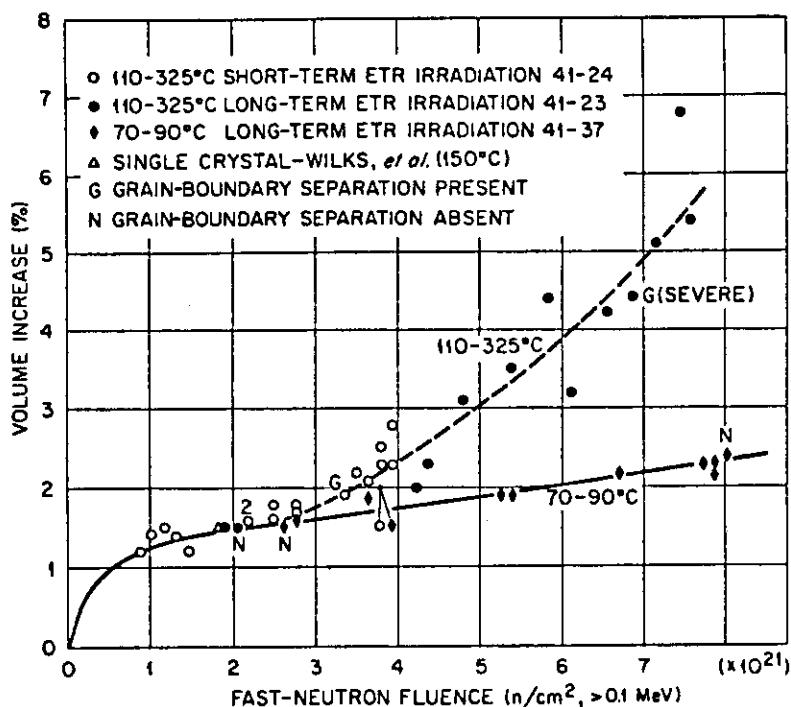
Type of Alumina ^a	Source	Bulk Density (g/cm³)	Average Grain Size (μm)	Total Impurities ^b (wt%)	Major Impurities (wt%)			
					Mg	Si	Fe	Other
I, Coors AD-995	Coors Porcelain Co.	3.86	13	0.42	0.1	0.08	0.06	Cu, 0.06 Cr, 0.1
II, Wesgo AL-995	Western Gold and Platinum Co.	3.85	23	0.25	0.1	0.1	0.03	
III, GE opaque Lucalox	General Electric Co.	3.91	6	0.06	0.02	0.007	0.01	Ni, 0.01
IV, GE translucent Lucalox	General Electric Co.	3.96	25	0.14	0.08	0.02	0.003	

^aAll specimens of the same type used in the irradiation program were of the same batch.

^bSummary of spectrographic analyses performed by C. Feldman and Anna M. Yosakum, Oak Ridge National Laboratory, Analytical Chemistry Division.

Reference	Fast-Neutron Damage to Polycrystalline Alumina at Temperatures from 60 to 1230°C
	G. W. Keilholtz, R. E. Moore and H. E. Robertson
	Nucl. Technol. 17 (1973) 234

Material	Al_2O_3	Property	Swelling	1/1
Irradiation Condition	8 $\times 10^{21}$ n/cm ² (E > 0.1 MeV) ETR 70 ~ 325°C			



Volume increase of alumina of type IV after irradiation at low temperatures.

Characteristics of Commercial Alumina Products

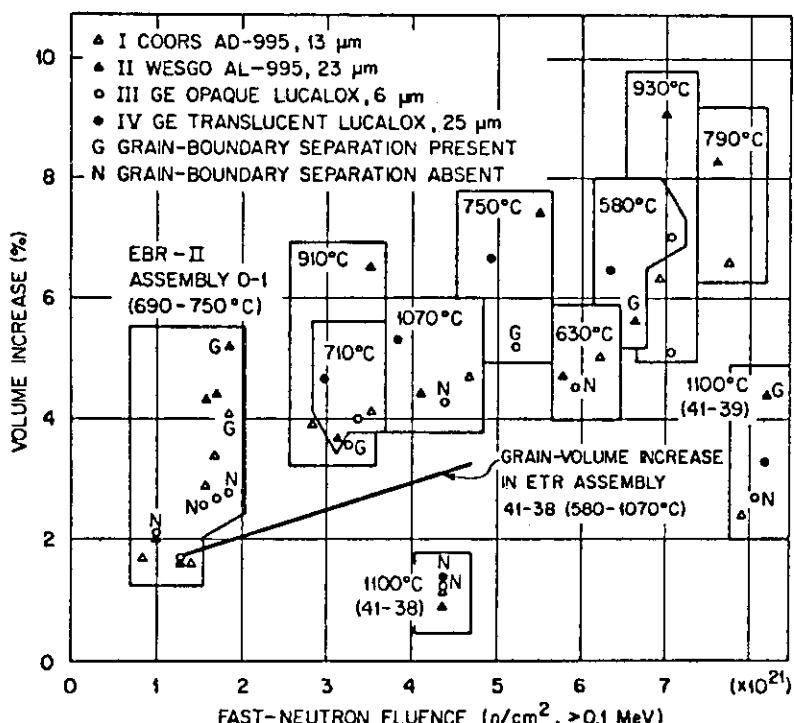
Type of Alumina ^a	Source	Bulk Density (g/cm³)	Average Grain Size (μm)	Total Impurities ^b (wt%)	Major Impurities ^b (wt%)			
					Mg	Si	Fe	Other
I, Coors AD-995	Coors Porcelain Co.	3.88	13	0.42	0.1	0.08	0.06	Cu, 0.06 Cr, 0.1
II, Wang AL-995	Western Gold and Platinum Co.	3.85	23	0.35	0.1	0.1	0.03	
III, GE opaque Lucalox	General Electric Co.	3.91	8	0.08	0.02	0.007	0.01	Ni, 0.01
IV, GE translucent Lucalox	General Electric Co.	3.96	25	0.16	0.08	0.02	0.003	

^aAll specimens of the same type used in the irradiation program were of the same batch.^bSummary of spectrographic analyses performed by C. Feldman and Anna M. Yonkum, Oak Ridge National Laboratory, Analytical Chemistry Division.

Reference	Fast-Neutron Damage to Polycrystalline Alumina at Temperatures from 60 to 1230°C
	G. W. Keilholtz, R. E. Moore and H. E. Robertson
	Nucl. Technol. 17 (1973) 234

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Material	Al_2O_3	Property	Swelling	1/1
Irradiation Condition	$8.2 \times 10^{21} \text{ n/cm}^2 (\text{E} > 0.1 \text{ MeV})$ EBR-II $690 \sim 1100^\circ\text{C}$			



Volume increase of four commercial types of alumina after irradiation at high temperatures in the long-term ETR assembly and the EBR-II assembly.

Characteristics of Commercial Alumina Products

Type of Alumina ^a	Source	Bulk Density (g/cm^3)	Average Grain Size (μm)	Total Impurities ^b (wt%)	Major Impurities ^b (wt%)			
					Mg	Si	Fe	Other
I, Coors AD-995	Coors Porcelain Co.	3.66	13	0.42	0.1	0.06	0.06	Cu, 0.06 Cr, 0.1
II, Wesgo AL-995	Western Gold and Platinum Co.	3.65	23	0.26	0.1	0.1	0.03	
III, GE opaque Lucalox	General Electric Co.	3.01	6	0.08	0.03	0.007	0.01	Ni, 0.01
IV, GE translucent Lucalox	General Electric Co.	3.06	25	0.14	0.08	0.02	0.003	

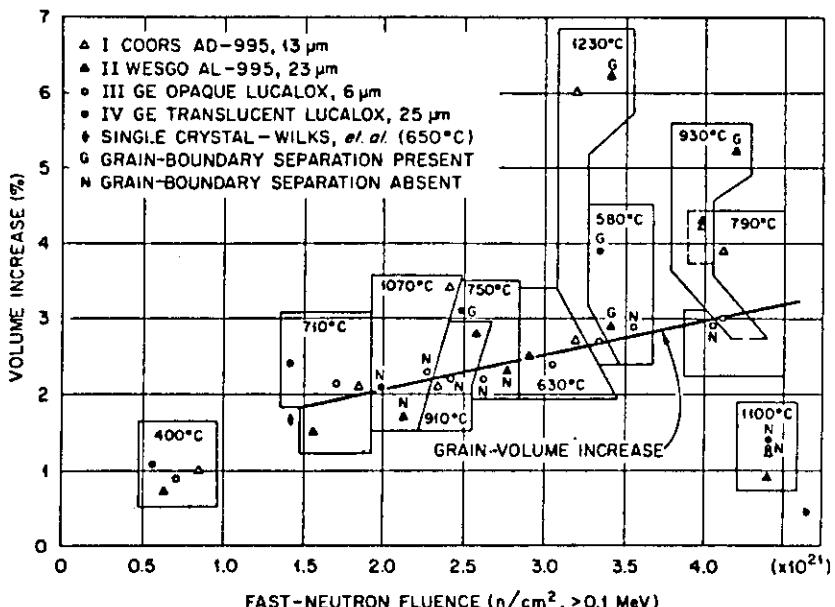
^aAll specimens of the same type used in the irradiation program were of the same batch.

^bSummary of spectrographic analyses performed by C. Feldman and Anna M. Yonkum, Oak Ridge National Laboratory, Analytical Chemistry Division.

Reference	Fast-Neutron Damage to Polycrystalline Alumina at Temperatures from 60 to 1230°C
	G. W. Keilhotz, R. E. Moore and H. E. Robertson
	Nucl. Technol. 17 (1973) 234

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Material	Al_2O_3	Property	Swelling	4/4
Irradiation Condition	4.2 $\times 10^{21}$ n/cm ² ($E > 0.1$ MeV) ETR 400 ~ 1230 °C			



Volume increase of four commercial types of alumina after irradiation at high temperatures in the short-term ETR assembly.

Characteristics of Commercial Alumina Products

Type of Alumina*	Source	Bulk Density (g/cm ³)	Average Grain Size (μm)	Total Impurities (wt%)	Major Impurities ^b (wt%)			
					Mg	Si	Po	Other
I, Coors AD-995	Coors Porcelain Co.	3.68	13	0.42	0.1	0.08	0.06	Cu, 0.06 Cr, 0.1
II, Wesgo AL-995	Western Gold and Platinum Co.	3.85	23	0.26	0.1	0.1	0.03	
III, GE opaque Lucalox	General Electric Co.	3.91	6	0.06	0.02	0.007	0.01	Ni, 0.01
IV, GE translucent Lucalox	General Electric Co.	3.96	25	0.14	0.08	0.02	0.003	

*All specimens of the same type used in the irradiation program were of the same batch.

^bSummary of spectrographic analyses performed by C. Feldman and Anna M. Yoakum, Oak Ridge National Laboratory, Analytical Chemistry Division.

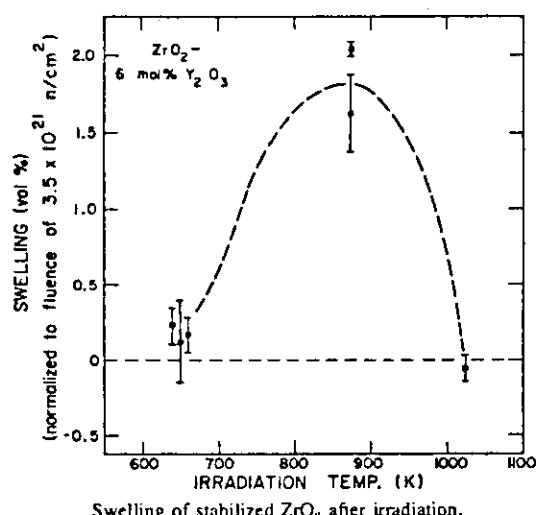
Reference	Fast-Neutron Damage to Polycrystalline Alumina at Temperatures from 60 to 1230 °C
	G. W. Keilhotz, R. E. Moore and H. E. Robertson
	Nucl. Technol. 17 (1973) 234

Material	ZrO ₂ (stabilized)	Property	Swelling	1/1
Irradiation Condition	$\sim 4.4 \times 10^{21} \text{ n/cm}^2$ ($E > 0.1 \text{ MeV}$) EBR-II 377°C, 602°C, 752°C			

**Irradiation Conditions and Swelling Values
for Stabilized ZrO₂ Samples**

Sample No.	Irradiation temp. (°K)	Fluence ($\times 10^{-21} \text{ n/cm}^2$)†	$\Delta V/V$ (%)
1*	650	4.4	0.21 ± 0.12
2	650	3.3	0.21 ± 0.12
3	650	2.8	0.10 ± 0.26
4*	875	2.5	1.45 ± 0.04
5*	875	3.8	1.76 ± 0.26
6*	1025	2.8	-0.05 ± 0.09

*Also evaluated by TEM. † $E_n > 0.1 \text{ MeV}$.



Reference	Neutron-Irradiation Damage in Stabilized ZrO ₂
	F. W. Clinard, Jr., D. L. Rohr and W. A. Ranken
	J. Am. Ceram. Soc. <u>60</u> (1979) 287

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Material	SiO ₂ SiO ₂ -based Glass Ceramic	Property	Swelling, Hardness	1/l
Irradiation Condition	$\sim 2.7 \times 10^{22} \text{ n/cm}^2$ ($E > 0.1 \text{ MeV}$) EBR-II 400°C, 550°C			

Swelling and Hardness Results

Sample	T _{irr} (°C)	$\phi t (10^{22} \text{ n/cm}^2)$, $E > 0.1 \text{ MeV}$	$\Delta V/V_0 (\%)$	Hardness,* kg/mm ²
Infracil	400	2.4	-1.4	583 (526)
Infracil	550	2.5	-1.1	621
Macor	550	2.7	1.1	475 (267)
DH	400	2.3	1.5	507 (320)
DH	550	2.7	0.7	443
DI	400	1.9	3.0	695 (347)
DI	550	2.2	2.1	537
DJ	400	2.2	2.8	545 (375)
DJ	550	2.5	2.0	498
ReX, ceramic	400	2.0	0.8	575 (544)
ReX, ceramic	550	2.1	1.0	624
ReX, glass	400	2.2	-0.4	527 (470)
ReX, glass	550	2.3	-0.7	574

* Numbers in parentheses represent unirradiated values.

Ceramic Compositions, wt.%

Sample	SiO ₂	Al ₂ O ₃	MgO	As ₂ O ₅	B ₂ O ₃	ZrO ₂	K ₂ O	MgF ₂	Li ₂ O	P ₂ O ₅	CoO	ZnO	BaO	Na ₂ O
Macor*	52.0	15.0	15.0	---	9.0	---	9.0	---	---	---	---	---	---	---
DH	60.5	---	13.5	2.0	---	---	13.5	10.4	---	---	---	---	---	---
DI	61.7	---	13.8	---	---	---	13.8	10.6	---	---	---	---	---	---
DJ	58.8	---	12.3	1.9	---	1.9	15.1	10.1	---	---	---	---	---	---
HR66B+CoO	60.0	---	---	---	---	---	---	---	9.0	---	0.5	---	28.5	---
MS011-A	46.2	9.5	---	---	---	---	---	---	---	2.0	---	32.2	4.8	4.8
ReX	71.8	5.1	---	---	3.2	---	4.8	---	12.6	2.5	---	---	---	---
Infracil	100.0	---	---	---	---	---	---	---	---	2.5	---	---	---	---

* Fluorine is added at 6.3 wt.% to substitute with oxygen.

Reference	Neutron Irradiation Effects on SiO ₂ and SiO ₂ -based Glass Ceramics
	D. L. Porter, M. R. Pascucci and B. H. Olbert
	J. Nucl. Mater. <u>103 & 104</u> (1981) 767

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Material	$\text{Al}_2\text{O}_3, \text{MgAl}_2\text{O}_4, \text{Y}_3\text{Al}_5\text{O}_12$ $\text{Y}_2\text{O}_3, \text{BeO}, \text{Si}_3\text{N}_4, \text{Sialon}$	Property	Swelling, Thermal diffusivity	1/1
Irradiation Condition	2.8 $\times 10^{21} \text{ n/cm}^2$ ($E > 0.1 \text{ MeV}$) EBR-II 740°C			

**Volume Swelling and Thermal Diffusivity Reduction
of Oxides after Irradiation***

Material	Type	Volume swelling (%)	Thermal diffusivity reduction (%)
Sapphire	Single crystal (0001)	1.6	45
Sapphire	Single crystal (1012)	"	"
Al_2O_3 (Ad 995)	Polycrystal	1.9	53
MgAl_2O_4	Single crystal	0.1 ^t	8
Spinel	Polycrystal	0.3	45
$\text{Y}_3\text{Al}_5\text{O}_12$	Single crystal	0.0	62
$\text{Y}_3\text{Al}_5\text{O}_12$	Polycrystal	0.2	54
Y_2O_3	Polycrystal	0.1 ^t	24
$\text{Y}_2\text{O}_3-\text{IZrO}_2$	Polycrystal	0.3	33
$\text{BeO}-\text{SiC}$	Polycrystal	3.3	60 ^t
Niberlox	Polycrystal	"	"

* $2.8 \times 10^{21} \text{ n/cm}^2$ ($E > 0.1 \text{ MeV}$) at 1015 K (740°C). ^tBelow level of significance.

^tEstimated starting value.

**Volume Swelling and Thermal Diffusivity Reduction
of Nitrides and Oxynitrides after Irradiation***

Material	Volume swelling (%)	Thermal diffusivity reduction (%)
Si_2ON_2	0.0	68
Si_3N_4 (NC-132)	0.4	52
Si_3N_4 ^t	0.3	53
Sialon	0.5	31

* $2.8 \times 10^{21} \text{ n/cm}^2$ ($E > 0.1 \text{ MeV}$) at 1015 K (740°C). ^tApproximate density 3.1.

Description of Materials Irradiated

Material	Description	Major impurities (ppm*)
Al_2O_3	Single crystal (1012) ^t	60 Fe, 50 Nb, 40 Mo
Al_2O_3	Single crystal (0001) ^t	80 Fe, 15 Ni, 100 Nb
Al_2O_3 (Ad-995)	Polycrystal ^s	2000 Mg, 2000 Si, 1000 Ca
MgAl_2O_4	Single crystal (111) ^t	100 Si, 20 Fe, 1-10 Ca
MgAl_2O_4	Polycrystal ^t	400 Si, 100 Ca, 80 Na
$\text{Y}_3\text{Al}_5\text{O}_12$	Single crystal (111) ^t	10 Si, 10 Fe, 1-10 Ca
$\text{Y}_3\text{Al}_5\text{O}_12$	Polycrystal ^t	2-6000 Si, 300 Ca, 300 Mg
Si_3N_4 (NC-132)	Polycrystal ^{**}	5300 WC, 6000 Mg, 2500 Fe, Al
Si_3N_4	Polycrystal ^{tt}	2% Mg, 2000 Al, 1800 C
Sialon	($2\text{Si}_3\text{N}_4\text{-}\text{Al}_2\text{O}_3\text{-AlN}$) + 5 wt% Y_2O_3 ^{tt}	400 Fe, 300 Mg, 200 Ca
Si_2ON_2	Porous polycrystal ^{**}	5000 Ca, 2000 Al, 2000 Fe
Y_2O_3	Polycrystal ^{tt}	<500 Zr
$\text{Y}_2\text{O}_3\text{-IZrO}_2$	Polycrystal ^{tt}	9000 Zr, 80 Al, 50 Si
BeO-SiC	Polycrystal-dispersed SiC ^{tt}	5.1% SiC, 5000 Al, 400 B
Niberlox	BeO polycrystal-dispersed second phase ^{tt}	2.39% Al, 2.9% Si, 1000 Mg

*Measured by LASL Analytical Chemistry Group. ^tTyco Laboratories, Inc., N.H. ^sLinde Div., Union Carbide Corp., New York, N.Y. ^oCoors Porcelain Co., Golden, Colo. ^{||}Los Alamos Scientific Lab, Los Alamos, N.M. ^{**}Norton Co., Worcester, Mass. ^{tt}Ceradyne, Inc., Santa Ana, Calif. ^{††}J. M. Wimmer, Air Force Materials Lab, Wright-Patterson AFB, Ohio. ^{§§}National Beryllia Corp., Haskell, N.J.

Reference	Swelling and Thermal Diffusivity Changes in Neutron-Irradiated Ceramics
	G. F. Hurley and J. M. Bunch
	Ceramic Bulletin 59 (1980) 457

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Material	MgO, MgAl ₂ O ₄	Property	Swelling, Mechanical properties	1/1
Irradiation Condition	2.1 × 10 ²² n/cm ² (E > 0.2 MeV) HFIR 157°C	4.6 × 10 ²² n/cm ² (thermal)		

Strength of MgO and MgAl₂O₄ by Diametral Compression Tests.Samples Irradiated to 2.1 × 10²⁶ n/m² E > 0.2 MeV.

Sample	Control, Mpa (No.)	Irradiated, MPa (No.)	Change, MPa (%)
MgO-1	23.1 ± 1.0 (6)	25.9 ± 1.1 (3)	+ 2.8 (12)
MgO-2	25.4 ± 1.1 (3)	31.6 ± 0.6 (3)	+ 6.2 (24)
MgAl ₂ O ₄	127 ± 4 (6)	152 ± 11 (9)	+25 (20)

Characterization of Irradiated Materials

Material	Source	%Full Density	Major Impurities Wt. Percent	Grain Size
MgO-1	Degussa Mg-25	75	.3 Fe, 1.2Ca, 1.7 Si, .8 Al	See Text
MgO-2	Honeywell M-30	79	.08Fe, .3Ca, .08Si, .02Al	See Text
MgAl ₂ O ₄ -1	American Lava	94	.01Fe, .01Ca, .04Si	10 μm

Material	Vol. Swelling, %
MgO-1	2.6
MgO-2	3.0
MgAl ₂ O ₄	0.8

Reference	Structural Properties of MgO and MgAl ₂ O ₄ after Fission Neutron Irradiation near Room Temperature
	G. F. Hurley, J. C. Kennedy and F. W. Clinard, Jr.
	J. Nucl. Mater. 103 & 104 (1981) 761

Material	MgO, Al ₂ O ₃ , MgAl ₂ O ₄	Property	Swelling	1/1			
Irradiation Condition	2.3 x 10 ²² n/cm ² (E > 0.1 MeV) EBR-II 157 ~ 827°C						
Irradiation parameters and measured swelling							
Sample	Neutron fluence (>0.1 MeV), ($\times 10^{26}$ n m ⁻²)	Estimated dpa	Irradiation temperature (K) (T/T_m)	Swelling (vol%)			
pc MgO (1)	2.1 *	30	430 0.14	2.6			
pc MgO (2)	2.1 *	30	430 0.14	3.0			
sc Al ₂ O ₃	0.03 *	0.5	430 0.19	-			
	0.3	3	1015 0.44	1.7			
	0.8	8	925 0.39	2.7			
	0.8	8	1100 0.47	3.1			
	1.2	12	925 0.39	3.2			
	1.2	12	1100 0.47	3.5			
	1.8	18	925 0.39	3.5			
	1.8	18	1100 0.47	3.9			
	2.2	22	925 0.39	4.0			
	2.2	22	1100 0.47	4.2			
	2.3	23	925 0.39	4.1			
	2.3	23	1100 0.47	4.4			
pc Al ₂ O ₃	0.3	3	1015 0.44	1.9			
	1.2	12	925 0.39	3.0			
	1.2	12	1100 0.47	6.0			
	1.9	19	925 0.39	3.5			
	1.9	19	1100 0.47	6.5			
	2.3	23	925 0.39	3.5			
	2.3	23	1100 0.47	6.5			
sc MgAl ₂ O ₄	0.3	3	1015 0.42	<0.1			
	0.8	8	925 0.38	0			
	2.3	23	925 0.38	0			
	2.3	23	1100 0.46	0			
pc MgAl ₂ O ₄ (1)	0.3	3	1015 0.42	0.4			
	2.3	23	925 0.38	0.2			
	2.3	23	1100 0.46	1.6			
pc MgAl ₂ O ₄ (2)	2.1 *	30	430 0.18	0.8			
* >0.2 MeV.							
Materials used in the present study							
Material	Source	Major impurities (wt ppm)			Grain size (μm)	Fraction of theoretical density	
pc MgO (1)	Degussa Corp.	17000 Si	12000 Ca	800 Al	14, 28 *	0.75 N	
pc MgO (2)	Honeywell, Inc.	3000 Ca	800 Fe	800 Si	300 Al	14, 28 *	0.79 N
sc Al ₂ O ₃	Linde Division Union Carbide Corp.	60 Fe	50 Nb	40 Mo			
sc Al ₂ O ₃	Tyco Laboratories, Inc.	100 Nb	80 Fe	15 Ni			
pc Al ₂ O ₃	Coors Porcelain Co Ad 995	2000 Mg	2000 Si	1000 Ca	2	0.97	
sc MgAl ₂ O ₄	Linde Division Union Carbide	100 Si	20 Fe	8 B	5 Ca		
pc MgAl ₂ O ₄ (1)	Reaction mintered	400 Si	100 Ca	80 Na	35 B 20 Fe	0.5 >0.99	
pc MgAl ₂ O ₄ (2)	American Lava Corp.	400 Si	100 Fe	100 Ca	10	0.94	
* Bimodal grain size distribution.							
* Density deliberately kept low for another study.							
sc = single crystal, pc = polycrystal.							
Reference	Neutron Irradiation Damage in MgO, Al ₂ O ₃ and MgAl ₂ O ₄ Ceramics						
	F. W. Clinard, G. F. Hurley and L. W. Hobbs						
	J. Nucl. Mater. 108 & 109 (1982) 655						

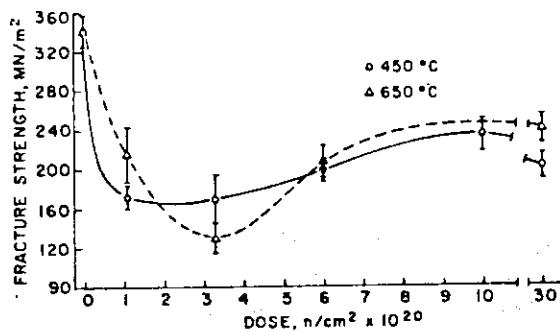
Material	MACOR	Property	Density	1/1
Irradiation Condition	$10^{16}, 10^{18}$ 14 MeV n/cm ² room temperature		RTNS-II	

Density changes in irradiated MACOR.

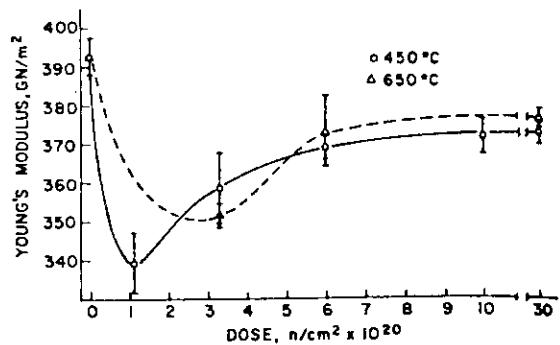
Sample fluence (n/m ²)	Number of samples	Normalized density range	Density change, %
control	3	1±.00008	-----
10^{20}	2	0.9999 - 1.0002	-----
10^{22}	2	1.0005 - 1.0010	+0.05 - +0.1

Reference	14 MeV Neutron Irradiation Effects in MACOR Glass Ceramic
	J.D.Fowler,Jr., G.F.Hurley, J.C.Kennedy and F.W.Clinard,Jr.
	J. Nucl. Mater. <u>103 & 104</u> (1981) 755

Material	SiC (reaction-bond SiC)	Property	Fracture strength Young's modulus	1/1
Irradiation Condition	3 \times 10 ²¹ n/cm ² (E > 1 MeV) 400, 650°C			



Fracture strengths of reaction-bonded SiC as a function of irradiation.



Young's modulus of reaction-bonded SiC as a function of irradiation.

Mechanical properties of irradiated silicon carbide.

Nominal dose (n/cm ²)	Temp (°C)	Fracture strength		
		Mean strength (MN/m ²)	Standard deviation (MN/m ²) ^a	Young's modulus (GN/m ²)
As rec'd	—	341	69 <i>n</i> = 30	393
1.1 \times 10 ²⁰	400	170	28 <i>n</i> = 12	339
3.3 \times 10 ²⁰	500	168	57 <i>n</i> = 12	358
6.0 \times 10 ²⁰	400	198	48 <i>n</i> = 31	369
10 \times 10 ²⁰	450	233	33 <i>n</i> = 8	372
30 \times 10 ²⁰	475	201	33 <i>n</i> = 12	373
1.1 \times 10 ²¹	700	214	64 <i>n</i> = 10	—
3.3 \times 10 ²⁰	600	130	40 <i>n</i> = 12	351
6.0 \times 10 ²⁰	650	207	38 <i>n</i> = 10	373
30 \times 10 ²⁰	660	240	27 <i>n</i> = 7	377

a) *n* = number of samples.

Reference	Irradiation Damage in Reaction-Bonded Silicon Carbide
	R. B. Matthews
	J. Nucl. Mater. 51 (1974) 203

Material	SiC (self-bonded SiC, Norton NC-430)	Property	Fracture strength	1/1
Irradiation Condition	52 MeV e ⁻ (RPI 100 MeV electron microwave linac)			

Linac test results for silicon carbide

Electron energy = 52 MeV Mean fracture strength = 266 MPa (38.6 ksi) }
 Flux = $2.3 \times 10^{17} \text{ e/m}^2 \cdot \text{s}$ Weibull modulus = 4.0 } omitting samples 3 and 4

Sample	Time-to-failure (s)	lbs at failure	kgm at failure	Fracture strength (ksi)	Fracture strength (MPa)
1	508	25.4	11.5	33.5	231
2	632	31.6	14.3	42.7	298
3	246	12.3	5.58	16.2 ^{a)}	112
4	984	49.1	22.3	64.7 ^{b)}	452
5	541	27.1	12.3	35.7	249
6	574	28.7	13.0	37.8	264
7	726	36.5	16.6	48.1	336
8	368	18.4	8.35	24.3	170
9	692	34.6	15.7	45.6	319

a) Sample subjected to temperature greater than 1673 K (1400°C).

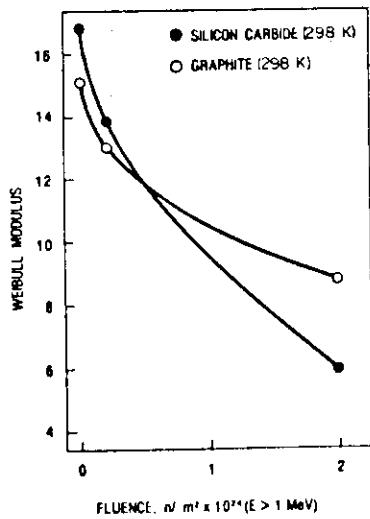
b) Sample subjected to unusual history: (a) loaded to 24 lbs (10.9 kg) with beam on; (b) load held constant for 15 min with beam on; (c) beam off-test restarted; (d) Beam on-load applied to failure.

Reference	Radiation Damage in Silicon Carbide and Graphite for Fusion Reactor First Wall Application
	R. A. Matheny, J. C. Corelli and G. G. Trantina
	J. Nucl. Mater. <u>83</u> (1979) 313

Material	SiC (self-bonded SiC, Norton NC-430)	Property	Fracture strength	1/1
Irradiation Condition	$2 \times 10^{19}, 2 \times 10^{20} \text{ n/m}^2$ ($E > 1 \text{ MeV}$) HFBR (BNL)			

Silicon carbide, three-point bend, average of 10 specimens

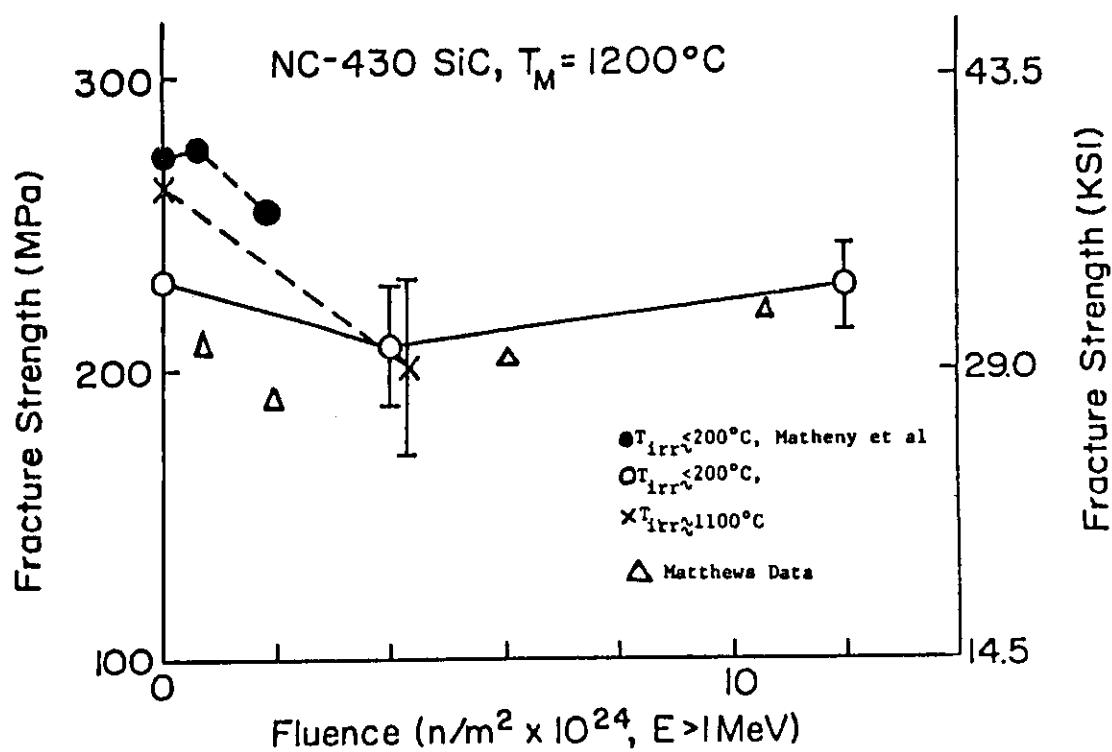
Dose	$T = 298 \text{ K}$				$T = 1473 \text{ K}$				Average sample width (in.)	$(\text{m}) \times 10^2$
	Time-to-failure (s)	Mean fracture strength (MPa)	Weibull modulus (ksi)		Time-to-failure (s)	Mean fracture strength (MPa)	Weibull modulus (ksi)	Strength degradation exponent		
Unirradiated	19.2	268	38.9	16.8	1164 4.8	270 281	39.2 40.2	14.1 11.2	217	0.1000 0.2540
$2 \times 10^{23} \text{ n/m}^2$ ($E > 1 \text{ MeV}$)	17.9	250	36.2	14.0	1188 4.8	276 270	40.1 39.2	14.1 10.2	242	0.1002 0.2545
$2 \times 10^{24} \text{ n/m}^2$ ($E > 1 \text{ MeV}$)	14.0	198	28.4	6.0	1062	248	35.9	7.6		0.1008 0.2560



Weibull modulus vs. neutron fluence for graphite and silicon carbide at room temperature.

Reference	Radiation Damage in Silicon Carbide and Graphite for Fusion Reactor First Wall Application
	R. A. Matheny, J. C. Corelli and G. G. Trantina
	J. Nucl. Mater. 83 (1979) 313

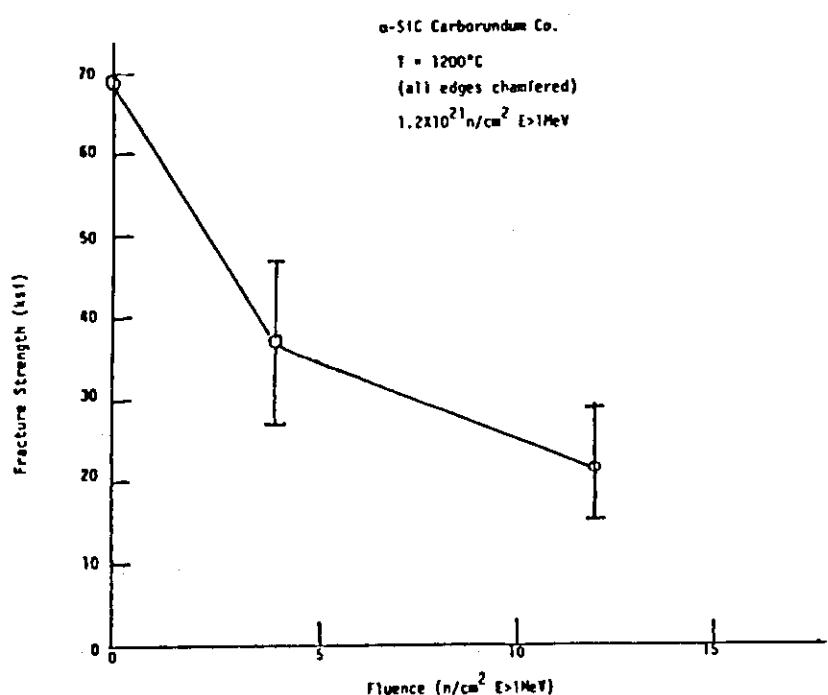
Material	SiC (NC-430)	Property	Fracture strength	1/3
Irradiation Condition	1.2 x 10 ²¹ n/cm ² (E > 1 MeV) HFBR (BNL)			



Reference	Ceramic Materials for Fusion Reactors
	G. Hopkins, G. C. Trantina and J. Corelli
	AP-1702, EPRI Research Project 992, Interim Report, February 1981

Material	α -SiC	Property	Fracture strength	2/3
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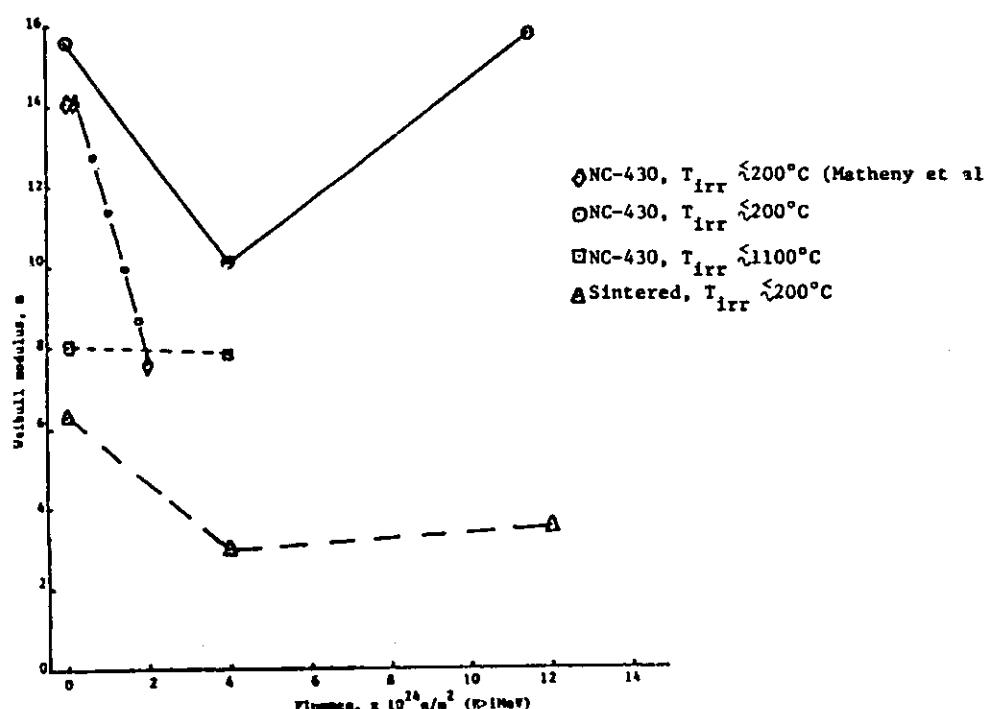
Irradiation Condition	$1.2 \times 10^{21} \text{ n/cm}^2 (E > 1 \text{ MeV})$ HFBR (BNL)
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Mean fracture strength vs fluence of sintered α -SiC at 1200°C

Reference	Ceramic Materials for Fusion Reactors
	G. Hopkins, G. C. Trantina and J. Corelli
	AP-1702, EPRI Research Project 992, Interim Report, February 1981

Material	α -SiC, SiC (NC-430)	Property	Fracture strength (Weibull modulus)	3/3
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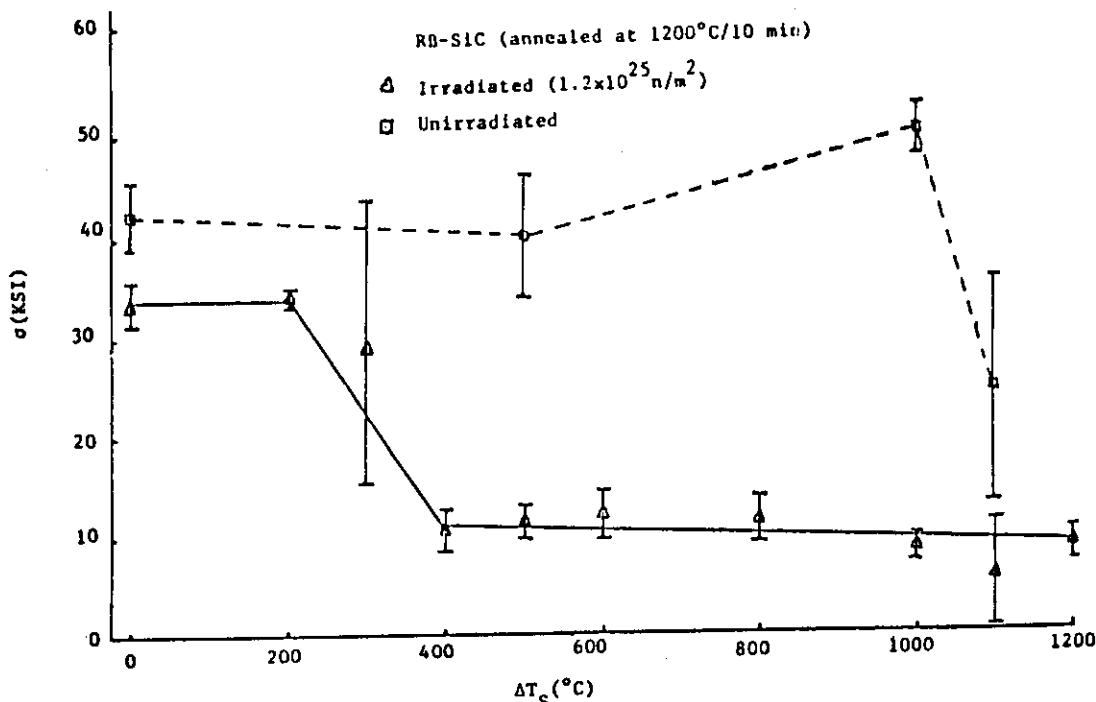
Irradiation Condition	$1.2 \times 10^{21} \text{ n/cm}^2 (\text{E} > 1 \text{ MeV})$ HFBR (BNL)
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Weibull Modulus vs Fluence for NC-430 SiC and sintered α -SiC

Reference	Ceramic Materials for Fusion Reactors
	G. Hopkins, G. C. Trantina and J. Corelli
	AP-1702, EPRI Research Project 992, Interim Report, February 1981

Material	SiC (NC-430)	Property	Fracture strength	1/1
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Irradiation Condition	$1.2 \times 10^{21} \text{ n/cm}^2$ ($E > 1 \text{ MeV}$) HFBR (BNC)
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Mean fracture strength (measured at 23°C) vs thermal shock temperature of Irradiated ($1.2 \times 10^{25} \text{ n/m}^2 E > 1 \text{ MeV}$) and Unirradiated NC-430 SiC

Reference	Ceramic Materials for Fusion Reactors
	G. Hopkins, G. C. Trantina and J. Corelli
	AP-1702, EPRI Research Project 992, Interim Report, February 1981

Material	MACOR	Property	Flexture strength	1/l
Irradiation Condition	10^{16} , 10^{18} 14 MeV n/cm ² room temperature		RTNS-II	

Flexure strength test results for MACOR.

Sample fluence (n/m ²)	MOR* (MN/m ²)	No. of samples	Standard deviation (MN/m ²)	Weibull m	σ_0
control	104	24	3.7	27.7	107
10^{20}	107	13	4.0	24.9	110
10^{22}	109	14	4.0	28.0	110

*MOR=Modulus of Rupture

Reference	14 MeV Neutron Irradiation Effects in MACOR Glass Ceramic
	J.D.Fowler,Jr., G.F.Hurley, J.C.Kennedy and F.W.Clinard,Jr.
	J. Nucl. Mater. <u>103 & 104</u> (1981) 755

Material	SiC (NC-430), α -SiC	Property	Fracture strength	1/1
Irradiation Condition	$1.2 \times 10^{21} \text{ n/cm}^2$ ($E > 1 \text{ MeV}$) HFBR (BNL) $\lesssim 147^\circ\text{C}$ $8.1 \times 10^{21} \text{ n/cm}^2$ ($E > 1 \text{ MeV}$) HFIR (ORNL) $\sim 730^\circ\text{C}$			

Summary of Fracture Strength Results for Reaction-Bonded Siliconized Silicon Carbide*

Fluence (10^{24} n/m^2) ($E > 1 \text{ MeV}$)	Irradiation temperature (K)	Fracture temperature (K)	Fracture strength (MPa)	Weibull modulus	Number of samples
0		298	268 ± 14	16.8	10
0		1473	270 ± 19	14.1	10
0.2	403	298	250 ± 21	14.0	10
0.2	403	1473	276 ± 17	14.1	10
2	403	298	198 ± 34	6.0	10
2	403	1473	248 ± 30	7.6	10
0 ^t		1473	231 ± 17	15.6	12
0 ^t		1473	257 ± 20	8.0	14
4 ^t	≤ 473	1473	208 ± 21	10.1	14
4 ^t	1373	1473	201 ± 14	7.8	15
12 ^t	≤ 473	1473	229 ± 16	15.7	14
0 ^b		1473	234 ± 14	17.7	13
3.6 ^b	413	1473	228 ± 34	6.20	11
7.6 ^b	413	1473	200 ± 14	11.7	11
0 ^d		296	279 ± 19	9.54	20
93 ^d	1013	296	116 ± 24	< 9.54	16
0		1013	232 ± 21	11.5	15
81	1013	1013	114 ± 7	14.6	7
81	1013	1473	185 ± 17	9.76	8

*NC-430, Norton Co., Worcester, MA. ^tThese samples had three machined surfaces and one as-fired surface. ^bThese samples had four machined surfaces. ^dThese samples were made of reaction-bonded SiC with ~ 0.3 wt% natural boron dopant. ^bData of Ref. 11.

Summary of Fracture Strength Results for Sintered Alpha Silicon Carbide*

Fluence (10^{24} n/m^2) ($E > 1 \text{ MeV}$)	Irradiation temperature (K)	Fracture temperature (K)	Fracture strength (MPa)	Weibull modulus	Number of samples
0 ^t		1473	487	6.3	5
4 ^t	≤ 473	1473	236 ± 69	3.0	12
12 ^t	≤ 473	1473	152 ± 46	3.5	10
0 ^d		1473	476 ± 103	3.59	10
3.6 ^b	413	1473	455 ± 41	9.80	12
7.6 ^b	413	1473	372 ± 55	6.18	11
0		296	400 ± 50	5.57	18
97 ^d	1013	296	265 ± 32	5.57	15
0 ^b		1013	695 ± 77	7.19	11
73	1013	1013	245 ± 9	23.8	5

*Carborundum Co., Niagara Falls, NY. ^tThese samples had three machined surfaces and one as-fired surface. ^bThese samples were commercially available and were sintered with ~ 0.5 wt% natural boron. ^dData of Ref. 11.

Reference	Mechanical, Thermal, and Microstructural Properties of Neutron-Irradiated SiC
	J. C. Corelli, J. Hoole, J. Lazzaro and C. W. Lee
	J. Am. Ceram. Soc. <u>66</u> (1983) 529

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Material	SiO ₂ SiO ₂ -based glass Ceramic	Property	Thermal Expansion Fracture Toughness	1/1
Irradiation Condition	~ 2.4 × 10 ²² n/cm ² (E > 0.1 MeV) EBR-II 400°C, 550°C			

Thermal Expansion and Fracture Toughness

Sample	α (10 ⁻⁶ °C ⁻¹), (25-450°C)	K _c (MN/m ^{3/2})	T _{irr} (°C)	ϕt (10 ²² n/cm ²)
Infracil	0.99	---	---	---
Infracil	1.05	---	400	2.4
Infracil	0.91	---	550	2.5
ReX, glass	9.41	NA*	---	---
ReX, glass	9.36	1.0	400	2.2
ReX, glass	9.75	1.2	550	2.3
ReX, ceramic	8.95	2.1	---	---
ReX, ceramic	9.37	1.1	400	2.0
ReX, ceramic	9.67	1.5	550	2.1

* K_c could not be measured in this way due to opening of lateral vent cracks.

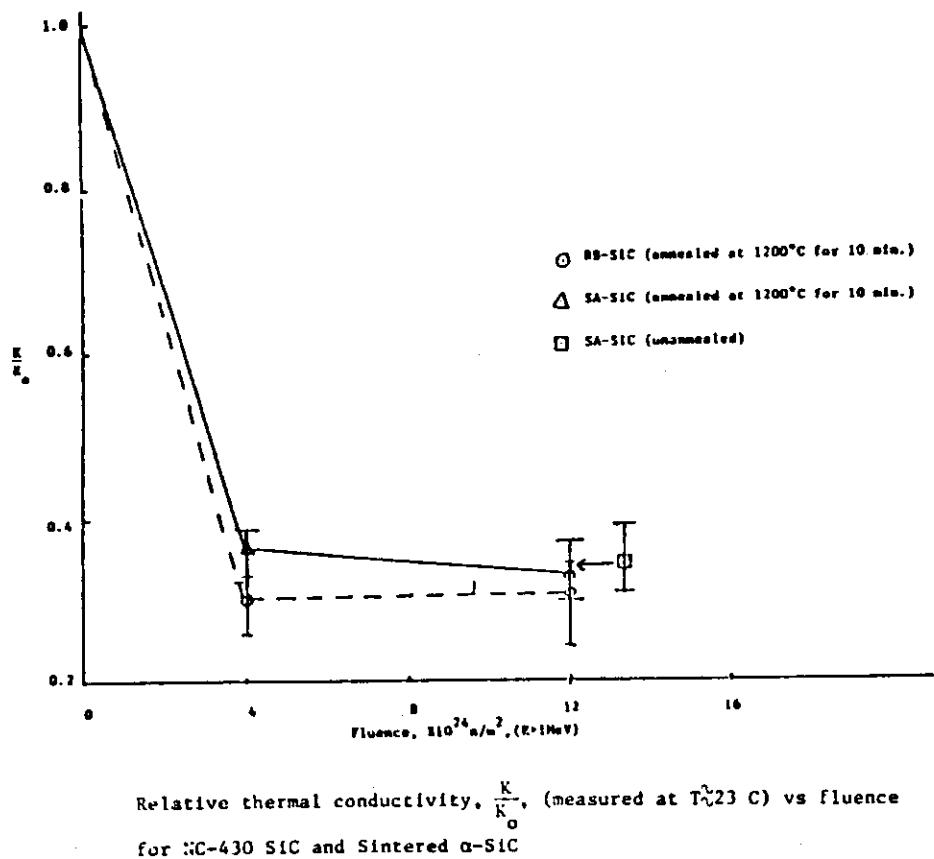
Ceramic Compositions, wt.-%

Sample	SiO ₂	Al ₂ O ₃	MgO	As ₂ O ₅	B ₂ O ₃	ZrO ₂	K ₂ O	MgF ₂	Li ₂ O	P ₂ O ₅	CoO	ZnO	BaO	Na ₂ O
Mscor*	52.0	15.0	15.0	---	9.0	---	9.0	---	---	---	---	---	---	---
DH	60.5	---	13.5	2.0	---	---	13.5	10.4	---	---	---	---	---	---
DI	61.7	---	13.8	---	---	---	13.8	10.6	---	---	---	---	---	---
DJ	58.8	---	12.3	1.9	---	1.9	15.1	10.1	---	---	---	---	---	---
HR66B+CoO	60.0	---	---	---	---	---	---	---	9.0	---	0.5	28.5	---	---
MS011-A	46.2	9.5	---	---	---	---	---	---	---	2.0	---	32.2	4.8	4.8
ReX	71.8	5.1	---	---	3.2	---	4.8	---	12.6	2.5	---	---	---	---
Infracil	100.0	---	---	---	---	---	---	---	---	2.5	---	---	---	---

* Fluorine is added at 6.3 wt.-% to substitute with oxygen.

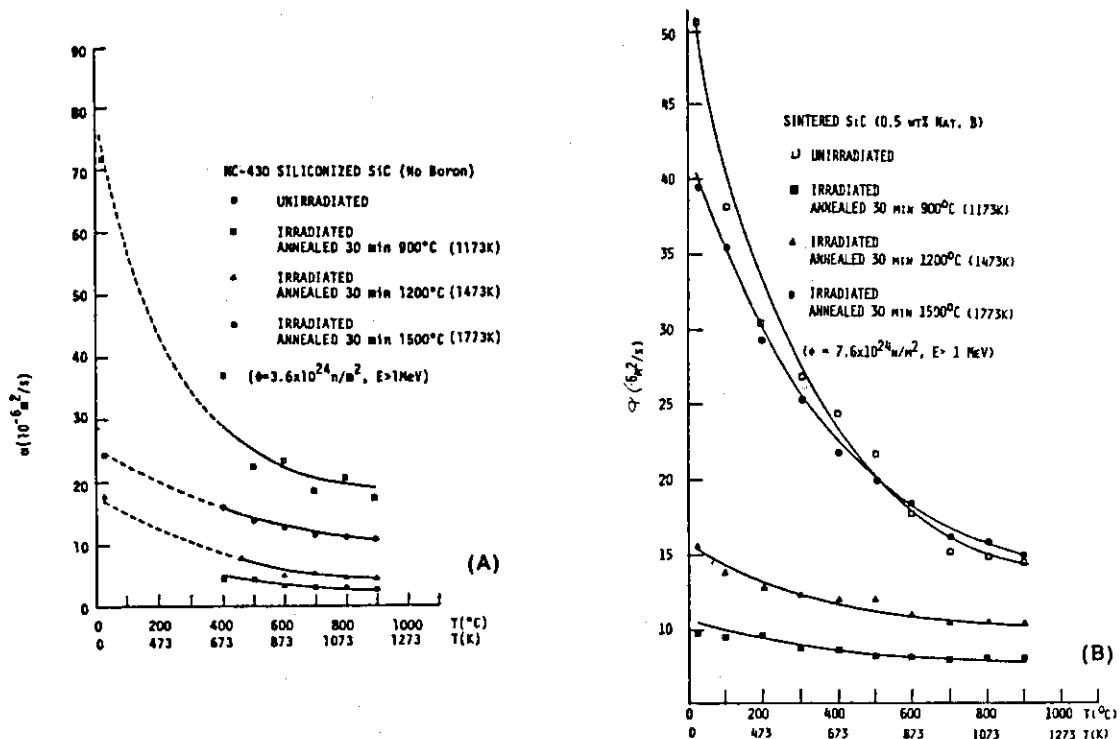
Reference	Neutron Irradiation Effects on SiO ₂ and SiO ₂ -based Glass Ceramics
	D. L. Porter, M. R. Passucci and B. H. Olbert
	J. Nucl. Mater. 103 & 104 (1981) 767

Material	α -SiC, SiC (NC-430)	Property	Thermal conductivity	1/1
Irradiation Condition	1.2 $\times 10^{21}$ n/cm ² ($E > 1$ MeV) HFBR (BNL)			



Reference	Ceramic Materials for Fusion Reactors
	G. Hopkins, G. C. Trantina and J. Corelli
	AP-1702, EPRI Research Project 992, Interim Report, February 1981

Material	SiC (NC-430), α -SiC	Property	Thermal diffusivity	1/1
Irradiation Condition	$1.2 \times 10^{21} \text{ n/cm}^2 (\text{E} > 1 \text{ MeV})$	HFBR (BNL) $\leq 147^\circ\text{C}$		
	$8.1 \times 10^{21} \text{ n/cm}^2 (\text{E} > 1 \text{ MeV})$	HFIR (ORNL) $\sim 730^\circ\text{C}$		

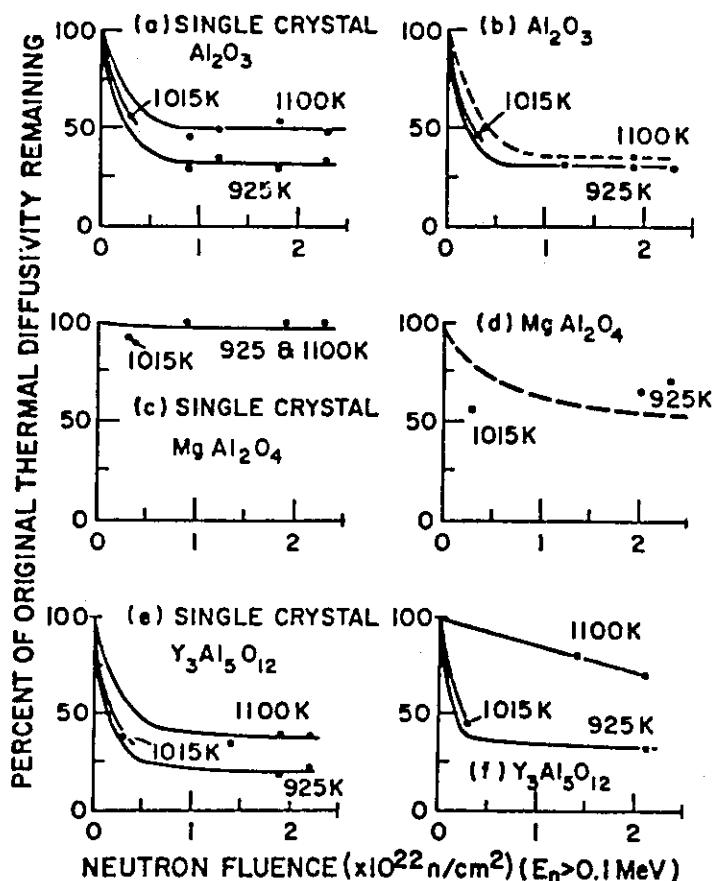


Thermal diffusivity vs temperature for (A) siliconized SiC, (B) sintered α -SiC sintered with 0.5 wt% natural boron, and (C) siliconized SiC doped with 0.3 wt% ^{10}B , showing effect of annealing.

Reference	Mechanical, Thermal, and Microstructural Properties of Neutron-Irradiated SiC
	J. C. Corelli, J. Hoole, J. Lazzaro and C. W. Lee
	J. Am. Ceram. Soc. <u>66</u> (1983) 529

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Material	Al_2O_3 , MgAl_2O_4 , $\text{Y}_2\text{Al}_5\text{O}_{12}$	Property	Thermal diffusivity	1/1
Irradiation Condition	$\sim 2.5 \times 10^{22} \text{ n/cm}^2$ ($E > 0.1 \text{ MeV}$) EBR-II $< 827^\circ\text{C}$			



Decrease in RT thermal diffusivity (approximately proportional to thermal conductivity) as a function of irradiation temperature and fission neutron fluence for several ceramics.

	The Inorganic Insulator Program at LASL
Reference	F. W. Clinard, Jr. and D. M. Parkin
	USDOE Report No. CONF-801237, 1981, Pl7.1

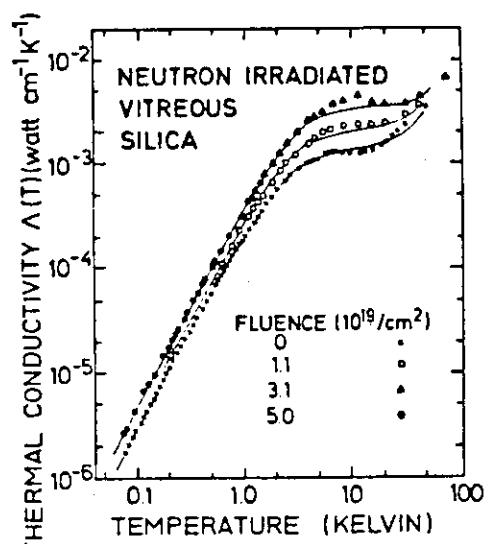
Material	MACOR	Property	Thermal diffusivity	1/1
Irradiation Condition	$10^{16}, 10^{18}$ 14 MeV n/cm ² room temperature		RTNS-II	

Thermal diffusivity changes in MACOR.

Sample fluence (n/m ²)	Number of samples	Thermal diffusivity (normalized)
Control	5	$1 (4.5 \times 10^{-7} \text{ m}^2/\text{s})$
10^{20}	4	0.998
10^{22}	2	0.978

Reference	14 MeV Neutron Irradiation Effects in MACOR Glass Ceramic
	J.D.Fowler,Jr., G.F.Hurley, J.C.Kennedy and F.W.Clinard,Jr.
	J. Nucl. Mater. <u>103 & 104</u> (1981) 755

Material	Silica	Property	Thermal conductivity	1/1
Irradiation Condition	$5 \times 10^{19} \text{ n/cm}^2$ ($E > 1 \text{ MeV}$)			

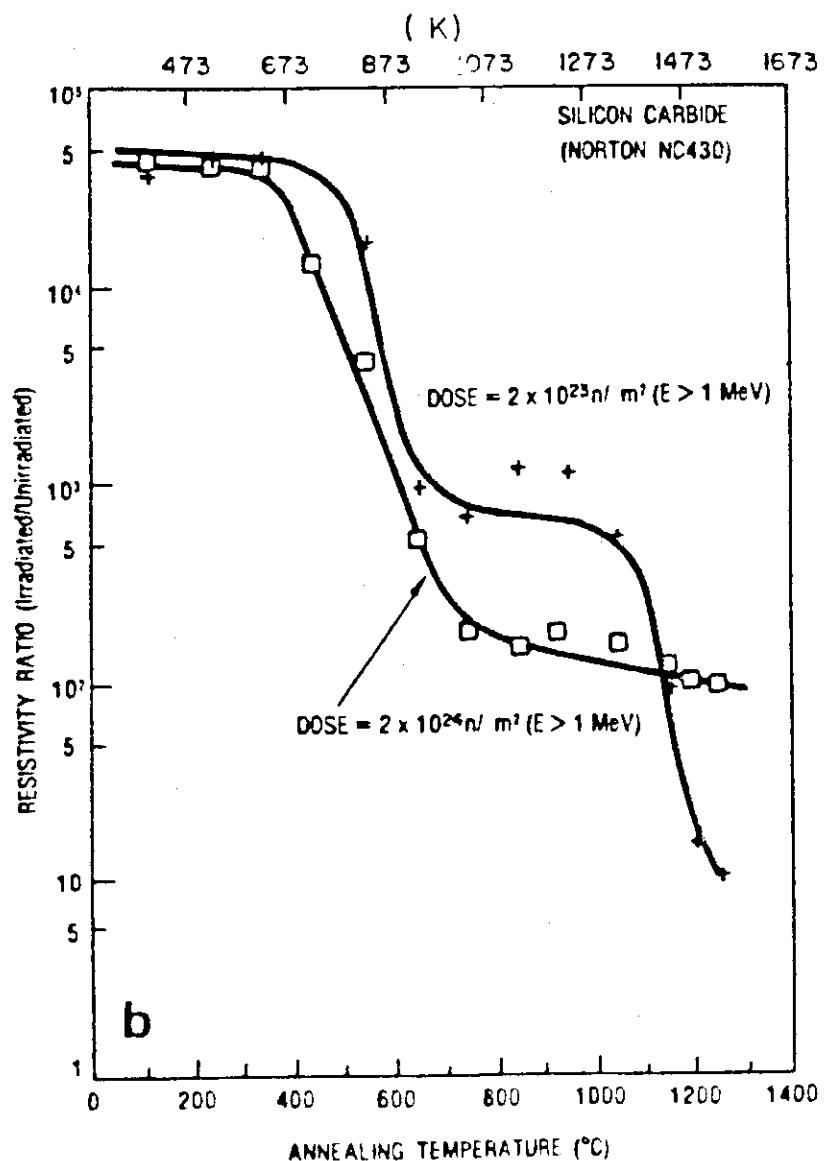


Thermal conductivity of neutron irradiated silica.

Reference	Thermal Conductivity of Neutron-Irradiated Silica
	A. K. Raychandhuri and R. O. Pohl
	Solid State Communication <u>44</u> (1982) 711

Material	SiC (self-bonded SiC, Norton NC-430)	Property	Resistivity	1/1
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Irradiation Condition	$2 \times 10^{19} \sim 2 \times 10^{20}$ n/cm ² ($E > 1$ MeV) HFBR (BNL)
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Isochronal annealing (600 s at each temperature),
resistivity ratio vs. annealing temperature for silicon carbide

Reference	Radiation Damage in Silicon Carbide and Graphite for Fusion Reactor First Wall Applications
	R. A. Matheny, J. C. Corelli and G. G. Trantina
	J. Nucl. Mater. 83 (1979) 313

Material	SiC (NC-430)	Property	Resistivity	1/1
Irradiation Condition	$1.2 \times 10^{21} \text{ n/cm}^2$ ($E > 1 \text{ MeV}$) 200, 1100 °C		HFBR (BNL)	

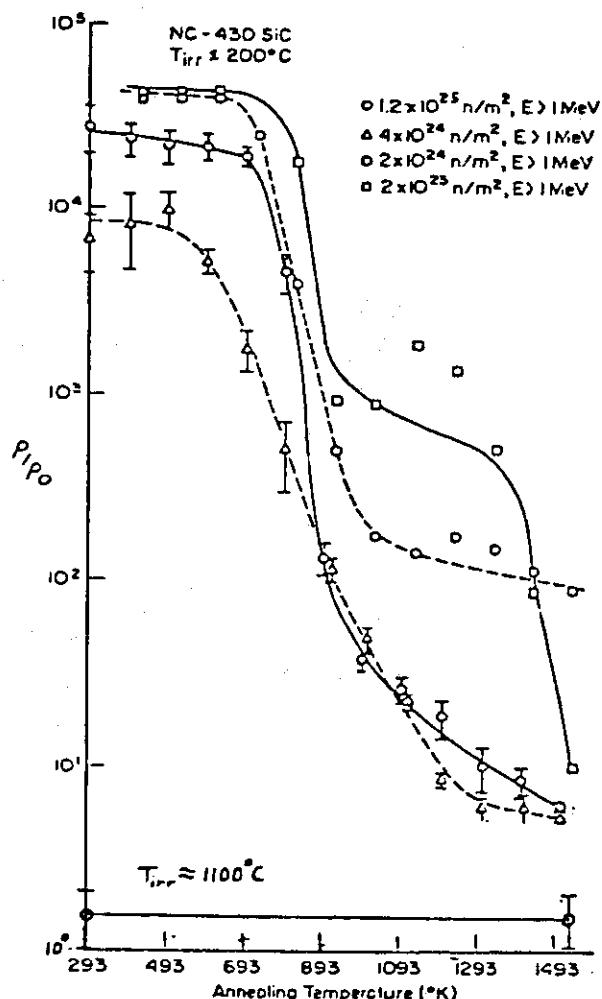


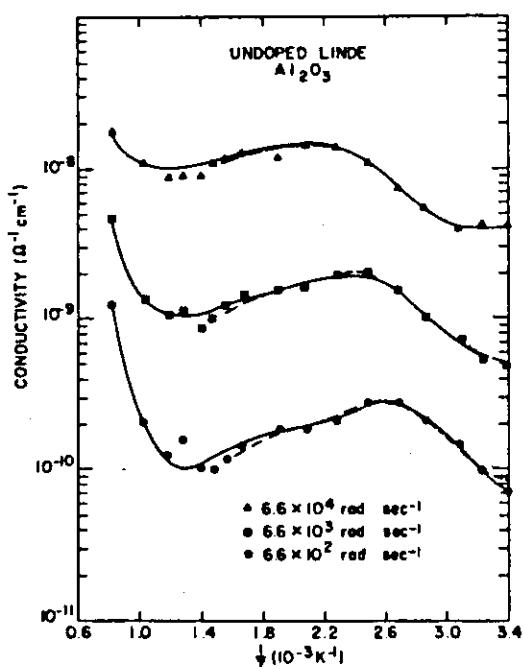
Figure 9

Resistivity Ratio, ρ/ρ_0 , vs Annealing Temperature for NC-430 SiC
Irradiated at $\leq 200^\circ\text{C}$ and 1100°C . The Two Lowest Fluences are data of Matheny et al (10). (Samples kept at each temperature 10 min.)

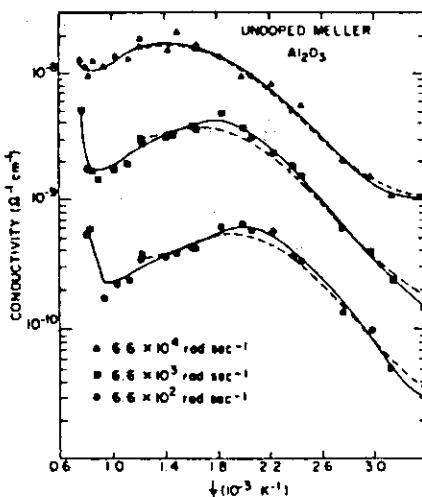
Reference	Ceramic Materials for Fusion Reactors
	G. Hopkins, G. C. Trantina and J. Corelli
	AP-1702, EPRI Research Project 992, Interim Report, February 1981

Material	Al ₂ O ₃ (single-crystal)	Property	Conductivity	1/1
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Irradiation Condition 1.5 MeV electron (BNL Dynamitron)
 1 nA electron beam = 2.2×10^2 rad/sec



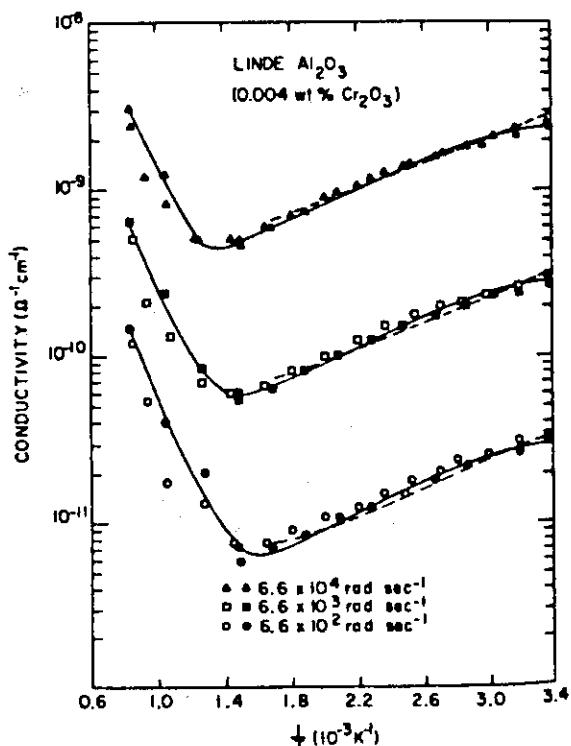
Temperature dependence of the RIC for the undoped Linde Al₂O₃ sample.



Temperature dependence of the RIC for the undoped Meller Al₂O₃ sample at the dose rates indicated.

Reference	Radiation-induced Conductivity of Al ₂ O ₃ : Experiment and theory
	R. W. Klaffky, B. H. Rose, A. N. Goland and G. J. Dienes
	Phys. Rev. B 21 (1980) 3610

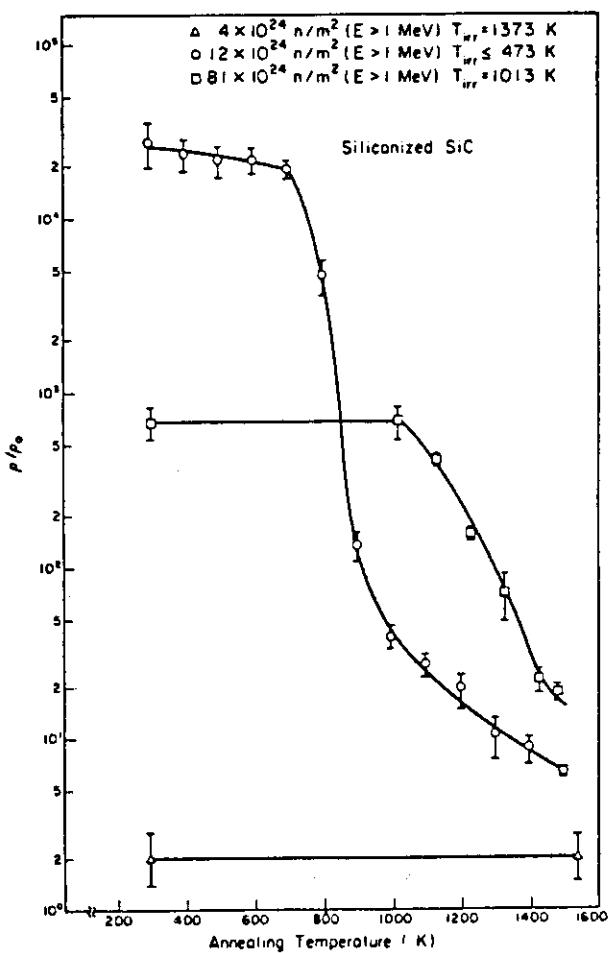
Material	Al_2O_3 (single-crystal)	Property	Conductivity	1/1
Irradiation Condition	1.5 MeV electron (BNL Dynamitron)			



Temperature dependence of the RIC for the
0.004-wt-%- Cr_2O_3 -doped Linde Al_2O_3 sample.

	Radiation-induced Conductivity of Al_2O_3 : Experiment and theory
Reference	R. W. Klaffky, B. H. Rose, A. N. Goland and G. J. Dienes
	Phys. Rev. B 21 (1980) 3610

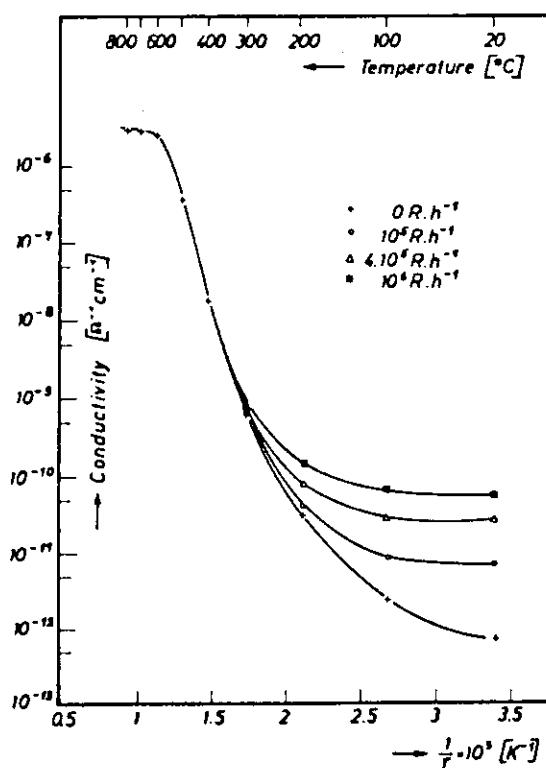
Material	SiC (NC-430)	Property	Resistivity	1/1
Irradiation Condition	1.2 $\times 10^{21}$ n/cm ² (E > 1 MeV) HRBR (BNL) $\lesssim 147^\circ\text{C}$ 8.1 $\times 10^{21}$ n/cm ² (E > 1 MeV) HFIR (ORNL) $\sim 730^\circ\text{C}$			



Relative resistivity vs annealing temperature for siliconized SiC; sample was held at each temperature for 10 min, and resistivity was measured at 296 K.

Reference	Mechanical, Thermal, and Microstructural Properties of Neutron-Irradiated SiC
	J. C. Corelli, J. Hoole, J. Lazzaro and C. W. Lee
	J. Am. Ceram. Soc. <u>66</u> (1983) 529

Material	Al_2O_3 insulated cable	Property	Electrical Conductivity	1/1
Irradiation Condition	γ -ray, $< 10^6 \text{ R/h}$, 20~800 °C			



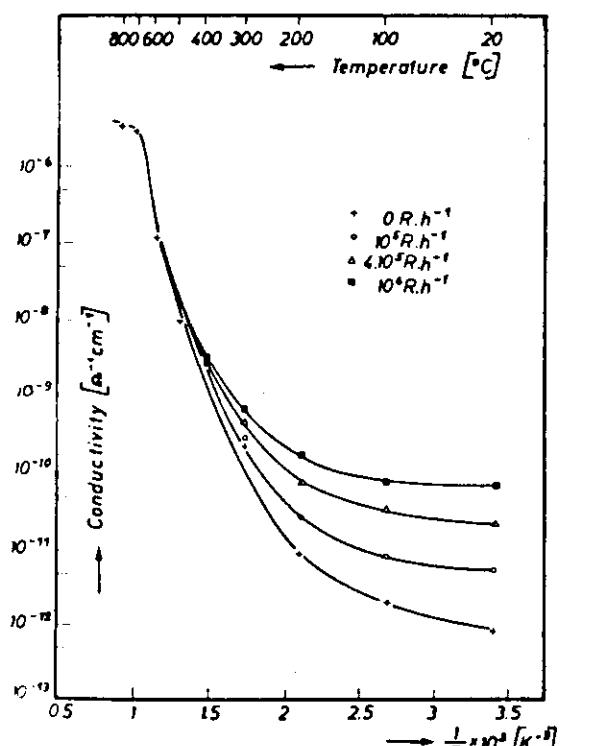
Conductivity as a function of temperature for a 1.5 mm Al_2O_3 insulated cable.

Reference	Investigation of Mineral Insulated Cables Exposed to High Temperature and Intense Gamma Radiation
	H. Böck and M. Suleiman
	Nucl. Inst. Methods <u>148</u> (1978) 43

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Material	MgO insulated cable	Property	Electrical Conductivity	1/1
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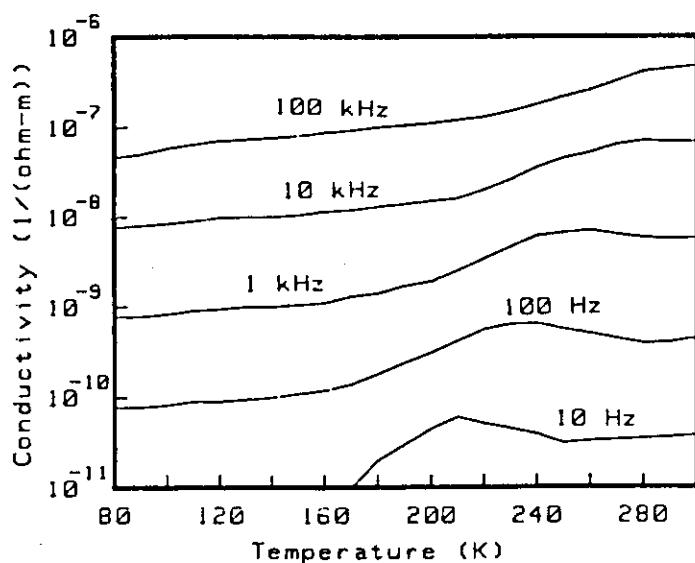
Irradiation Condition	γ -ray, $< 10^6$ R/h, 20~800 °C
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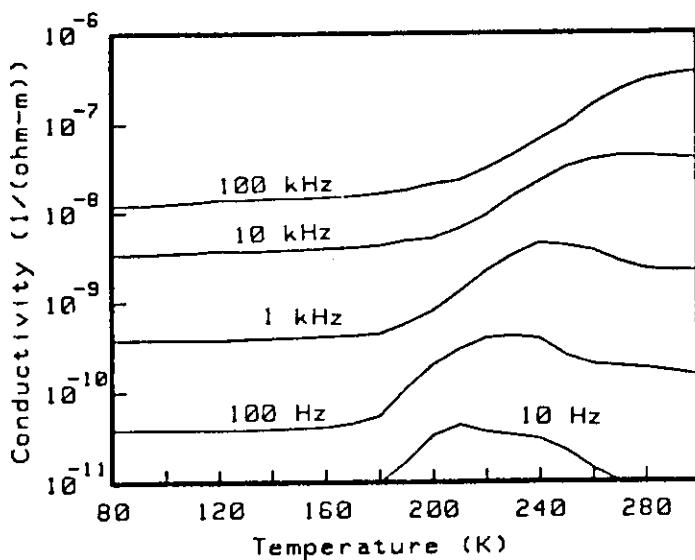
Reference	Investigation of Mineral Insulated Cables Exposed to High Temperature and Intense Gamma Radiation
	H. Böck and M. Suleiman
	Nucl. Inst. Methods <u>148</u> (1978) 43

Material	Glass-bonded mica	Property	Electrical conductivity	1/1
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Irradiation Condition $\sim 10^{18} \text{ n/cm}^2 (\text{E} > 0.1 \text{ MeV})$ ORR



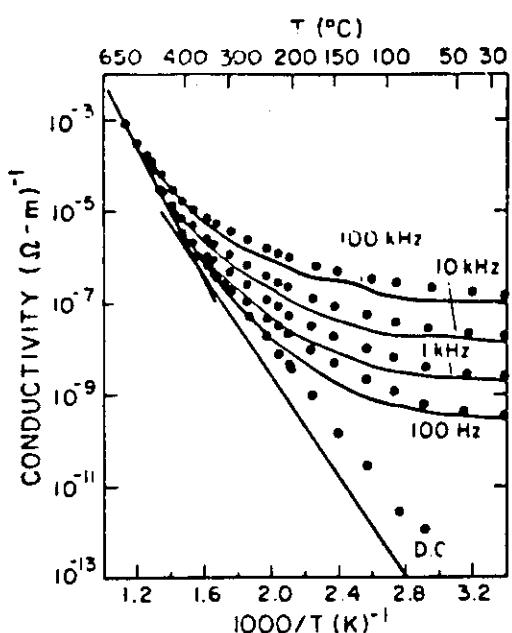
Electrical conductivity of glass-bonded mica control sample below room temperature. Frequencies of measurement are indicated.



Electrical conductivity for glass-bonded mica sample irradiated to $10^{22} \text{ fast n/m}^2$. Frequencies are indicated.

Reference	Electrical Conductivity of Neutron-Irradiated Glass-bonded MICA Insulator from 80-800K
	J. D. Fowler, Jr.
	DOE/ER-0113/1, August 1982, P. 57

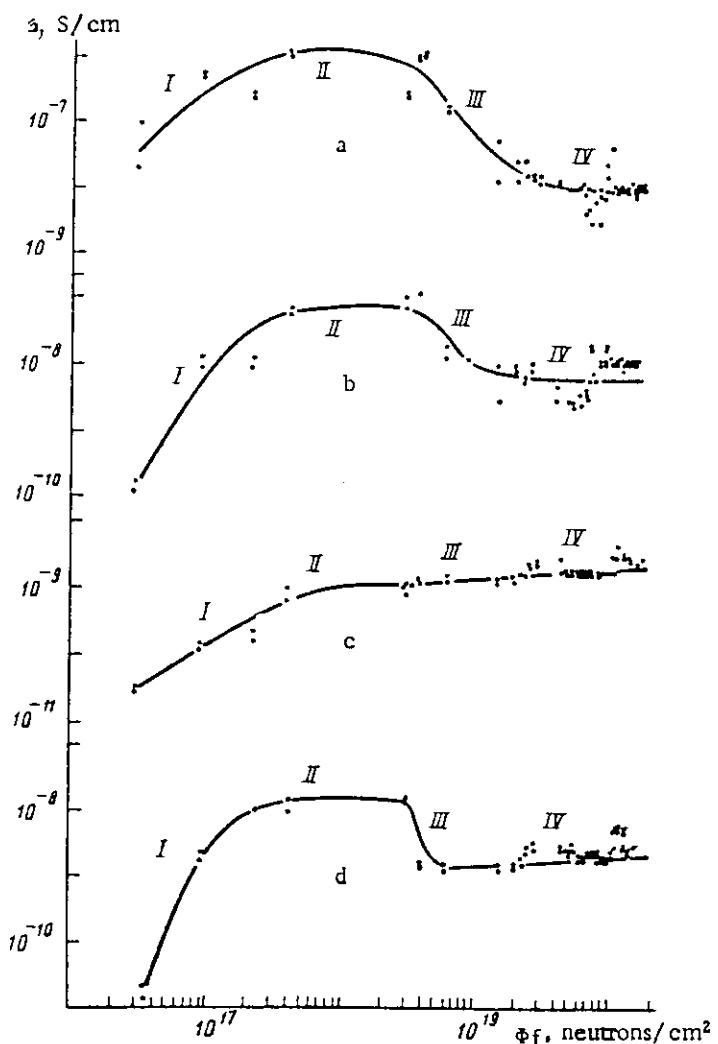
Material	MACOR	Property	Electrical conductivity	1/1
Irradiation Condition	$10^{16}, 10^{18}$ 14 MeV n/cm ² room temperature		RTNS-II	



Electrical conductivity of MACOR.
Lines are fits to controls; points are data
for samples irradiated to 10^{22} 14 MeV n/m².

Reference	14 MeV Neutron Irradiation Effects in MACRO Glass Ceramic
	J.D.Fowler,Jr., G.F.Hurley, J.C.Kennedy and F.W.Clinard,Jr.
	J. Nucl. Mater. <u>103 & 104</u> (1981) 755

Material	Al_2O_3 , MgAl_2O_4	Property	Electrical conductivity	1/1
Irradiation Condition	$< 3 \times 10^{20} \text{ n/cm}^2$ ($E > 0.1 \text{ MeV}$) 445°C			



Electric conductivity σ of plasma-deposited materials vs dose Φ_f of fast neutrons.
a) Al_2O_3 (no fractionation); b) MgAl_2O_4 ; c)
30 : 70 solid solution; d) Al_2O_3 ($< 40 \mu\text{m}$ frac-
tion).

Reference	Electrophysical Properties of Plasma-Deposited Refractory Oxides under Reactor Irradiation	
	V. M. Ivanov, G. M. Kalinin, V. F. Kuzovotkin, S. P. Sklizkov, N. V. Markina, V. V. Sarkisyan and V. A. Skobeleva	
	Inorg. Mater. 17 (1981) 1203	

Material	SiO_2 $\alpha\text{-Al}_2\text{O}_3$ (coor AD-995)	Property	Loss tangent, Density dielectric constant	1/l
Irradiation Condition	$6 \times 10^{17} \text{ n/cm}^2$ (fast) Brookhaven Reactor 95°C $2.5 \times 10^{19} \text{ n/cm}^2$ (fast) Sterling Forest Reactor 47°C			

Changes in dielectric constant ϵ' , dissipation factor $\tan\delta$, density, and cell constants upon irradiation with fast neutrons.

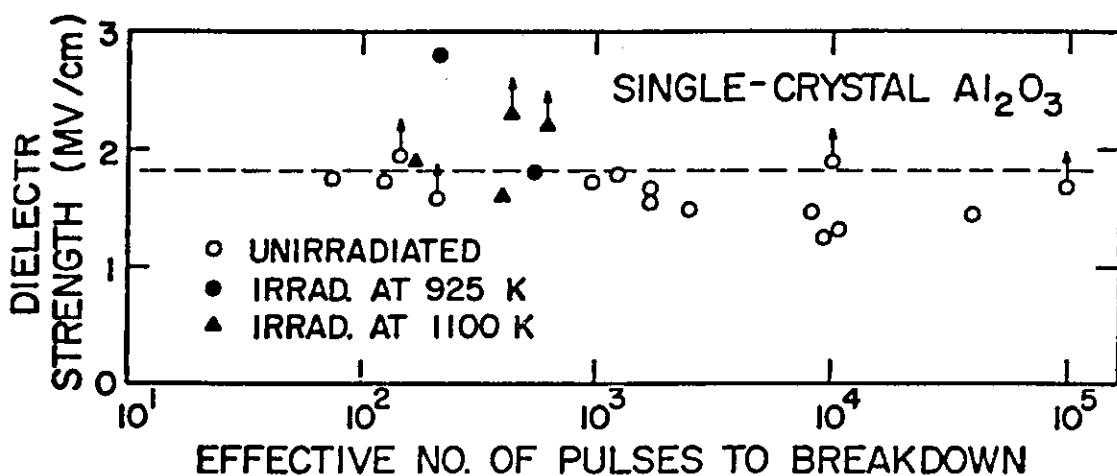
Irradiation (neutrons per cm^2)	Fused Silica				
	ϵ'	$\tan\delta$ (10^{-4})	Density (g/cm^3)	Density change (%)	
Unirradiated	3.8 ± 0.1	0.2 ± 0.1	2.196	0	
6×10^{16}	3.7 ± 0.1	0.2 ± 0.1	...	...
2×10^{17}	3.7 ± 0.1	0.4 ± 0.1	...	...
6×10^{17}	3.7 ± 0.1	6.0 ± 0.5	2.216	+0.94	
2×10^{19}	3.6 ± 0.1	14.0 ± 1	2.238	+1.95	
5×10^{19}	3.6 ± 0.1	18.0 ± 1	2.241	+2.05	

Irradiation (neutrons per cm^2)	α Alumina				
	ϵ'	$\tan\delta$ (10^{-4})	Cell constants	a (\AA)	c (\AA)
Unirradiated	9.2 ± 0.1	0.3 ± 0.1	4.757 ± 0.002	12.978 ± 0.002	0
6×10^{16}	9.2 ± 0.1	0.3 ± 0.1	...	...	...
2×10^{17}	9.0 ± 0.1	0.5 ± 0.1	...	...	...
6×10^{17}	8.9 ± 0.1	4.0 ± 0.5	4.759 ± 0.002	12.984 ± 0.002	-0.28
2×10^{19}	8.4 ± 0.1	2.0 ± 0.25	4.759 ± 0.002	12.996 ± 0.002	-0.38
5×10^{19}	8.3 ± 0.1	1.0 ± 0.25	4.759 ± 0.002	12.997 ± 0.002	-0.39

$\tan\delta$ was measured at 1 MHz

Reference	Room-Temperature Dielectric Properties of Fast-Neutron-Irradiated Fused Silica and α Alumina
	J. B. MacChesney and G. E. Johnson
	J. Appl. Phys. <u>35</u> (1964) 2784

Material	Al_2O_3 (single crystal)	Property	Dielectric strength	1/1
Irradiation Condition	$\sim 2 \times 10^{22} \text{ n/cm}^2$ ($E > 0.1 \text{ MeV}$) EBR-II 650°C, 827°C			

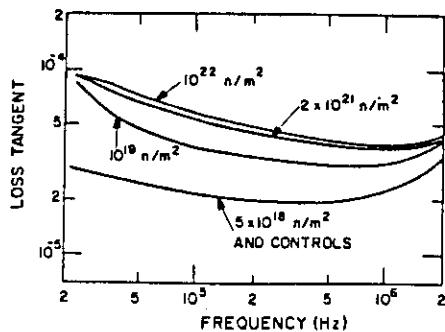


RT, short-pulse dielectric breakdown strength of Al_2O_3 before and after elevated-temperature irradiation to $\sim 2 \times 10^{26} \text{ n/m}^2$ ($E > 0.1 \text{ MeV}$).

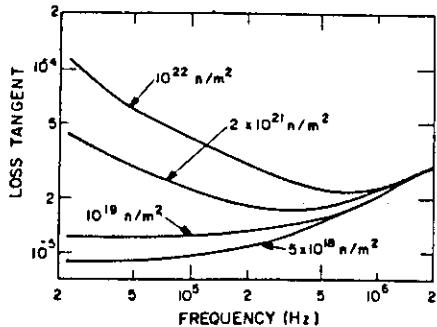
Reference	The Inorganic Insulator Program at LASL
	F. W. Clinard, Jr. and D. M. Parkin
	USDOE Report No. CONF-801237, 1981, Pl7.1

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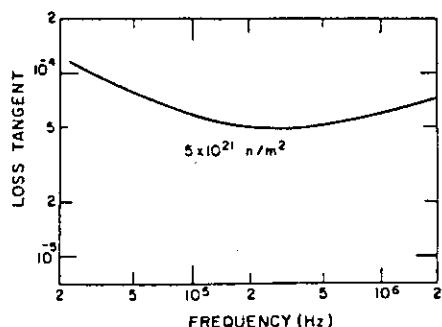
Material	Al_2O_3 (single-crystal and polycrystalline)	Property	Loss tangent	1/1
Irradiation Condition	5 $\times 10^{17}$ n/cm ² (RTNS-II) 1 $\times 10^{18}$ n/cm ² (LAMPF)			



Loss tangents for polycrystalline Al_2O_3 irradiated with fast neutrons.



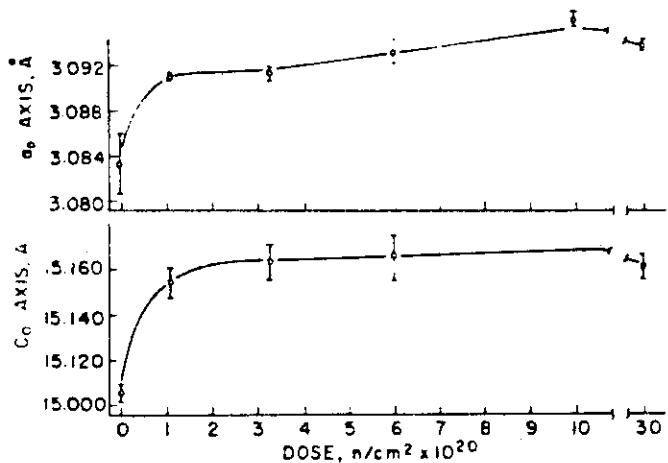
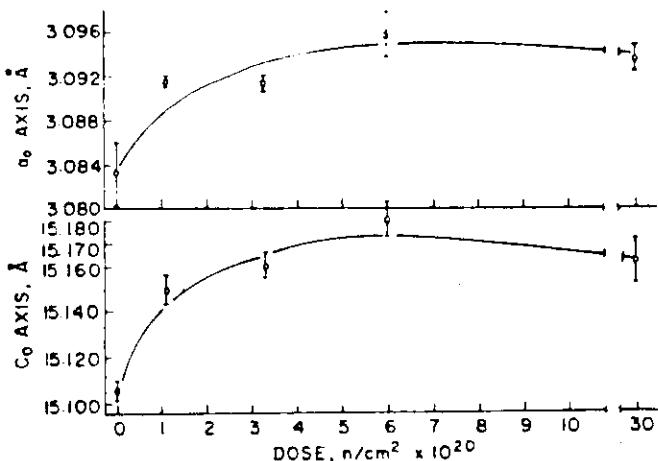
Loss tangents for single crystal Al_2O_3 irradiated with high-energy neutrons.



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

Reference	Radiation-Induced RF Loss Tangent and Thermal Stress Calculation for Ceramic Windows
	J. D. Fowler, Jr.
	J. Nucl. Mater. <u>122 & 123</u> (1984) 1359

Material	SiC (α -SiC)	Property	Lattice parameter	1/1
Irradiation Condition	$3 \times 10^{21} \text{ n/cm}^2$ ($E > 1 \text{ MeV}$) 450, 650°C			

 α -SiC lattice parameters as a function of irradiation at 450°C. α -SiC lattice parameters as a function of irradiation at 650°C.

Reference	Irradiation Damage in Reaction-bonded Silicon Carbide
	R. B. Matthews
	J. Nucl. Mater. <u>51</u> (1974) 203

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Material	BeO	Property	Lattice parameter	1/1
Irradiation Condition	< 2×10^{21} n/cm ² (E > 1 MeV) ETR 110, 650, 1100°C			

Results of X-ray Diffraction Examination of BeO Irradiated at 110°C*

BeO Type	Fast-Neutron Dose (>1 MeV) (n/cm ²)	Fast-Neutron Flux (>1 MeV) [n/(cm ² sec)]	$\Delta a/a_0$	$\Delta c/c_0$	$\Delta V/V_0$
	($\times 10^{21}$)	($\times 10^{14}$)	(± 0.0001)	(± 0.0003)	(± 0.0003)
IV	0.4	0.9	0.0010	0.0100	0.0120
I	0.7	1.7	0.0012	0.0256	0.0280
IV	1.0	2.4	0.0013	0.0298	0.0324
I	1.0	2.4	0.0013	0.0326	0.0352

Experiment*	BeO Type	Fast-Neutron Dose (>1 MeV) (n/cm ²)	Fast-Neutron Flux (>1 MeV) [n/(cm ² sec)]	Temp. (°C)	$\Delta a/a_0$	$\Delta c/c_0$	$\Delta V/V_0$
		$\times 10^{21}$	$\times 10^{14}$		(± 0.0001)	(± 0.0003)	(± 0.0003)
41-9	IV	0.8	1.0	650	0	0.0150	0.0150
41-9	I	0.9	1.1	650	0	0.0158	0.0158
41-9	I	1.7	2.1	650	0.0001	0.0140	0.0142
41-9	IV	1.7	2.1	650	0	0.0226	0.0226
41-8	IV	1.3	0.8	650	0.0001	0.0152	0.0154
41-8	II	1.6	1.0	650	0	0.0114	0.0114
41-8	II	1.8	1.1	650	0	0.0205	0.0205
41-8	II	1.9	1.2	650	0	0.0191	0.0191
41-8	II	2.0	1.3	650	0	0.0194	0.0194
41-8	I	2.9	1.8	650	0	0.0212	0.0212
41-8	IV	4.3	2.7	650	0.0004	0.0209	0.0217
41-8	I	4.5	2.8	650	0.0005	0.0204	0.0214
41-9	I	0.7	0.9	1100	0	0	0
41-9	IV	0.8	1.0	1100	0	0	0
41-9	IV	1.9	2.4	1100	0	0.0019	0.0019
41-9	I	1.9	2.4	1100	0	0.0034	0.0034
41-8	II	1.0	0.6	1100	0.0001	0.0016	0.0018
41-8	IV	1.8	1.1	1100	0.0001	0	0.0002
41-8	IV	3.2	2.0	1100	0	0.0028	0.0028
41-8	I	3.4	2.2	1100	0.0001	0	0.0002

*Lattice parameters were calculated from measurements of the 21-1 and 21-0 reflections of Ni K α x radiation from BeO compacts irradiated in Experiments 41-8 and 41-9, which were ground to a fine powder.

^aIrradiation times of Experiments 41-8 and 41-9 were 1.59×10^7 and 7.95×10^6 sec, respectively.

^bThe fractional volume increase $\Delta V/V_0$ was calculated from the equation $\Delta V/V_0 = 2\Delta a/a_0 + \Delta c/c_0$.

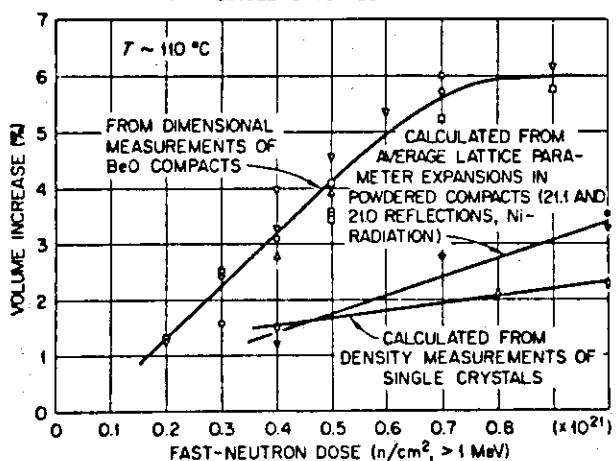
Reference	Irradiation Damage to Sintered Beryllium Oxide as Function of Fast-Neutron Dose and Flux at 110, 650, and 1100°C
	G. W. Keilholtz, J. E. Lee, Jr. and R. E. Moore
	Nucl. Sic. and Eng. <u>26</u> (1966) 329

Material	BeO	Property	Lattice parameter	1/2
Irradiation Condition	$< 2 \times 10^{21} \text{ n/cm}^2 (\text{E} > 1 \text{ MeV})$	ETR		

OPEN SYMBOLS - VOLUME INCREASE FROM DIMENSIONAL MEASUREMENTS

SOLID SYMBOLS - VOLUME INCREASE CALCULATED FROM LATTICE PARAMETERS

- I LOW DENSITY ($\approx 2.7 \text{ g/cm}^3$)
SMALL GRAIN SIZE ($\approx 17 \mu$)
- II LOW DENSITY ($\approx 2.7 \text{ g/cm}^3$)
LARGE GRAIN SIZE ($\approx 34 \mu$)
- III HIGH DENSITY ($\approx 2.9 \text{ g/cm}^3$)
SMALL GRAIN SIZE ($\approx 25 \mu$)
- ▼ IV HIGH DENSITY ($\approx 2.9 \text{ g/cm}^3$)
LARGE GRAIN SIZE ($\approx 74 \mu$)
- SINGLE CRYSTALS



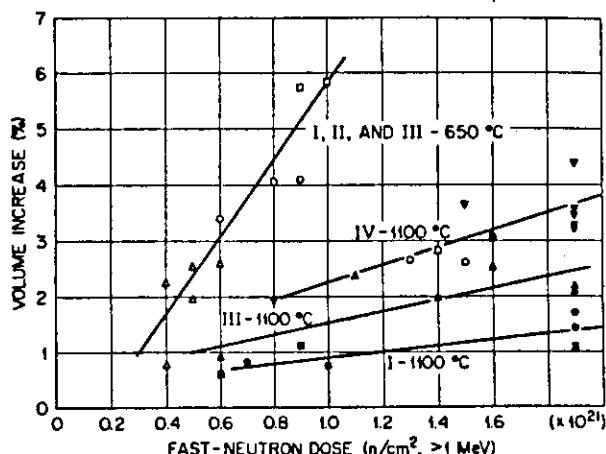
Volume increase of $\frac{1}{2}$ -in. BeO compacts and single crystals irradiated at 110°C vs fast-neutron dose.

Reference	Irradiation Damage to Sintered Beryllium Oxide as a Function of Fast-Neutron Dose and Flux at 110, 650, and 1100°C
	G. W. Keilhertz, J. E. Lee, Jr. and R. E. Moore
	Nucl. Soc. and Eng. <u>26</u> (1966) 329

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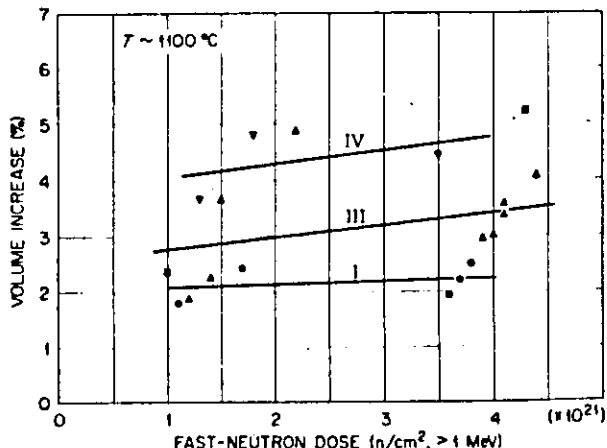
Material	BeO	Property	Lattice parameter	1/1
Irradiation Condition	$< 2 \times 10^{21} \text{ n/cm}^2 (\text{E} > 1 \text{ MeV})$ ETR 110, 650, 1100°C			

- 1100°C I LOW DENSITY ($\approx 2.7 \text{ g/cm}^3$)
- 650°C I SMALL GRAIN SIZE ($\approx 17 \mu$)
- 1100°C II LOW DENSITY ($\approx 2.7 \text{ g/cm}^3$)
- 650°C II LARGE GRAIN SIZE ($\approx 34 \mu$)
- ▲ 1100°C III HIGH DENSITY ($\approx 2.9 \text{ g/cm}^3$)
- △ 650°C III SMALL GRAIN SIZE ($\approx 25 \mu$)
- ▼ 1100°C IV HIGH DENSITY ($\approx 2.9 \text{ g/cm}^3$)
- ▼ 650°C IV LARGE GRAIN SIZE ($\approx 74 \mu$)



Volume increase of 1/2-in. BeO specimens irradiated at 650 and 1100°C in short-term experiment 41-9 ($7.95 \times 10^6 \text{ sec}$) vs fast-neutron dose.

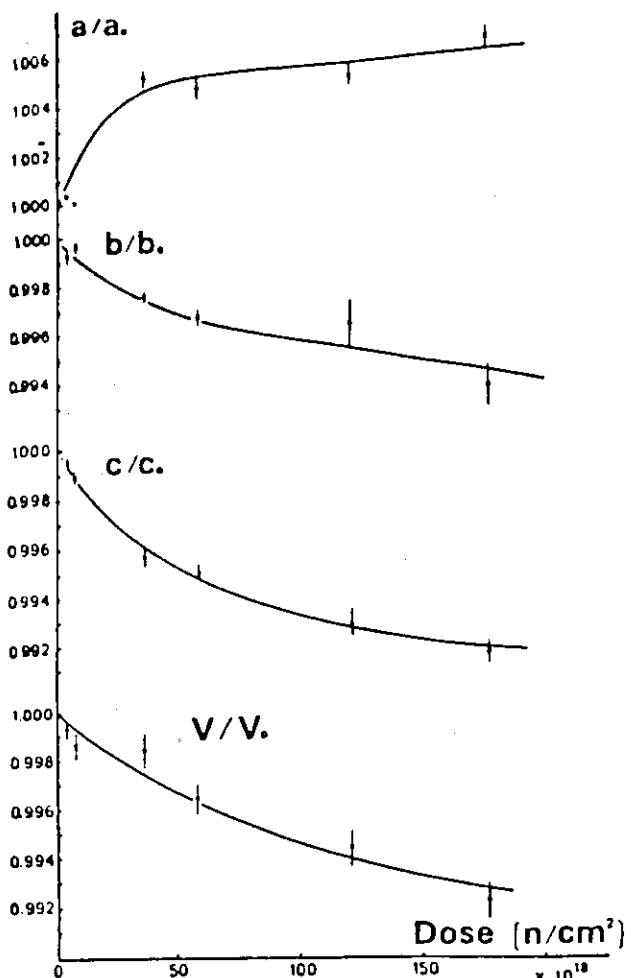
- I LOW DENSITY ($\approx 2.7 \text{ g/cm}^3$)
- II SMALL GRAIN SIZE ($\approx 17 \mu$)
- II LOW DENSITY ($\approx 2.7 \text{ g/cm}^3$)
- III LARGE GRAIN SIZE ($\approx 34 \mu$)
- ▲ III HIGH DENSITY ($\approx 2.9 \text{ g/cm}^3$)
- △ IV SMALL GRAIN SIZE ($\approx 25 \mu$)
- ▼ IV HIGH DENSITY ($\approx 2.9 \text{ g/cm}^3$)
- ▼ IV LARGE GRAIN SIZE ($\approx 74 \mu$)



Volume increase of 1/2-in. BeO specimens irradiated at 1100°C in long-term experiment 41-8 ($1.59 \times 10^7 \text{ sec}$) vs fast-neutron dose.

Reference	Irradiation Damage to Sintered Beryllium Oxide as a Function of Fast-Neutron Dose and Flux at 110, 650, and 1100°C
	G. W. Keilholtz, J. E. Lee, Jr. and R. E. Moore
	Nucl. Sic. and Eng. 26 (1966) 329

Material	$\text{Si}_2\text{N}_2\text{O}$	Property	Lattice Parameter	1/1
Irradiation Condition	$10^{17} \sim 3 \times 10^{20}$ fast n/cm ² SILOE (CENG) ≤ 327°C			



Relative lattice parameters and unit-cell volume change of orthorhombic $\text{Si}_2\text{N}_2\text{O}$ with fast neutron irradiation.

Reference	Variation of the Lattice Parameters of $\text{Si}_2\text{N}_2\text{O}$ with Fast Neutron Irradiation
	M. Billy, J. C. Labbe, A. Selvaraj, G. Roult and L. Cartz
	J. Am. Ceram. Soc. <u>62</u> (1979) 540

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Material	Si_3N_4 Sialon	Property	Lattice parameter	1/l
Irradiation Condition	$3 \times 10^{21} \text{ n/cm}^2$ ($E > 0.1 \text{ MeV}$) 742°C	EBR-II		

Material	Major Phase	Impurity Phases
Norton Si_3N_4	$\beta\text{-Si}_3\text{N}_4$	$\sigma\text{-Si}_3\text{N}_4$ Si_2ON_2 MgO
Ceradyne Si_3N_4	$\beta\text{-Si}_3\text{N}_4$	MgO
Si_2ON_2	Si_2ON_2	$\beta\text{-Si}_3\text{N}_4$ SiC

Lattice Parameter Changes

	$\Delta a/a_0$	$\Delta b/b$	$\Delta c/c$
Si_2ON_2	+0.17%	-0.17%	-0.26%
Si_3N_4^a	+0.02%	--	+0.01%
Si_3N_4^b	-0.08%	--	0
Sialon	-0.17%	--	+0.16%

aNorton NC-132bCeradyne

Reference	X-ray Analysis of Internal Strain in Neutron-Irradiated Silicon Nitride and Oxynitrides
	G. F. Hurley and F. H. Cocks
	USDOE Report, DOE/ER-0113, Nov. 1981, 2.3

Material	BeO, Al ₂ O ₃ , Al ₂ O ₃ -SiO ₂	Property	Helium liberation Helium migration	1/1
Irradiation Condition	0.73 ~ 1 x 10 ²¹ n/cm ² (E ≥ 0.8 MeV)			

Concentration of Helium in Stored Vacancies in Different Specimens after Irradiation in a Reactor

Material	Chemical composition, mass %						Nuclear reaction	Neutron fluence (E ≥ 0.8 MeV), neut./cm ²	Irradiation temp., °C	Concn. of helium, atom/cm ³ [calculation]	Concn. of stored vacancies per 1 cm ³ [12-14]	
	Al ₂ O ₃	SiO ₂	Fe ₂ O ₃	CaO	B ₂ O ₃	MgO						
BeO							⁷ Be(n, α) ⁸ Li	6 · 10 ²⁰	~ 75	1,44 · 10 ¹⁹	2,88 · 10 ²¹	
GB-7	97,07	0,92	0,08	0,9	0,02	—	¹⁰ B(n, α) ⁷ Li	1,25 · 10 ²⁰ 1,0 · 10 ²¹	— 100	6,4 · 10 ¹⁹ 1,22 · 10 ²⁰	1,15 · 10 ²⁰ 9,2 · 10 ²⁰	
MG-2	60,14	21,12	0,4	2,32	1,67	2,54	—	¹⁰ B(n, α) ⁷ Li	1,25 · 10 ²⁰ 1,0 · 10 ²¹	~ 100	9,38 · 10 ¹⁹ 1,06 · 10 ²⁰	1,15 · 10 ²⁰ 9,2 · 10 ²⁰
L-24	47,5	41,67	2,01	0,61	—	7,2	0,5	⁷ Li(n, α) ⁴ H	1,25 · 10 ²⁰ 1,0 · 10 ²¹	~ 100	2,52 · 10 ¹⁹ 3,88 · 10 ¹⁹	4,15 · 10 ²⁰ 9,2 · 10 ²⁰

Activation Energy for Migration of Helium in Different Irradiated Ceramic Specimens

Specimen	Activation en- ergy, eV	Annealing temp., °C	Fluence, 10 ²⁰ neutrons/cm ²
BeO	0,1-0,3	100-250	6,0
	0,6-0,8	400-500	
MG-2	0,1-0,3	100-300	1,26
	0,5-1,2	350-500	
	0,3	100-300	
GB-7	0,5-1,4	350-500	10,0
	0,1-0,6	100-300	1,26
	0,5-1,0	400-600	
	0,1-0,4	100-300	
	0,4-0,6	400-600	10,0
L-24	0,4-0,5	100-300	1,26
	0,8-1,2	500-700	
	0,25-0,5	100-300	
	1,0-1,3	500-700	10,0
AIN	0,1-0,2	100-300	1,26
	0,5-0,8	200-400	
	0,25-1,0	600-800	12,0

Note. Temperature of BeO irradiation ~ 75°C; for the remaining materials studied ~ 100°C.

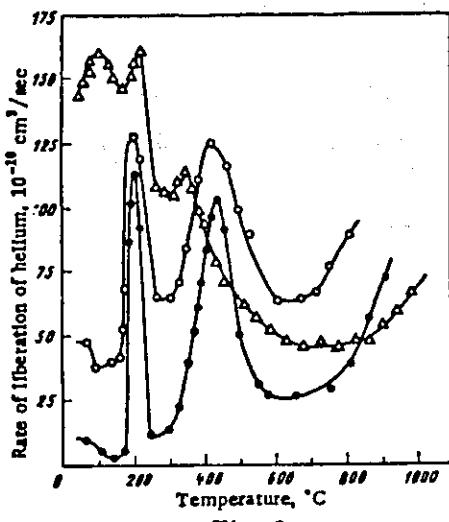


Fig. 3

Temperature dependence of the rate of liberation of helium out of beryllium oxide, irradiated to a fluence of 6 · 10²⁰ (●); 7 · 10²⁰ (○); and 1.2 · 10²¹ (Δ) neutrons/cm². The annealing rate was 5°C/min.

Reference	Helium liberation from Irradiated Ceramic Materials	
	A. V. Khudyakov, G B. Shchekina and A. N .Lepikhov	
	Sov. At. Energy 52 (1982) 173	

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Material	Al_2O_3 (single crystal)	Property	Optical Absorption Coefficient	1/2
Irradiation Condition	5 ~ 15 MeV proton (LASL Tanden Van de Graff) - 14 MeV n RTNS (LLL)			

Optical Absorption vs. Particle Energy

Energy (MeV)		Fluence (cm ²)	Optical Abs. Coeff. (cm ⁻¹)	Ratio of Abs. to Fluence
In	Out			
5	2	6.75×10^{15}	24	3.6×10^{-15}
9	6	$5.6 \times 10^{16}*$	55.8	1.0×10^{-15}
12	9.5	2.1×10^{16}	37	1.8×10^{-15}
15	13	2.1×10^{16}	30.5	1.5×10^{-15}
14 MeV n		1×10^{17}	124**	1.24×10^{-15}

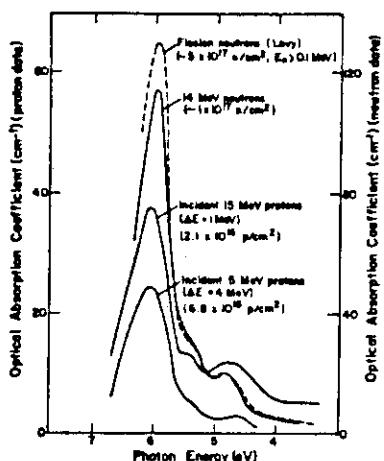
* Estimated

**This may have underestimated by ~30% because of spectrophotometer stray light.

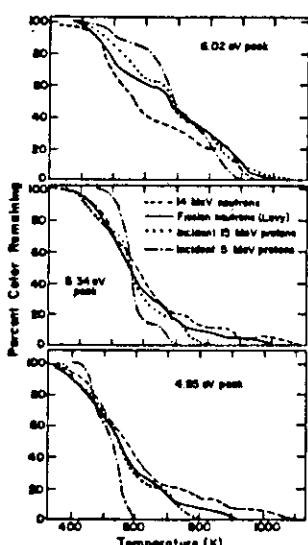
	High Energy Proton Simulation of 14-MeV Neutron Damage in Al_2O_3
Reference	D. W. Muir and J. M. Bunch
	Conf. Proc. Radiation Effects and Tritium Technology for Fusion Reactor, CONF-750989 (1976) II-517

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Material	Al_2O_3 (single crystal)	Property	Optical Absorption Coefficient	2/2
Irradiation Condition	5 ~ 15 MeV proton 14 MeV n RTNS (LLL)			



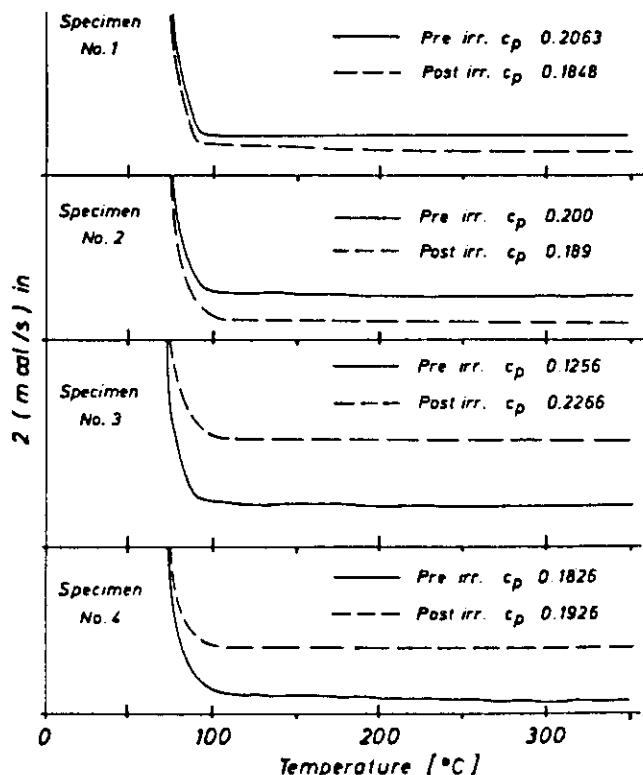
Optical Absorption of Sapphire Irradiated and Measured at Room Temperature.



Isochronal Annealing Curves for the Three Principal Absorption Peaks of sapphire

Reference	High Energy Proton Simulation of 14 MeV Neutron Damage in Al_2O_3
	D. W. Muir and J. M. Bunch
	Conf. Proc. Radiation Effects and Tritium Technology for Fusion Reactor, CONF. 750989 (1976), II-517

Material	Porcelain	Property	Specific heat	1/1
Irradiation Condition	14.3 MeV n (Neutron Generator) 8.4, 16.8, 21.0×10^{10} n/cm ²			



Specific heat curves of porcelain specimens No.1,2,3 and 4 before and after irradiation with 16.8×10^{10} n/cm²

Composition of the prepared porcelain bodies

Body No.	Raw materials in wt.-%				
	Feldspar	Quartz	Alumina	Sinai kaolin	Aswan clay
1	20	30	-	30	20
2	20	25	-	35	20
3	20	-	20	40	20

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	W. A. Fattach and D. S. El-Alousi
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6. Summary

A data base of radiation effects on ceramic insulators was made by collecting the published literatures. As the study of radiation effects on ceramics is now in progress and many kinds of properties should be examined, the data base is thought to be insufficient for getting a sound understanding of radiation effects and for optimizing ceramic materials to fusion application. As compared to the data base of metal, the amount of data on ceramic materials is found to be much less.

The effort for extending the data base and studying the fundamental process of radiation damage in ceramics would be important.