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DATA COMPILATION FOR RADIATION DAMAGE ON CERAMIC INSULATORS
(REVISED WITH UPDATED DATA AND REVIEWS)

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Data Compilation for Radiation Damage on Ceramic Insulators※ (Revised with Updated Data and Reviews)

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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 of 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. As to swelling, the data were complied according to the dose dependence and the temperature dependence for each ceramics and reviewed briefly.

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※
（新データの追加および評価による改正版）

日本原子力研究所東海研究所
原子分子データ研究委員会
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核融合炉においては各種絶縁材料が使用されているが，その環境は従来の核分裂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，絶縁材料の中の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。さらに，比較的データの多いスエリングについて，照射量依存性，温度依存性を材料毎にとりまとめた。

※　本報告書は，JAERI－M 86-127 の改訂版である。本報告書入手についての問合せは白井稔三（原研）まで。

本報告書は㈱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, inorganic 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 an 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 inorganic 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. Furthermore, as to swelling, the data were compiled as a function of neutron fluence and irradiation temperature for each ceramics.

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 results of data compilation of swelling is shown in chapter 4. The data sheets and the literatures are shown in chapter 5 and chapter 6 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 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/cm^2, 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.

Table 2-1 Radiation environment of ceramics in fusion devices

Component	Operating Conditions				Stress	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^{19}	10^4 10^5	<1200 <1200^a	– –	High High	SiC, Si_3N_4 Coated graphite^b	Sputtering erosion High transient temperatures, sputtering erosion
Armor	10^{19}	10^5	<1200	–	Medium	Coated graphite^b	High particle fluxes
Blanket structure	10^{17}–10^{19}	10^4	<1000	–	High	SiC, Al_2O_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_2O_3, MgO, MACOR glass ceramic	Resistivity >10^6Ωm
Toroidal current break	10^{16}–10^{18}	1–100	~500	<1	High	Al_2O_3, $MgAl_2O_4$	
Shaping and diverter coil insulators	10^{18}	100	~500	~1	High	Al_2O_3, $MgAl_2O_4$	
Direct converter Insulators	10^{14}–10^{16}	>10	~1000	~10	Low	Al_2O_3, MACOR glass ceramic	DC field could induce electrolysis failure
Windows for rf^a heating	<10^{19}	<10^4	~500	0.1–1	High	BeO, Al_2O_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

3. Data

The data collected from the literatures are summarized in Table 3-1 to Table 3-8. The data were selected from the literatures published in 1960-1986 which contained the data in the form of tables or graphs. The main scope of the study in the literatures are listed as follows:

- application of ceramics to fusion devices,
- incore monitor cable insulation in fission reactors,
- SiC encapsulation of fuel element in a high temperature gas cooled reactor,
- neutron reflector of BeO.

The data on ceramic neutron absorber such as B_4C and ceramic fuel such as UO_2 were omitted because they are not expected to be used as insulator.

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 5. The number of the data sheet and the literature are given in the tables. The list of the literatures are shown in chapter 6.

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

3.1 Swelling (Table 3-1)

Swelling is expressed by the percentage of the volume increase or decrease to the original volume of ceramics. In some literatures, the dimensional change in one direction are expressed as linear expansion or growth. The swelling is measured by the density change or by the calculation from the measured void diameter and void number density by using a transmission electron microscope. The early studies on BeO, Al_2O_3 and MgO were performed by using research reactors such as ETR, HIFAR and DIDO at the fluence below 10^{22} n/cm^2 ($E > 1$ MeV). Most of the recent irradiations were performed by using EBR-II at the fluence above 10^{22} n/cm^2 ($E > 0.1$ MeV).

Swelling of ceramics is considered to occur by dilatation of lattices under the presence of point defects and by volume increase under the nucleation and growth of voids. At lower temperature and at low fluences, the former mechanism may be dominant because no voids were observed in many cases and because the calculated volume increase based on the measured lattice parameter increase is corresponding to the measured volume increase. Under high temperature and high dose irradiations, void formation seems to be dominant because voids were usually observed in ceramics.

Al_2O_3, BeO and MgO have been well examined while other ceramics were examined less systematically. The results of data compilation of swelling will be shown in chapter 4.

3.2 Mechanical Property (Table 3-2)

Most of the strength data were obtained as the fracture strength by using three or four point bend test method after irradiation. SiC, Al_2O_3 and $MgAl_2O_4$ have been examined but nonsystematically. In the case of brittle materials, the probability of fracture is usually analyzed by the Weibul statistics. In some literatures, this method has been tried to apply. From the current data base, no conclusive review can be made on the radiation effect because of the lack of data. Further irradiation test and the establishment of standarized method to evaluate the mechanical property change should be necessary.

3.3 Thermal Property (Table 3-3)

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.

In general, thermal conductivity and thermal diffusivity are decreased during irradiation. As the fluence increases, these values decrease rapidly and reach to a constant value of 40 - 80% of the original values. Single crystal $MgAl_2O_4$ seems to be highly resistant to irradiation exceptionaly.

3.4 Electrical Property (Table 3-4)

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 of Al_2O_3 irradiated by electrons, protons, X-ray and γ-ray.

3.5 Dielectric Property (Table 3-5 and Table 3-6)

Several nonsystematical data were found. They are the data of dielectric constant on irradiated Al_2O_3 and SiO_2 and the data of the short pulse dielectric breakdown strength on Al_2O_3, as shown in Table 3-5. In general the dielectric constant decreases as the irradiation dose increases.

The measurement of loss tangent has been made on only Al_2O_3 and SiO_2, as shown in Table 3-6. As to Al_2O_3, the fluence dependence and the frequency dependence have been measured under the restricted fluence and temperature range. The loss tangent tends to increase with fluence and the degree of increase is larger at lower temperature.

3.6 Lattice Parameter (Table 3-7)

The change of lattice parameter by irradiation in BeO and other ceramics has been reported. The lattice parameter generally increases with fluence and reachs to the maximum value and then decreases. As mentioned in swelling, the increase of lattice parameter is corresponding to the volume increase at low fluence.

3.7 Miscellaneous (Table 3-8)

The data of optical absorption coefficient in Al_2O_3 and MgO and helium reemission from BeO and Al_2O_3 were found.

Table 3-1 Swelling (1)

MATERIAL		IRRADIATION			DATA	REF
		DOSE	FACILITY	TEMPERATURE		
β-SiC		1.2×10^{22} n/cm^2 ($E > 0.18$ MeV)	ETR	625, 1500°C	A-24	20
		$2.0 \sim 4.2 \times 10^{21}$ n/cm^2 ($E > 0.18$ MeV)	ETR	460, 1040°C	A-23	18
α-SiC		1.2×10^{21} n/cm^2 ($E > 1$ MeV)	HFBR	200°C	A-38 A-39	36
SiC	NC-430	1.2×10^{21} n/cm^2 ($E > 1$ MeV)	HFBR	200°C	A-38 A-39	36
Al_2O_3	sapphire	5.6×10^{21} n/cm^2 ($E > 0.1$ MeV)	EBR-II	377, 602, 752°C	A-29 A-30 A-31	23
		2.8×10^{21} n/cm^2 ($E > 0.1$ MeV)	EBR-II	740°C	A-34	30
	sc	2.3×10^{22} n/cm^2 ($E > 0.1$ MeV)	EBR-II	157, 652, 827°C	A-40	39
		2.2×10^{22} n/cm^2 ($E > 0.1$ MeV)	EBR-II	407, 542°C	A-44	48
		2×10^{22} n/cm^2 ($E > 0.1$ MeV)	EBR-II	387°C	A-46	54
		$10^{18} \sim 1.1 \times 10^{21}$ n/cm^2 ($E > 1$ MeV)	DIDO	150, 650°C	A-20 ∿ A-22	17
		$< 4 \times 10^{20}$ n/cm^2 ($E > 1$ MeV)	DIDO PLUTO	< 150°C 1000°C	A-12 ∿ A-14	8
		< 500 MC/m^2 1 MeV	HVEM	607 ∿ 857°C	A-41 ∿ A-43	46
	sc pc	$< 5 \times 10^{20}$ n/cm^2 ($E > 1$ MeV)	HIFAR	75 ∿ 100°C	A-17	15
	Lucalox	4.1×10^{21} n/cm^2 ($E > 0.1$ MeV)	EBR-II	377, 602, 752°C	A-29 A-30	23
		8.2×10^{21} n/cm^2 ($E > 0.1$ MeV)	EBR-II	690 ∿ 1100°C	A-27	21
		8×10^{21} n/cm^2 ($E > 0.1$ MeV)	ETR	70 ∿ 325°C	A-28	21

Table 3-1 Swelling (2)

MATERIAL		IRRADIATION			DATA	REF
		DOSE	FACILITY	TEMPERATURE		
Al_2O_3	AD-995	8.2×10^{21} n/cm^2 (E > 0.1 MeV)	ETR EBR-II	690 ∿ 1100°C	A-25 ≀ A-28	21
		2.8×10^{21} n/cm^2 (E > 0.1 MeV)	EBR-II	740°C	A-34	30
		2.3×10^{22} n/cm^2 (E > 0.1 MeV)	EBR-II	157, 652, 827°C	A-40	39
	AL-995	8.2×10^{21} n/cm^2 (E > 0.1 MeV)	EBR-II ETR	690 ∿ 1100°C	A-27	21
	AD-999X	4.8×10^{21} n/cm^2 (E > 0.1 MeV)	EBR-II	337, 602, 752°C	A-29 A-30	23
	Avco	4.8×10^{21} n/cm^2 (E > 0.1 MeV)	EBR-II	337, 602, 752°C	A-29	23
MgO		2.1×10^{22} n/cm^2 (E > 0.2 MeV) 4.6×10^{22} n/cm^2 thermal	HFIR	157°C	A-36	33
		2.1×10^{22} n/cm^2 (E > 0.1 MeV)	EBR-II	157°C	A-40	39
	sc	$< 4 \times 10^{20}$ n/cm^2 (E > 1 MeV)	DIDO PLUTO	< 150°C 1000°C	A-12 ≀ A-14	8
	sc pc	$0.14 \sim 6.5 \times 10^{20}$ n/cm^2 (E > 1 MeV)	HIFAR	75 ∿ 100°C	A-16	13
BeO	Niberlox	2.8×10^{21} n/cm^2 (E 0.1 MeV)	EBR-II	740°C	A-34	30

Table 3-1 Swelling (3)

MATERIAL		IRRADIATION			DATA	REF
		DOSE	FACILITY	TEMPERATURE		
BeO	Hot pressed, sintered	$< 6 \times 10^{20}$ n/cm^2 (E > 1 MeV)	DIDO DLUTO	< 150°C 1000°C	A-12 ∼ A-14	8
		$< 6 \times 10^{20}$ n/cm^2 (E > 1 MeV)	BR2	150°C	A-13	8
		$0.3 \sim 4.2 \times 10^{21}$ n/cm^2 (E > 1 MeV)	ETR	100, 650, 1100°C	A-8	6
		$< 2 \times 10^{21}$ n/cm^2 (E > 1 MeV)	ETR	110 ∿ 1100°C	A-18 A-19	16
		$1.2 \sim 3.65 \times 10^{21}$ n/cm^2	ETR	583 ∿ 1100°C	A-15	12
		$2.5 \sim 14 \times 10^{21}$ n/cm^2	HIFAR	75 ∿ 100°C 500 ∿ 700°C	A-9 ∼ A-11	7
		1.5×10^{21} n/cm^2 (E > 1 MeV)	ETR	100 ∿ 1200°C	A-1 ∼ A-6 A-7	5
Y_2O_3		6×10^{21} n/cm^2 (E > 0.1 MeV)	EBR-II	377, 602, 752°C	A-29 A-32	23
		2.8×10^{21} n/cm^2 (E > 0.1 MeV)	EBR-II	740°C	A-34	30
Y_2O_3+ 1 % ZrO_2		2.8×10^{21} n/cm^2 (E > 0.1 MeV)	EBR-II	740°C	A-34	30
Y_2O_3+ 10 % ZrO_2		6×10^{21} n/cm^2 (E > 0.1 MeV)	EBR-II	377, 602, 752°C	A-29 A-32	23
$Y_2Al_5O_{12}$	sc pc	2.8×10^{21} n/cm^2 (E > 0.1 MeV)	EBR-II	740°C	A-34	30
BeO-5SiC		2.8×10^{21} n/cm^2 (E > 0.1 MeV)	EBR-II	740°C	A-34	30
ZrO_2-Y_2O_3	stabilized	4.4×10^{21} n/cm^2 (E > 0.1 MeV)	EBR-II	377, 602, 752°C	A-33	28
Si_3N_4	NC-132 pc	2.8×10^{21} n/cm^2 (E > 0.1 MeV)	EBR-II	740°C	A-34	30
	pc	2.2×10^{22} n/cm^2 (E 0.1 MeV)	EBR-II	407, 542°C	A-44	48

Table 3-1 Swelling (4)

MATERIAL		IRRADIATION			DATA	REF
		DOSE	FACILITY	TEMPERATURE		
$MgAl_2O_4$	sc pc	2.8×10^{21} n/cm^2 ($E > 0.1$ MeV)	EBR-II	740°C	A-34	30
	sc pc	2.3×10^{22} n/cm^2 ($E > 0.1$ MeV)	EBR-II	652, 827°C	A-40	39
	sc pc	2.2×10^{22} n/cm^2 ($E > 0.1$ MeV)	EBR-II	407, 542°C	A-44	48
	pc	2.1×10^{22} n/cm^2 ($E > 0.2$ MeV) 4.6×10^{22} n/cm^2 thermal	HFIR	157°C	A-36	33
	sc	$0.47 \sim 7.9 \times 10^{18}$n/cm^2 ($E > 0.1$ MeV)	OWR	∿ 50°C	A-45	53
		2×10^{22} n/cm^2 ($E > 0.1$ MeV)	EBR-II	387°C	A-46	54
Si_2ON_2	pc	2.8×10^{21} n/cm^2 ($E > 0.1$ MeV)	EBR-II	740°C	A-34	30
Sialon		2.8×10^{21} n/cm^2 ($E > 0.1$ MeV)	EBR-II	740°C	A-34	30
SiO_2	sc	2.3×10^{22} n/cm^2 ($E > 0.1$ MeV)	EBR-II	400, 550°C	A-37	34
SiO_2-based glass ceramic		2.4×10^{22} n/cm^2 ($E > 0.1$ MeV)	EBR-II	400, 550°C	A-37	34
MACOR		2.7×10^{22} n/cm^2 ($E > 0.1$ MeV)	EBR-II	550°C	A-37	34
		10^{16}, 10^{18} n/cm^2 (14 MeV)	RTNS-II	RT	A-35	32

Table 3-2 Mechanical property (1)

MATERIAL		IRRADIATION			DATA	REF
		DOSE	FACILITY	TEMPERATURE		
SiC	reaction-bonded	3×10^{21} n/cm^2 (E > 1 MeV)		400, 650°C	A-50	22
		8.1×10^{21} n/cm^2 (E > 1 MeV)	HFIR	730°C	A-59	45
	self-bonded	2.3×10^{13} e/cm^{2}s (52 MeV)	Linac	ambient	A-51	27
		2×10^{20} n/cm^2 (E > 1 MeV)	HFBR	ambient	A-52	27
	α-SiC	9.7×10^{21} n/cm^2 (E > 1 MeV)	HFIR	730°C	A-59	45
	NC-430	1.2×10^{21} n/cm^2 (E > 1 MeV)	HFBR	200°C	A-55 A-56	36
		1.2×10^{21} n/cm^2 (E > 1 MeV)	HFBR	200 ∿ 1100°C	A-57 A-58	36
	fiber	2×10^{19} n/cm^2 (E > 1 MeV)	JMTR	< 300°C	A-62	50
		4×10^{17} n/cm^2 (E = 14 MeV)	RTMS-II	RT	A-62	50
	β-SiC	4.2×10^{21} n/cm^2 (E > 0.18 MeV)	ETR	460, 1040°C	A-49	18
Al_2O_3	sc	2.2×10^{22} n/cm^2 (E > 0.1 MeV)	EBR-II	407, 542°C	A-44	48
		< 2×10^{22} n/cm^2 (E > 0.1 MeV)	EBR-II	652, 742, 827°C	A-61	49
	sc pc	< 5×10^{20} n/cm^2 (E > 1 MeV)	HIFAR	75 ∿ 100°C 500 ∿ 700°C	A-48	15
		2×10^{22} n/cm^2 (E > 0.1 MeV)	EBR-II	387°C	A-46	54
$MgAl_2O_4$	sc pc	2.2×10^{22} n/cm^2 (E > 0.1 MeV)	EBR-II	407, 542°C	A-44	48
		2.1×10^{22} n/cm^2 (E > 0.2 MeV)	HFIR	157°C	A-36	33
		< 2×10^{22} n/cm^2 (E > 0.1 MeV)	EBR-II	652, 742, 827°C	A-60	49
		2×10^{22} n/cm^2 (E > 0.1 MeV)	EBR-II	387°C	A-46	54

Table 3-2 Mechanical property (2)

MATERIAL		IRRADIATION			DATA	REF
		DOSE	FACILITY	TEMPERATURE		
Si_3N_4	pc	2.2×10^{22} n/cm^2 (E > 0.1 MeV)	EBR-II	407, 542°C	A-44	48
SiO_2	sc	2.4×10^{22} n/cm^2 (E > 0.1 MeV)	EBR-II	400, 550°C	A-54	34
SiO_2-based glass ceramic		2.4×10^{22} n/cm^2 (E > 0.1 MeV)	EBR-II	400, 550°C	A-54	34
MACOR		2.4×10^{22} n/cm^2 (E > 0.1 MeV)	EBR-II	400, 550°C	A-54	34
		10^{16}, 10^{18} n/cm^2 (14 MeV)	RTNS-II	RT	A-53	32
BeO	sintered	< 1.5×10^{21} n/cm^2 (E > 1 MeV)	ETR	100 ∿ 1200°C	A-47 A-5	5
MgO		2.1×10^{22} n/cm^2 (E > 0.2 MeV)	HFIR	157°C	A-36	33

Table 3-3 Thermal property (1)

MATERIAL		IRRADIATION			DATA	REF
		DOSE	FACILITY	TEMPERATURE		
SiC	β-SiC	$2.7 \sim 7.7 \times 10^{21}$ n/cm^2 (E > 0.18 MeV)	ETR	550 $\sim$ 1100°C	A-73 A-74	19
	α-SiC	1.2×10^{21} n/cm^2 (E > 1 MeV)	HFBR	$<$ 147°C	A-63	36
		8.1×10^{21} n/cm^2 (E > 1 MeV)	HFIR	730°C	A-65	45
	NC-430	8.1×10^{21} n/cm^2 (E > 1 MeV)	HFIR	730°C	A-65	45
Al_2O_3	sc	2.5×10^{22} n/cm^2 (E > 0.1 MeV)	EBR-II	650 $\sim$ 827°C	A-66	37
		2.8×10^{21} n/cm^2 (E > 0.1 MeV)	EBR-II	740°C	A-34	30
		3×10^{19} e/cm^2 (2 MeV) + 3×10^{18} n/cm^2 (E > 0.1 MeV)		RT	A-75	55
	pc	2.5×10^{22} n/cm^2 (E > 0.1 MeV)	EBR-II	650 $\sim$ 827°C	A-66	37
	Ad-995	2.8×10^{21} n/cm^2 (E > 0.1 MeV)	EBR-II	740°C	A-34	30
$MgAl_2O_4$	sc pc	2.5×10^{22} n/cm^2 (E > 0.1 MeV)	EBR-II	650 $\sim$ 827°C	A-66	37
	sc pc	2.8×10^{22} n/cm^2 (E > 0.1 MeV)	EBR-II	740°C	A-34	30
$Y_3Al_5O_{15}$	sc pc	2.5×10^{22} n/cm^2 (E > 0.1 MeV)	EBR-II	650 $\sim$ 827°C	A-66	37
Y_2O_3	pc	2.8×10^{22} n/cm^2 (E > 0.1 MeV)	EBR-II	740°C	A-34	30
Y_2O_3+ZrO_2	pc	2.8×10^{22} n/cm^2 (E > 0.1 MeV)	EBR-II	740°C	A-34	30
BeO-5SiC	pc	2.8×10^{22} n/cm^2 (E > 0.1 MeV)	EBR-II	740°C	A-34	30
MACOR		10^{16}, 10^{18} n/cm^2 (14 MeV)	RTNS-II	RT	A-64	32
SiO_2	Vitreous	5×10^{19} n/cm^2 (E > 1 MeV)			A-67	46

Table 3-3 Thermal property (2)

MATERIAL		IRRADIATION			DATA	REF
		DOSE	FACILITY	TEMPERATURE		
Porcelain		2.1×10^{11} n/cm^2 (14.3 MeV)	neutron generator		A-68	43
BeO	Hot pressed, sintered	$< 1 \times 10^{21}$ n/cm^2 ($E > 1$ MeV)	HIFAR	-75°C	A-71	11
		1×10^{11} n/cm$^2\cdot$sec ($E > 0.6$ MeV)	ORGR	-182°C	A-72	3
		$1.2 \sim 3.6 \times 10^{21}$ n/cm^2 ($E > 1$ MeV)	ETR	583 ∿ 1100°C	A-70	12
		$< 4 \times 10^{20}$ n/cm^2 ($E > 1$ MeV)	HIFAR	70 ∿ 100°C 510 ∿ 660°C	A-69	1

Table 3-4 Electrical property

MATERIAL		IRRADIATION			DATA	REF
		DOSE	FACILITY	TEMPERATURE		
SiC	NC-430	$< 2 \times 10^{20}$ n/cm^{2} (E > 1 MeV)	HFBR	< 200°C	A-78	27
		1.2×10^{21} n/cm^{2} (E > 1 MeV)	HFBR	200, 1100°C	A-83	36
		$< 4 \times 10^{21}$ n/cm^{2} (E > 1 MeV)	HFBR	147, 1100°C	A-87	45
		8.1×10^{21} n/cm^{2} (E > 1 MeV)	HFIR	730°C	A-87	45
Al_2O_3	sc	$6.6 \times 10^{2} \sim 6.6 \times 10^{4}$ rad/s 1.5 MeV electron	-		A-79 A-80	31
	pc	∿ 7 Gy/s (X-ray) 2×10^{6} W/cm^{2} (20 MeVp)		∿ 500°C	A-88	52
	cable	$< 10^{6}$ R/h	-	ambient	A-76	25
		$< 3 \times 10^{20}$ n/cm^{2} (E > 0.1 MeV)		445°C	A-82	35
MgO	cable	$< 10^{6}$ R/h	-	ambient	A-77	25
Glass-bonded MICA		1×10^{18} n/cm^{2} (E > 0.1 MeV)	ORR		A-86	44
MACOR		10^{16}, 10^{18} n/cm^{2} (14 MeV)	RTNS-II	RT	A-81	32
$MgAl_2O_4$		$< 3 \times 10^{20}$ n/cm^{2} (E > 0.1 MeV)		445°C	A-82	35
Alumina porcelain		3×10^{11} n/cm^{2}			A-85 A-84	41

Table 3-5 Dielectric property

MATERIAL		IRRADIATION			DATA	REF
		DOSE	FACILITY	TEMPERATURE		
Al_2O_3	sc	2×10^{22} n/cm^2 (E > 0.1 MeV)	EBR-II	650, 828°C	A-90	37
	AD-995	< 2.5×10^{19} n/cm^2 (fast)		47, 95°C	A-89	14
	pc	$1 \times 10^{17} \sim 10^{20}$ n/cm^2 (E > 1 MeV)	Herald Reactor	67°C	A-92	52
SiO_2	Fused	< 2.5×10^{19} n/cm^2 (fast)		47, 95°C	A-89	14

Table 3-6 Dielectric property

MATERIAL		IRRADIATION			DATA	REF
		DOSE	FACILITY	TEMPERATURE		
Al_2O_3	sc	5×10^{17} n/cm^2 (14 MeV)	RTNS-II	RT	A-91	47
	sc pc	1×10^{18} n/cm^2 (fast)	LAMPF	RT	A-91	47
	ADD-995	2.5×10^{19} n/cm^2 (fast)		47, 95°C	A-89	14
	pc	$1 \times 10^{17} \sim 10^{20}$ n/cm^2 (E > 1 MeV)	Herald Reactor	67°C	A-93	52
SiO_2	Fused	2.5×10^{19} n/cm^2 (fast)		47, 95°C	A-89	14

Table 3-7 Lattice parameter

MATERIAL		IRRADIATION			DATA	REF
		DOSE	FACILITY	TEMPERATURE		
α-SiC	reaction-bonded	3×10^{21} n/cm^2 ($E > 1$ MeV)		450, 650°C	A-102	22
β-SiC		$2.0 \sim 4.2 \times 10^{21}$ n/cm^2 ($E > 0.18$ MeV)	ETR	460, 1040°C	A-23	18
Al_2O_3	sc pc	$< 5 \times 10^{20}$ n/cm^2 ($E > 1$ MeV)	HIFAR	75∿100°C 500∿700°C	A-100	15
BeO	hot pressed, sintered	$< 1.2 \times 10^{21}$ n/cm^2		75∿100°C 500∿700°C	A-96	9
		$1.2 \sim 3.7 \times 10^{21}$ n/cm^2	ETR	583∿1100°C	A-98	12
		$< 2 \times 10^{21}$ n/cm^2 ($E > 1$ MeV)	ETR	110∿1100°C	A-101	16
		$1 \times 10^{20} \sim 1 \times 10^{21}$ n/cm^2	HIFAR	75∿100°C	A-94	2
		$< 1.5 \times 10^{20}$ n/cm^2 ($E > 1$ MeV)	ETR	100∿1200°C	A-6 A-7	5
		$0.3 \sim 4.2 \times 10^{21}$ n/cm^2 ($E > 1$ MeV)	ETR	580∿1100°C	A-8	6
	sc	$< 6.5 \times 10^{20}$ n/cm^2		75∿100°C	A-97	10
MgO	sc	4×10^{19} n/cm^2		200°C	A-95	4
	sc pc	$0.14 \sim 6.5 \times 10^{20}$ n/cm^2 ($E > 1$ MeV)	HIFAR	75∿100°C	A-99	13
Si_3N_4		3×10^{21} n/cm^2 ($E > 0.1$ MeV)	EBR-II	742°C	A-104	38
Si_2N_2O		3×10^{21} n/cm^2 ($E > 0.1$ MeV)	EBR-II	742°C	A-104	38
		$< 3 \times 10^{20}$ n/cm^2 (fast)	SILOE	< 327°C	A-103	29
Sialon		3×10^{21} n/cm^2 ($E > 0.1$ MeV)	EBR-II	742°C	A-104	38

Table 3-8 Miscellaneous

MATERIAL		IRRADIATION			DATA	REF
		DOSE	FACILITY	TEMPERATURE		
BeO		$< 1 \times 10^{21}$ n/cm^2 (E $>$ 0.8 MeV)			A-107	42
Al_2O_3						
Al_2O_3-SiO_2						
Al_2O_3	sc	$< 5.6 \times 10^{16}$ n/cm^2 (5 ∿ 15 MeVp)			A-105 A-106	24
		1×10^{17} n/cm^2 (14 MeV)	RTNS		A-105 A-106	24
MgO	sc	1.4×10^{10} n/cm^2	KUR	100°C	A-108	51
		8×10^{16} n/cm^2 (E=14MeV)	RTNS-II	RT		

4. Data Compilation on Swelling

From the brief review of current data base in the previous chapter, only the data amount of swelling is enough for data compilation. Thus the swelling data were replotted as a function of fluence and irradiation temperature in order to get further knowledge of swelling behavior. In the replottings, the data were classified according to ceramic species with further classification by polycrystal and single crystals. In the case of BeO, the data were classified according to the fabrication method because the swelling behavior in the literatures was obviously different to each other. For one species of ceramics, the data were also classified according to the reactor used in irradiation experiments. This is because the energy range of neutron fluence in the literatures was different, usually $E > 0.1$ MeV or $E > 1$ MeV. As to the data of linear expansion and growth, the value multiplied by three was used as the swelling value when the ceramics has isotropic lattice structure.

The neutron fluence and the irradiation temperature were divided into decade ranges as shown in Table 4-1.

Table 4-2 shows list of the material, reactor, fluence energy range and figure number. The T-No figures show the temperature dependence of swelling and the F-No figures show the neutron fluence dependence of swelling. In Table 4-2 the data source of each figure is shown as data sheet number.

By comparing the compiled data, the followings can be pointed out.

- The swelling of Al_2O_3 and BeO seems to be larger than those of other ceramics and the swelling is linearly dependent on neutron fluence. $MgAl_2O_4$ (single crystal) and Y_2O_3 is considered to be swelling resistant ceramics.

- The peak swelling temperature is 800 - 900°C for Al_2O_3, below 500°C for BeO and 600°C for ZrO_2. For other ceramics, it is not clearly observed.

- The fluence dependence behavior similar to that of metallic materials seems not to be observed, in which the incubation period, transient period and steady-state swelling are occurred in this order. High fluence data are necessary to confirm this point.

- When comparing the swelling of polycrystal Al_2O_3 in EBR-II data (Fig. F-2) with that in ETR data (Fig. F-3) under similar fluence and temperature range, the former data is found to be systematically higher than the latter one in spite that the same neutron energy range of fluence is used. One reason of this may be that the different materials are irradiated in these studies. Another possibility is the difference of neutron spectrum between EBR-II and ETR. The better damage parameter such as dpa (displacement per atom) can not be used in the present compilation because of the absence of neutron spectrum information and standard calculation procedure of dpa of multicomponent materials. It has been well known that the fluence is not suitable for a damage parameter in analyzing radiation effect in metallic materials. Further analysis of radiation damage on ceramics based on dpa will be necessary.

Table 4-1 Plotting mark and corresponding fluence and temperature range

Class	Mark	Fluence (n/cm^2)	Temperature (°C)
0	+	<1E19	<200
1	□	1E19 – 5E19	201 - 300
2	■	5E19 – 1E20	301 - 400
3	△	1E20 – 5E20	401 – 500
4	▲	5E20 – 1E21	501 – 600
5	▽	1E21 – 5E21	601 – 700
6	▼	5E21 – 1E22	701 - 800
7	◇	1E22 – 5E22	801 – 900
8	◆	5E22 – 1E23	901–1000
9	×	>1E23	>1000

Table 4-2 List of materials and figure numbers

Material		Irradiation Reactor	Fluence Energy Range	Figure Number		Data Sheet Number
				vs Temp.	vs Flue.	
Al_2O_3	sc	EBR-II	>0.1 MeV	T-1	F-1	A-30,34,40
	pc	EBR-II	>0.1 MeV	T-2	F-2	A-29,34,40,44
	pc	ETR	>0.1 MeV	T-3	F-3	A-25,26,27,28
	sc	HIFAR	>1 MeV	*	F-4	A-17
	pc	HIFAR	>1 MeV	*	F-5	A-17
BeO	AOX	ETR	>1 MeV	T-6	F-6	A-1,3,4
	UOX-MgO	ETR	>1 MeV	T-7	F-7	A-1,3,4
	UOX-HP	ETR	>1 MeV	T-8	F-8	A-15
	UOX-CP	ETR	>1 MeV	T-9	F-9	A-15
$MgAl_2O_4$	sc	FBR-II	>0.1 MeV	T-10	F-10	A-34,40,44
	pc	EBR-II	>0.1 MeV	T-11	F-11	A-34,40,44
MgO	sc	HIFAR, DIDO, PLUTO	>1 MeV	T-12	F-12	A-12,13,16
	pc	HIFAR, DIDO, PLUTO	>1 MeV	*	F-13	A-12,13,16
Si_3N_4	pc	EBR-II	>0.1 MeV	T-14	F-14	A-34
SiO_2		EBR-II	>0.1 MeV	T-15	F-15	A-37
β-SiC		ETR	>0.18 MeV	T-16	F-16	A-23,24,73
ZrO_2		EBR-II	>0.1 MeV	T-17	F-17	A-33
Y_2O_3 Y_2O_3+ 1,10ZrO_2		EBR-II	>0.1 MeV	T-18	F-18	A-29,32,34
$Y_2Al_5O_{12}$	sc,pc	EBR-II	>0.1 MeV	*	F-19	A-34
Si_2ON_2 Sialon,		EBR-II	>0.1 MeV	*	F-20	A-34

* These figures were omitted because the data were so less that the temperature dependence was not clearly observed.

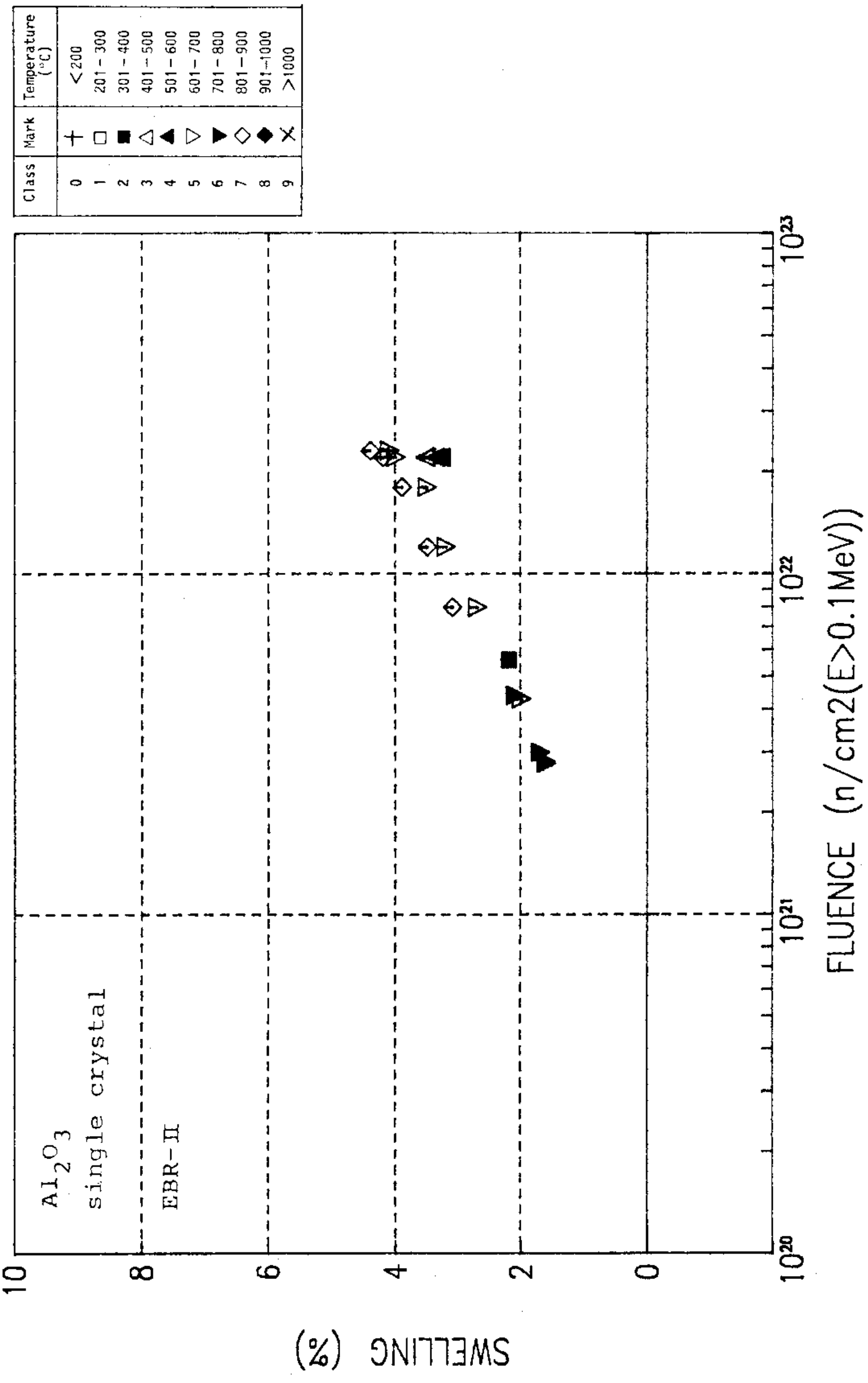


Fig. F-1 Al_2O_3 single crystal ; EBR-II

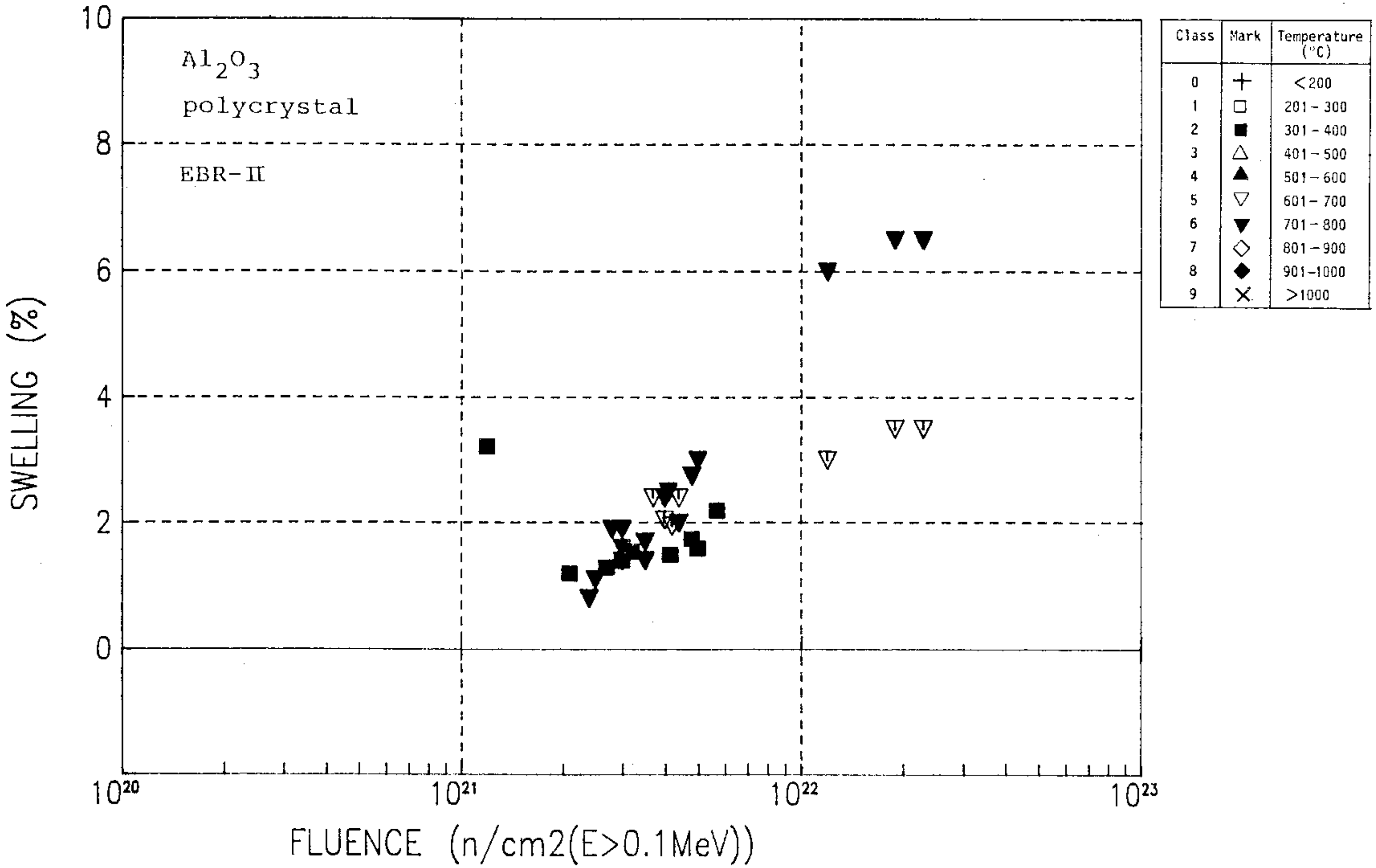


Fig. F-2 Al_2O_3 polycrystal; EBR-II

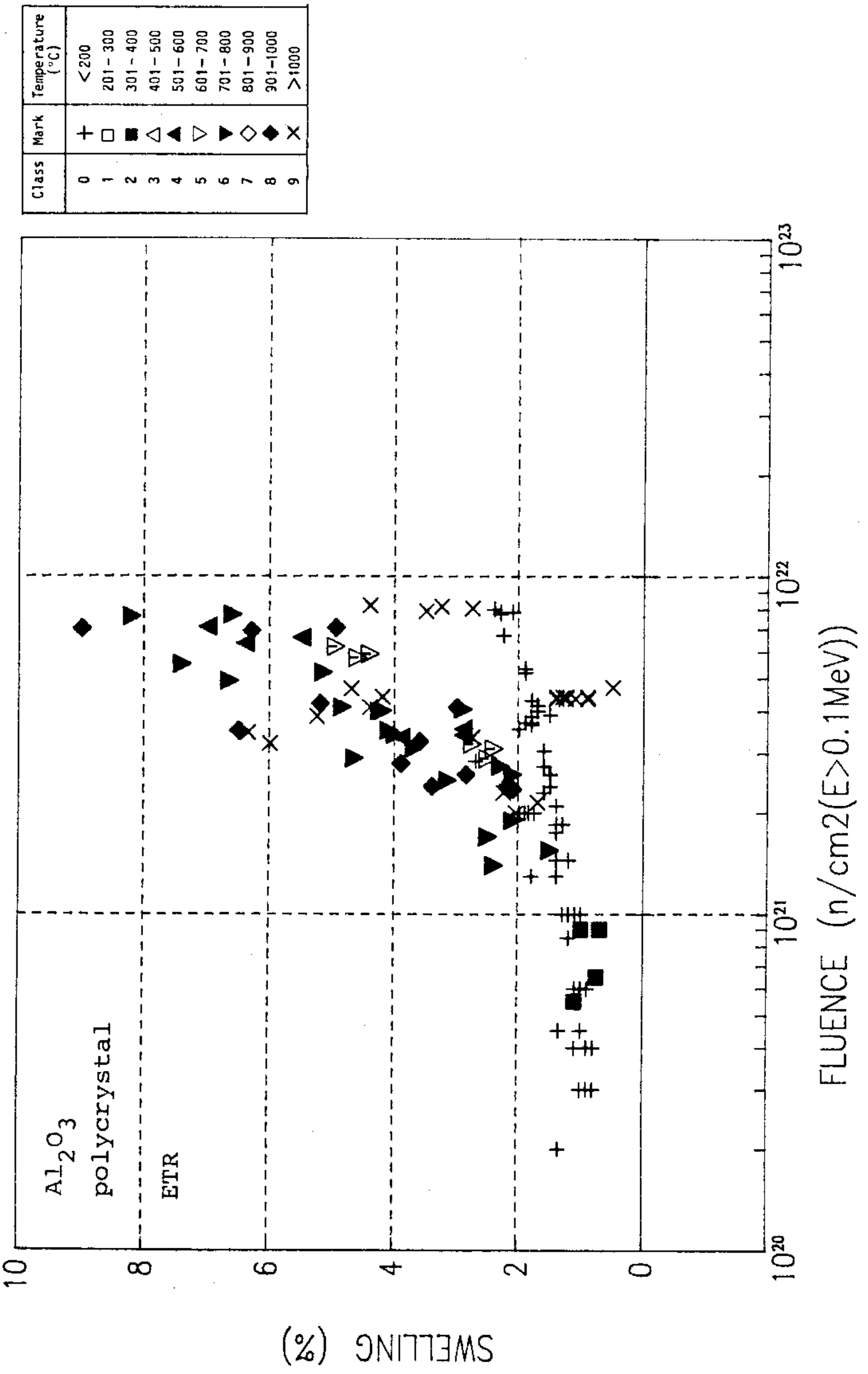


Fig. F-3 Al_2O_3 polycrystal ; ETR

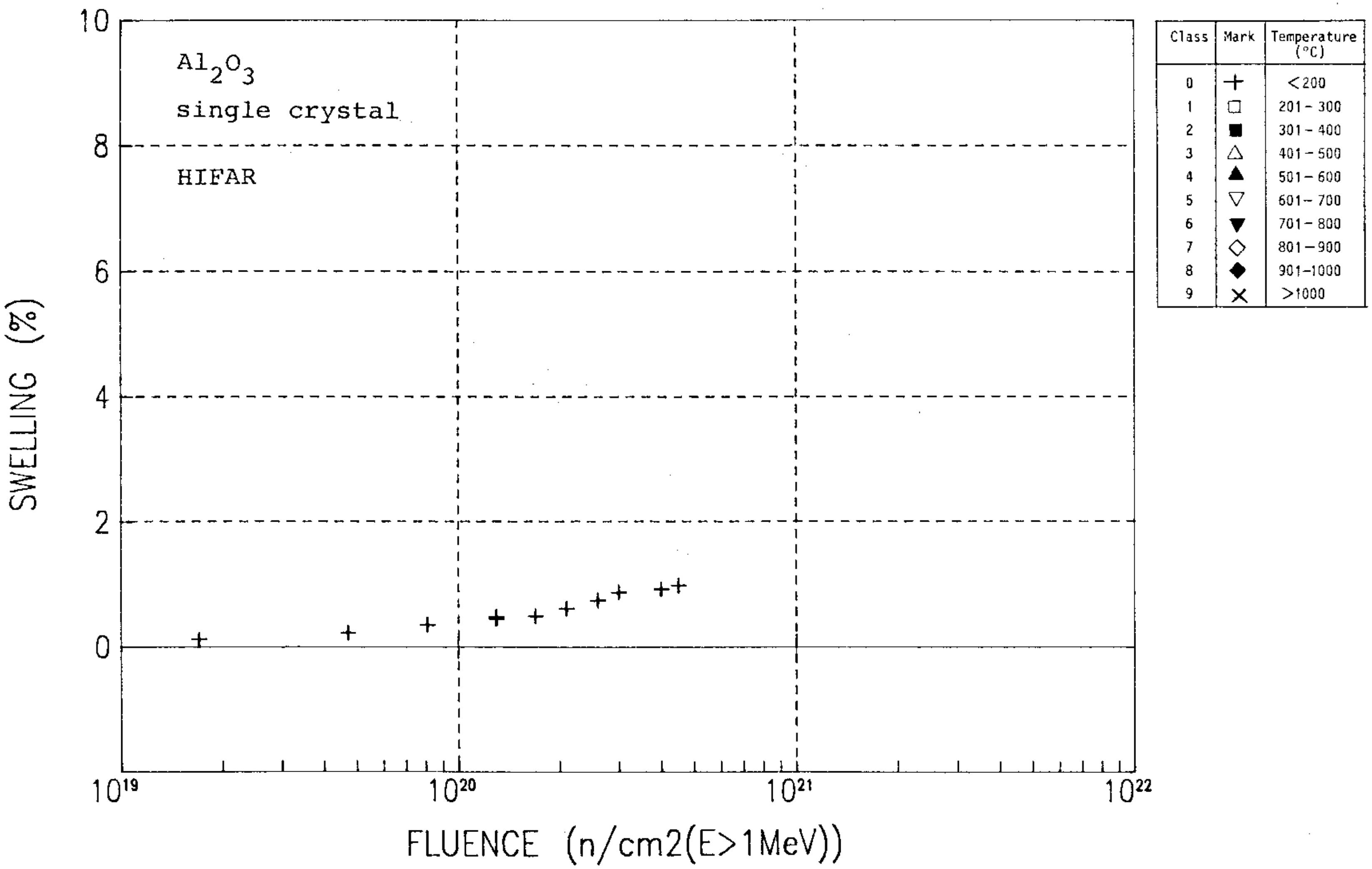


Fig. F-4 Al_2O_3 single crystal; HIFAR

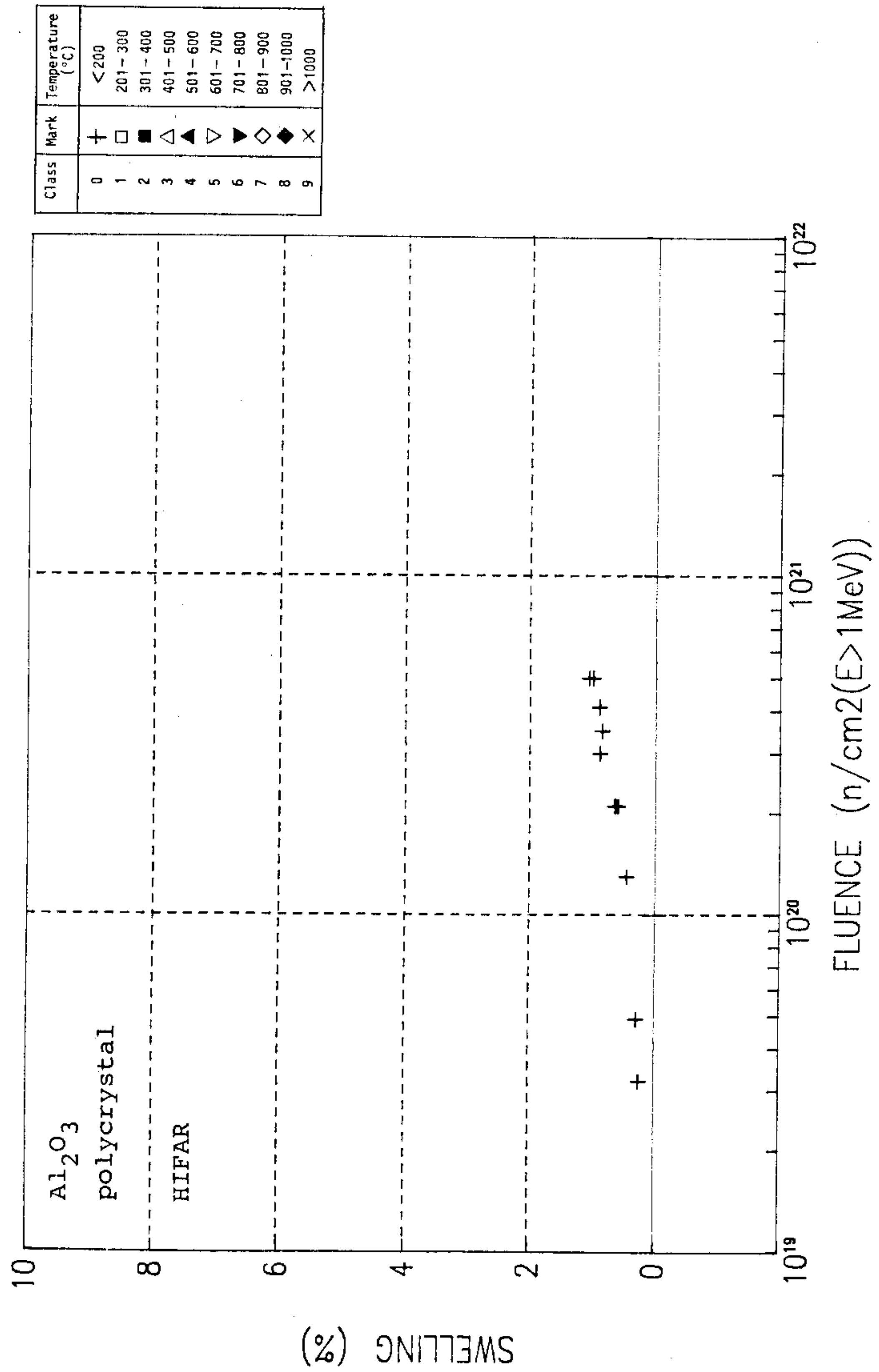


Fig. F-5　Al$_2$O$_3$ polycrystal ; HIFAR

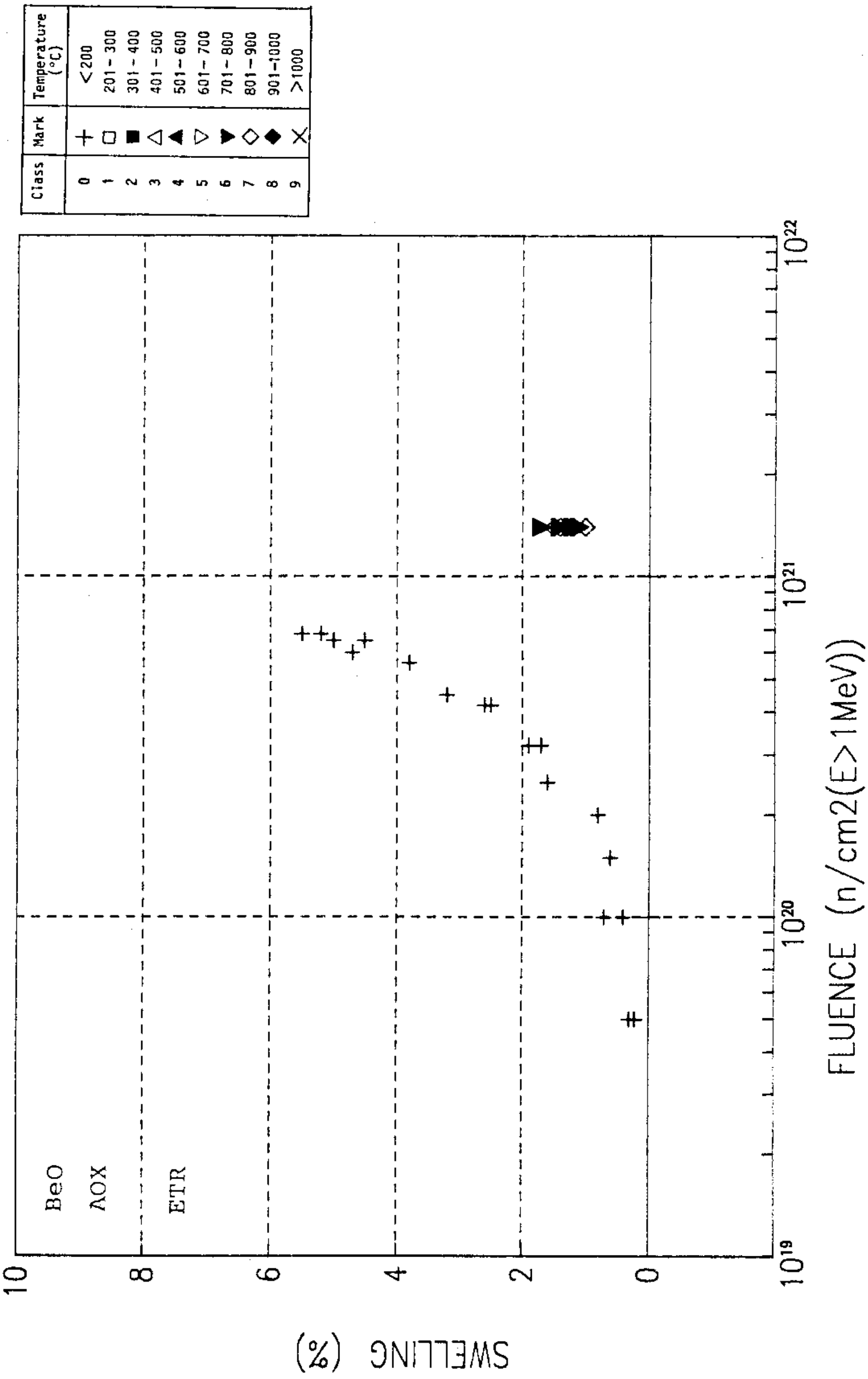


Fig. F-6 BeO AOX ; ETR

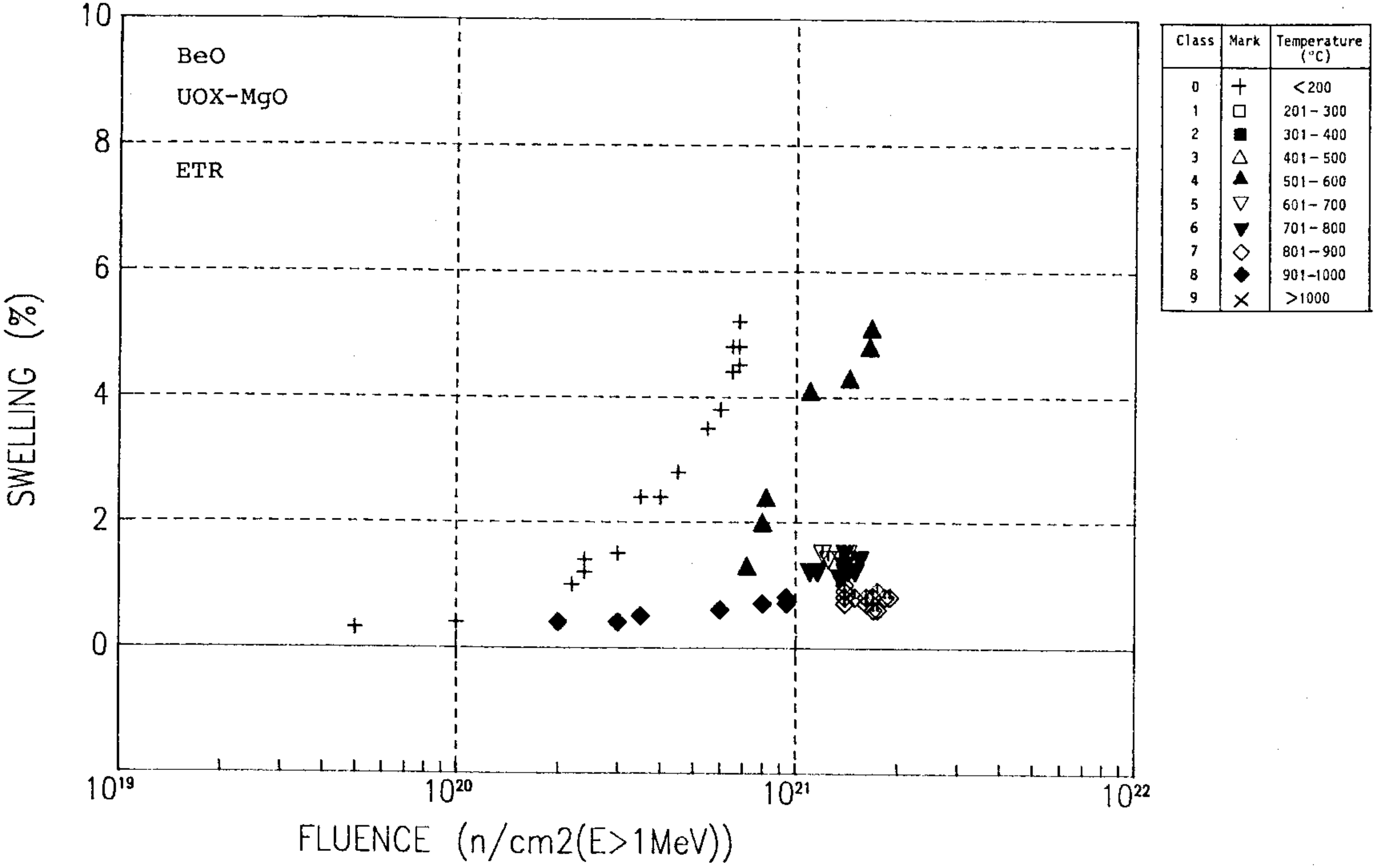


Fig. F-7 BeO UOX-MgO ; ETR

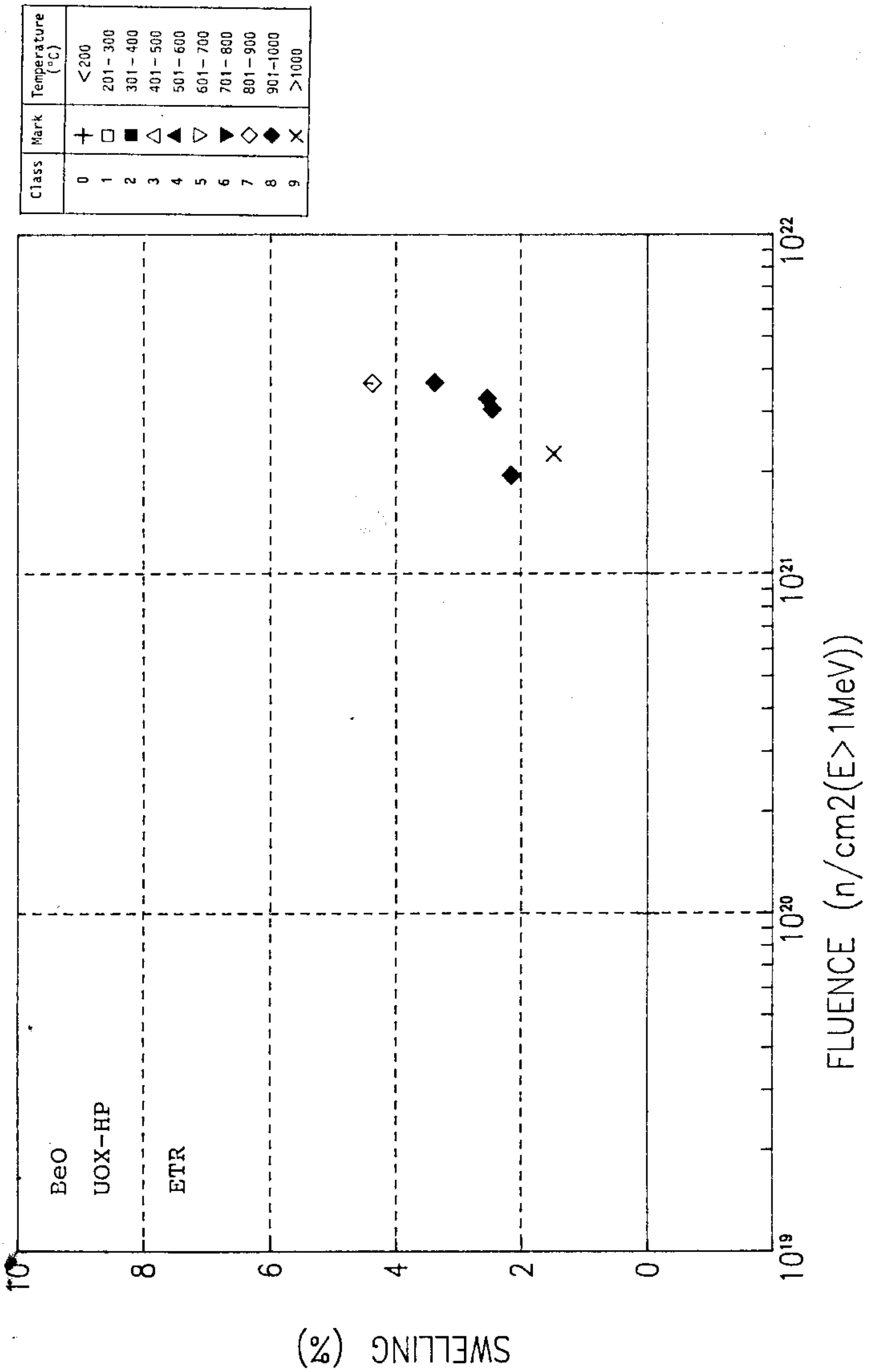


Fig. F-8 BeO UOX-HP ; ETR

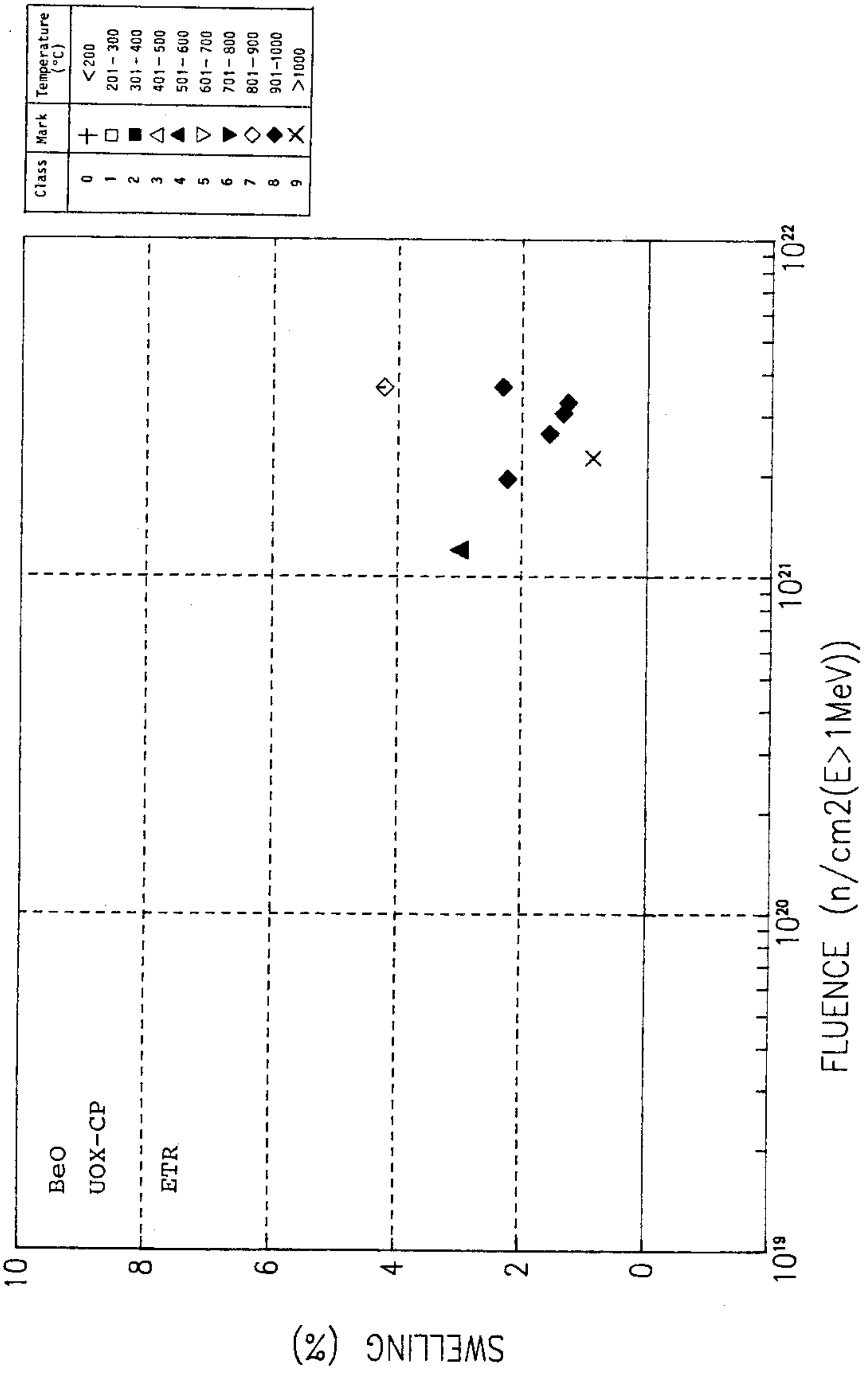


Fig. F-9 BeO UOX-CP ; ETR

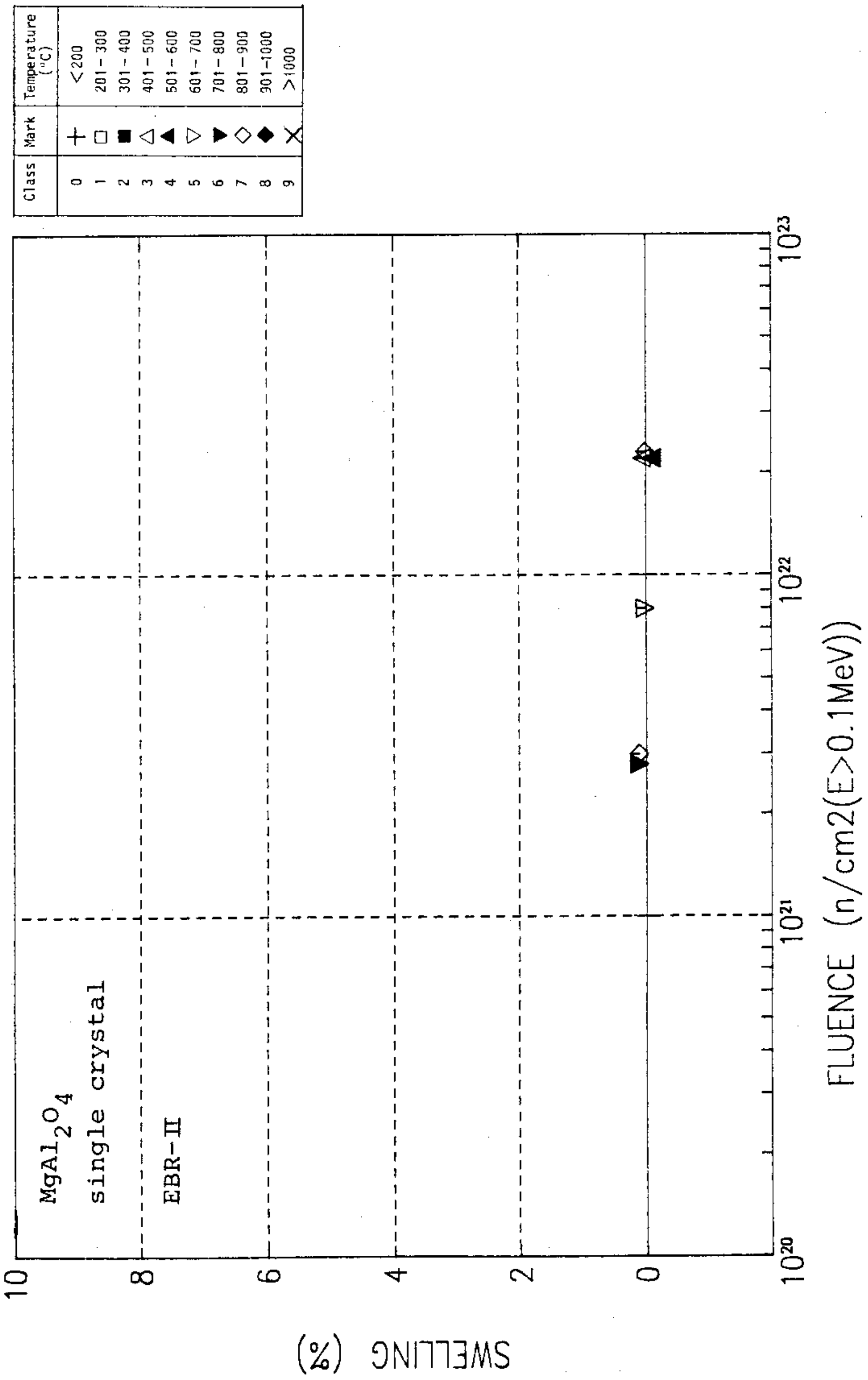


Fig. F-10 MgAl$_2$O$_4$ single crystal; EBR-II

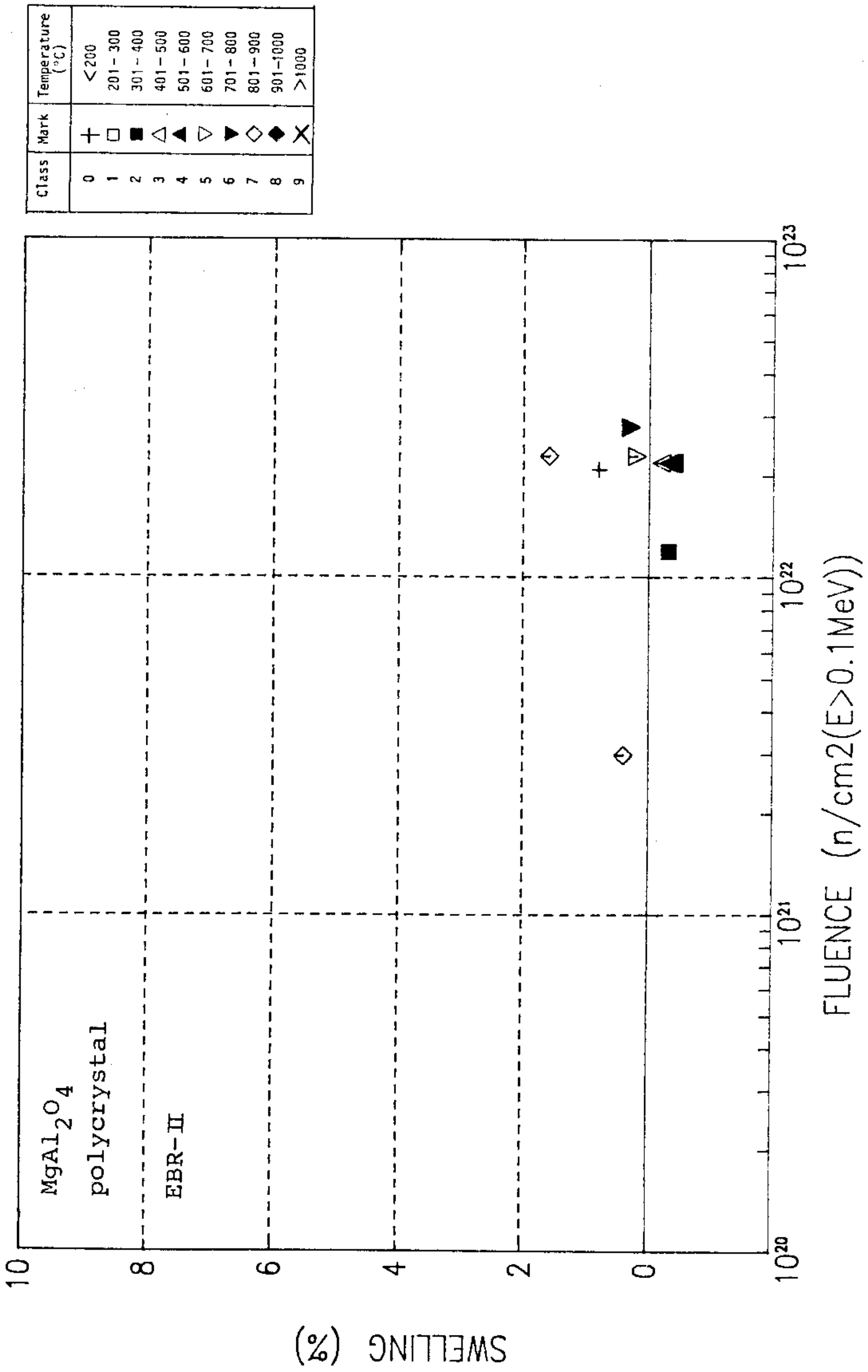


Fig. F-11 $MgAl_2O_4$ polycrystal ; EBR-II

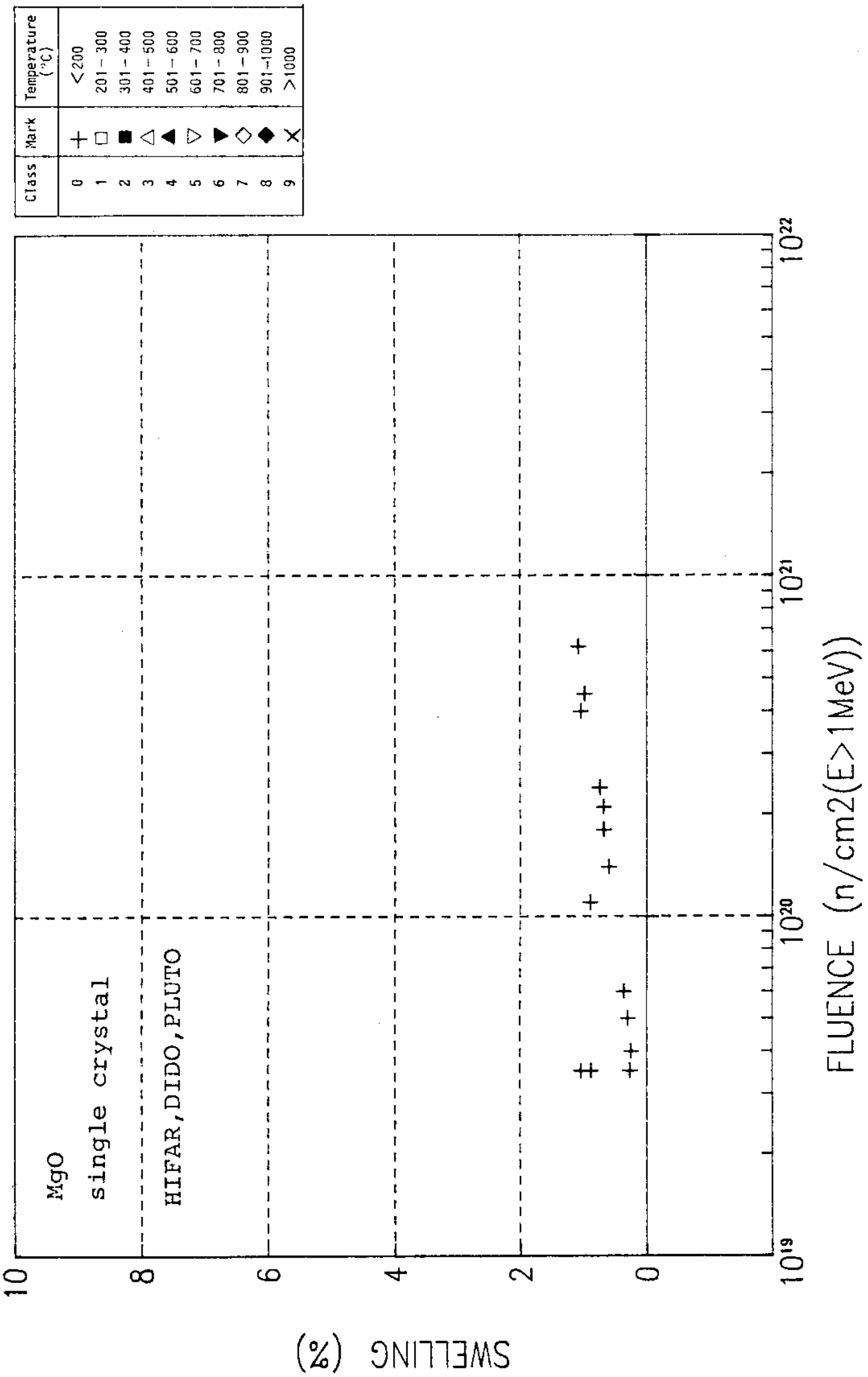


Fig. F-12 MgO single crystal ; HIFAR,DIDO,PLUTO

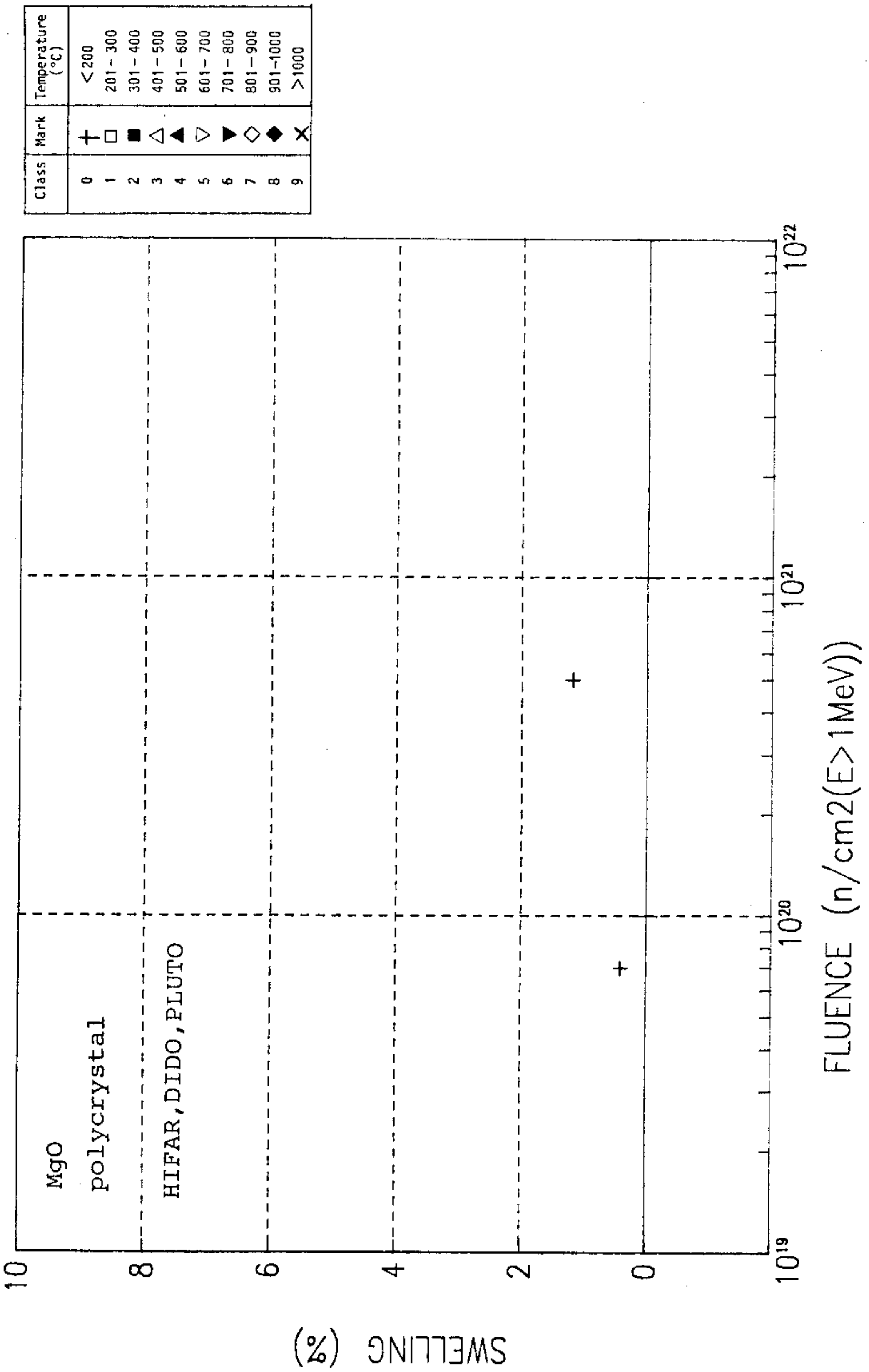


Fig. F-13 MgO polycrystal ; HIFAR,DIDO,PLUTO

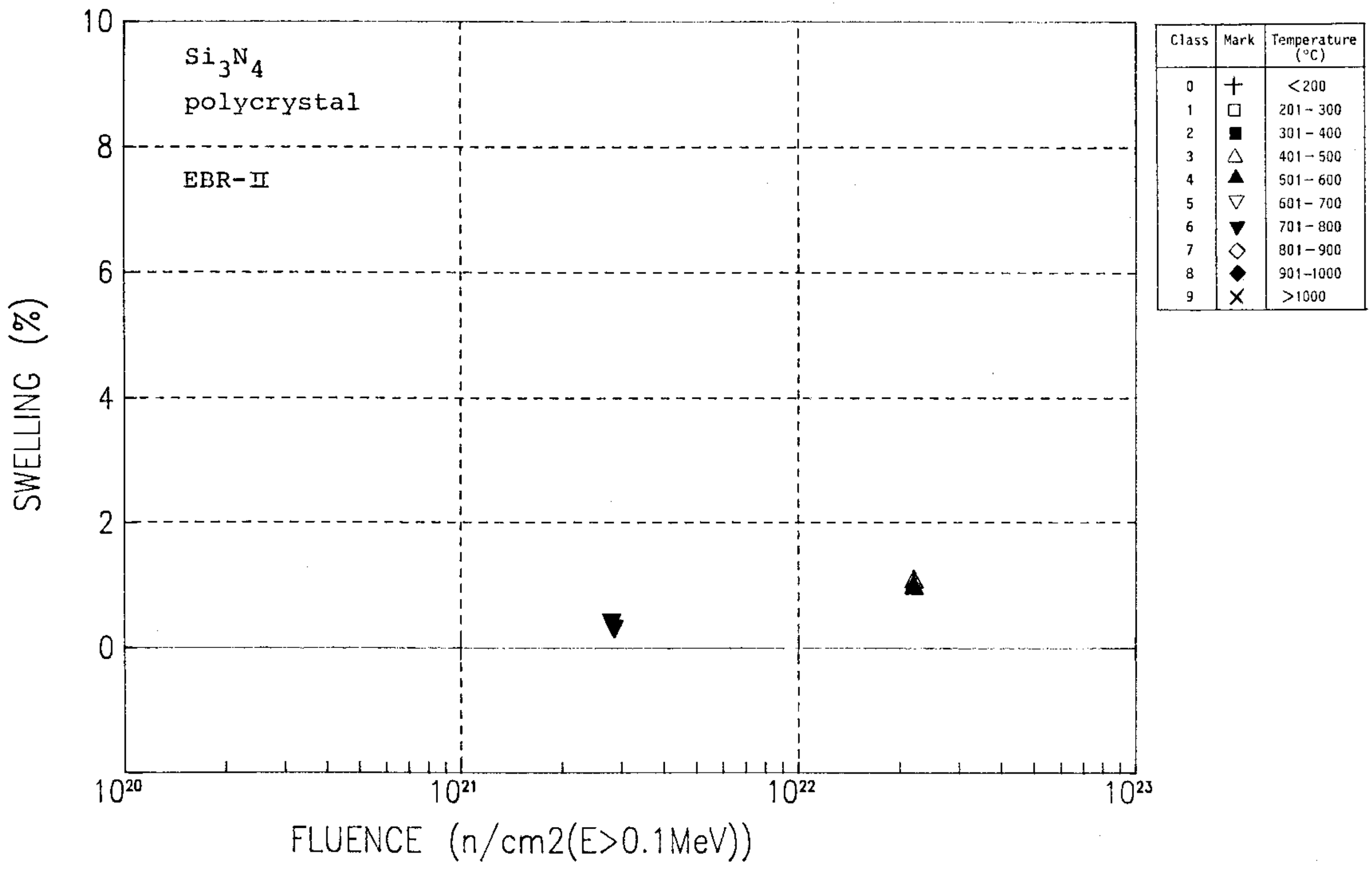


Fig. F-14 Si_3N_4 polycrystal ; EBR-II

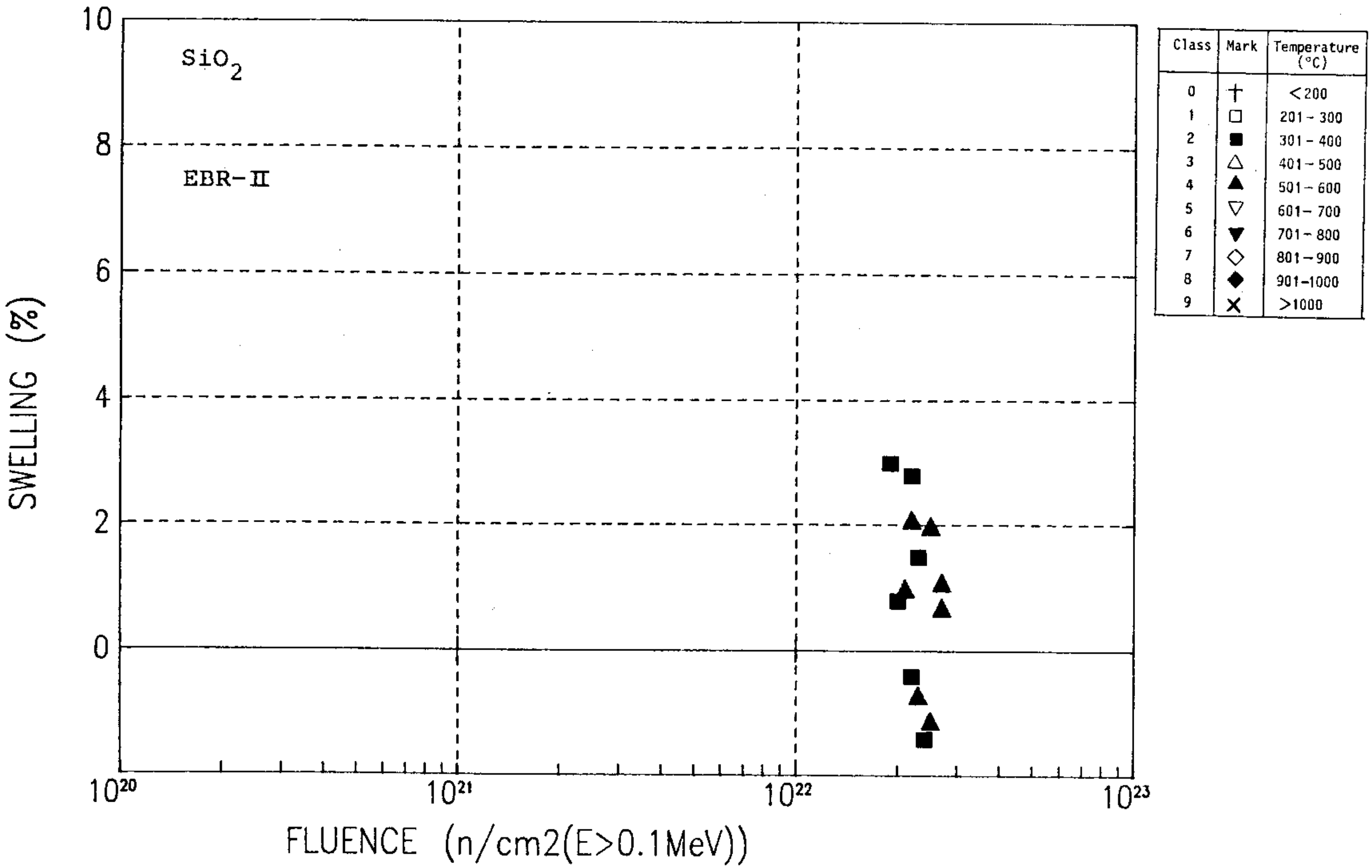


Fig. F-15 SiO$_2$; EBR-II

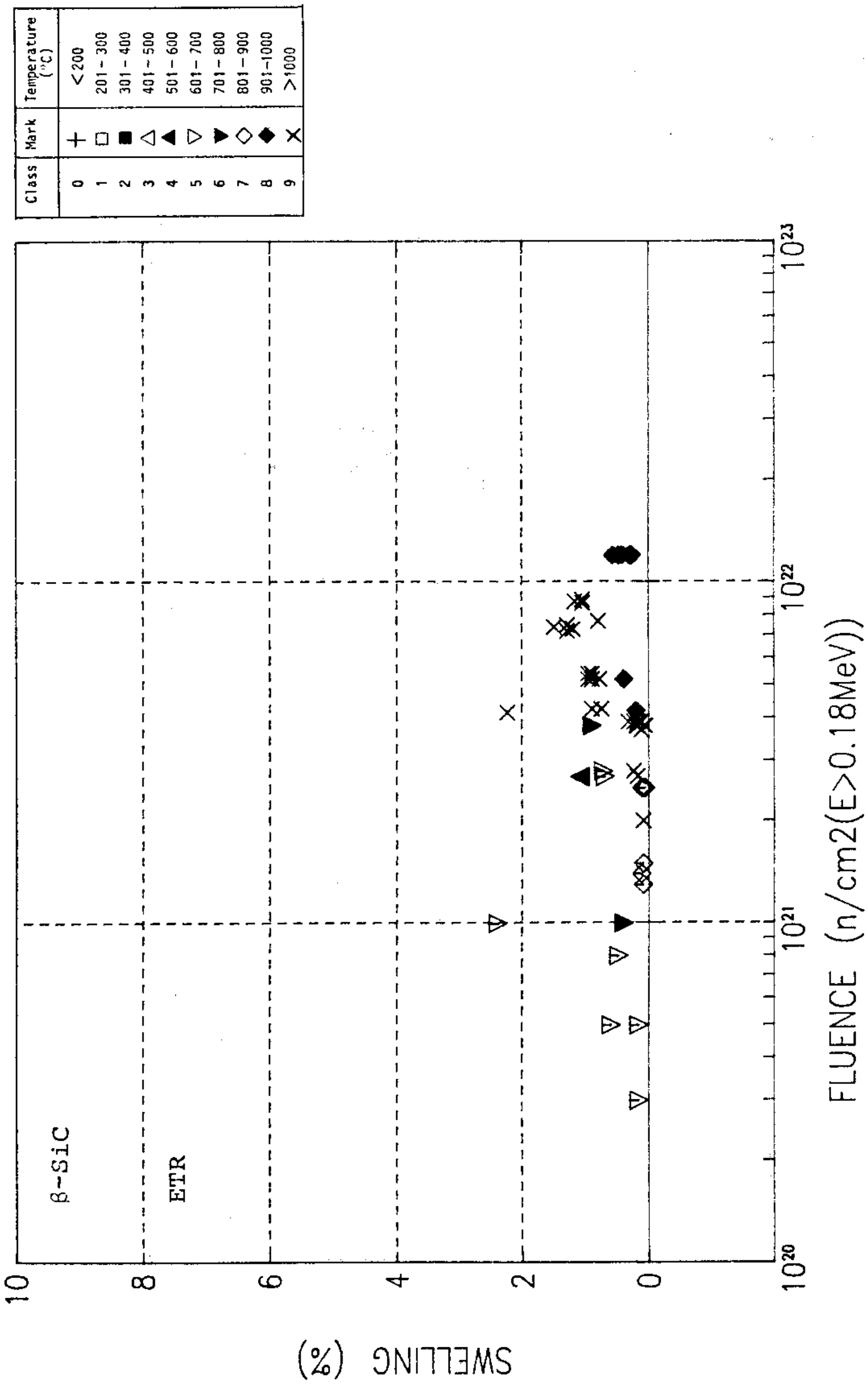


Fig. F-16 β-SiC ; ETR

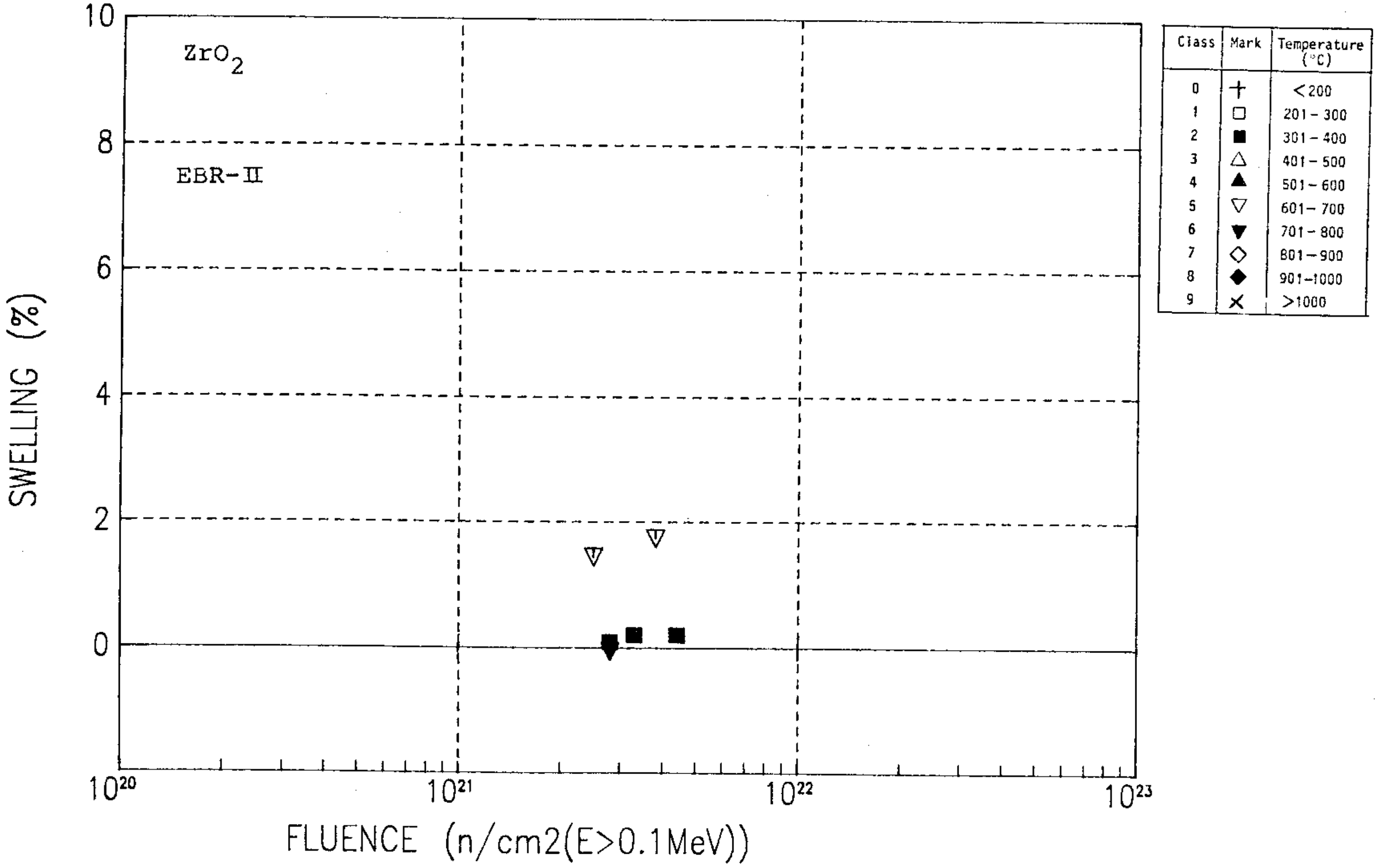


Fig. F-17 ZrO_2 ; EBR-II

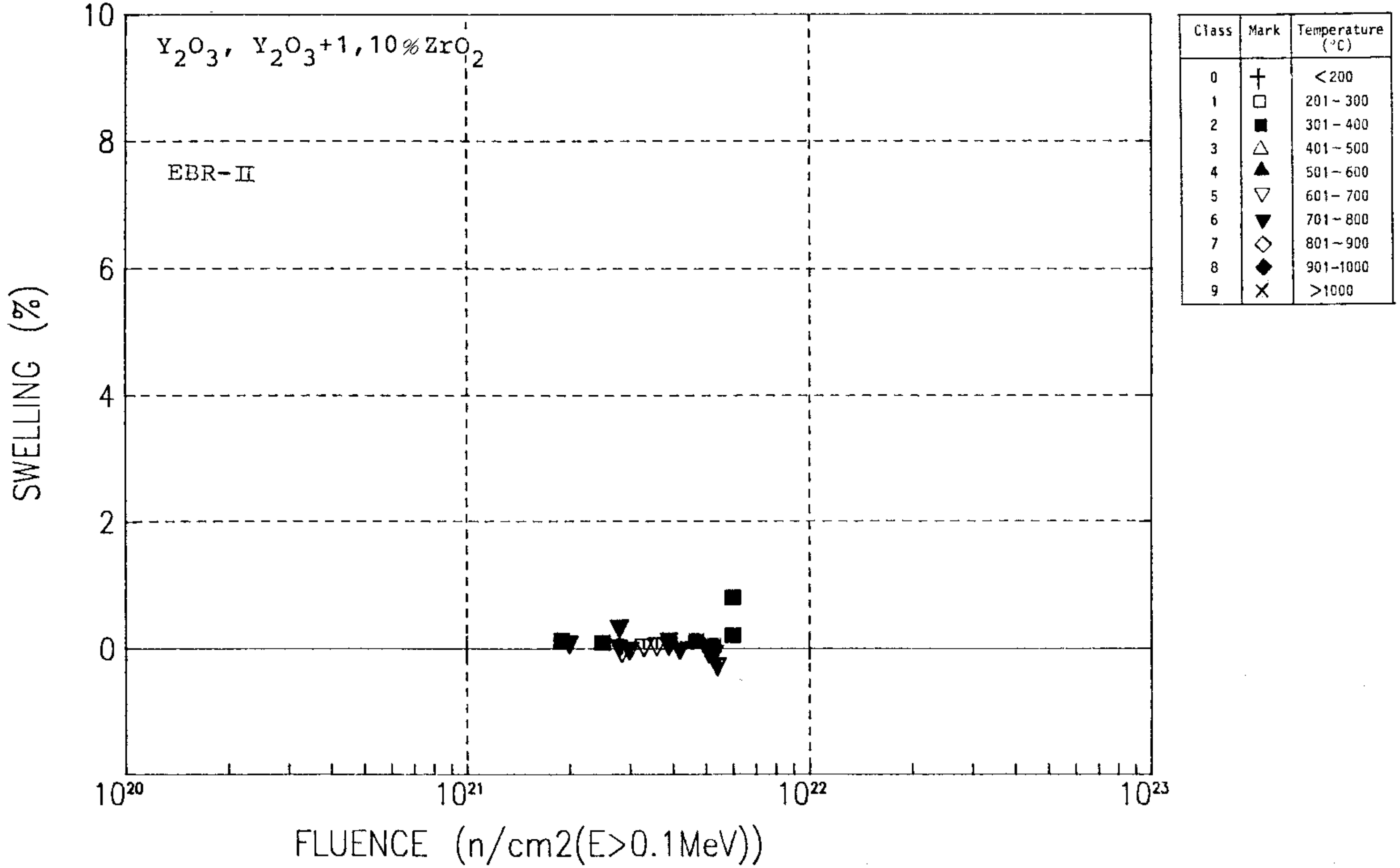


Fig. F-18 Y_2O_3, Y_2O_3+1, 10% ZrO_2 ; EBR-Ⅱ

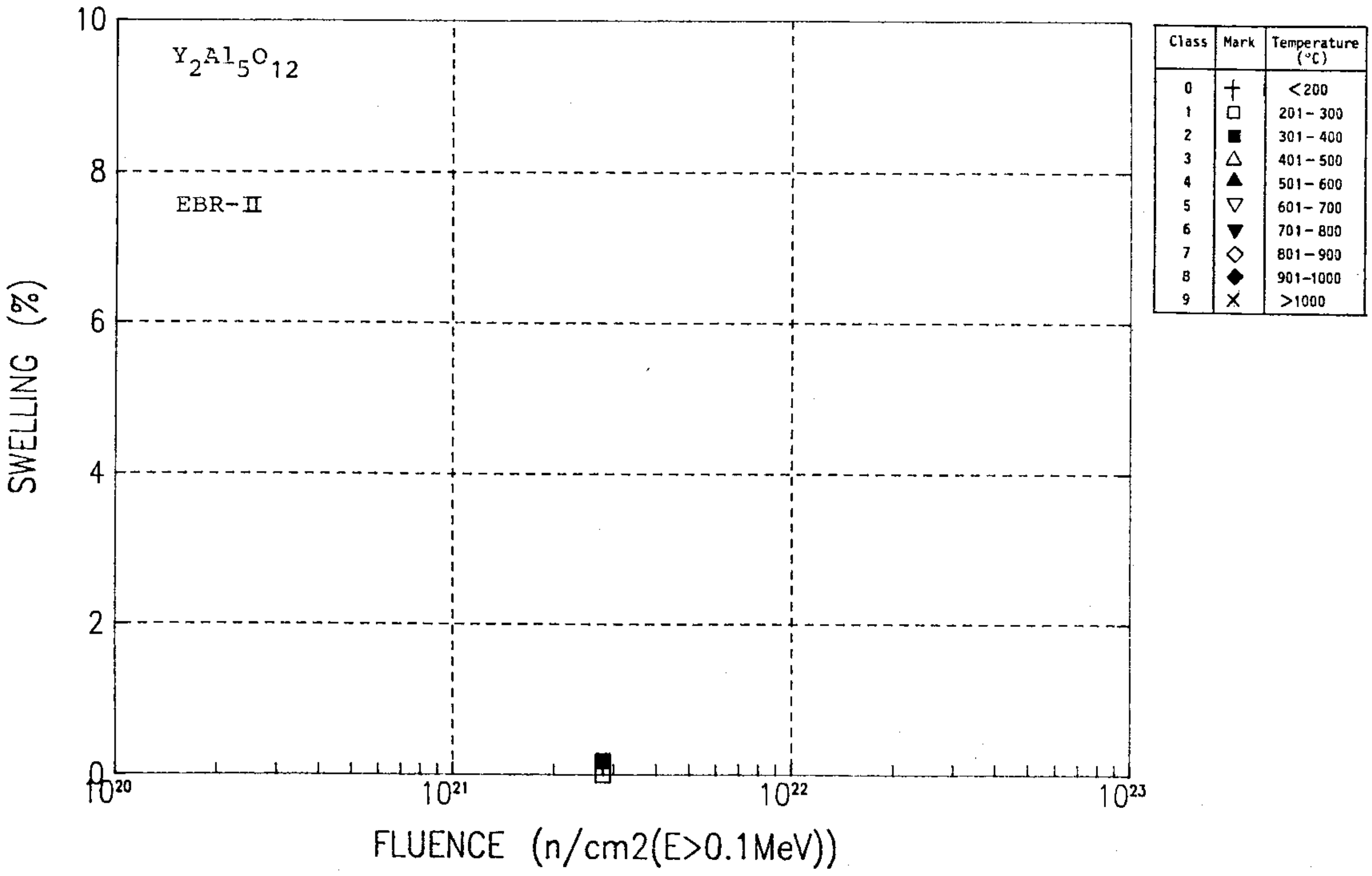


Fig. F-19 $Y_2Al_5O_{12}$; EBR-II

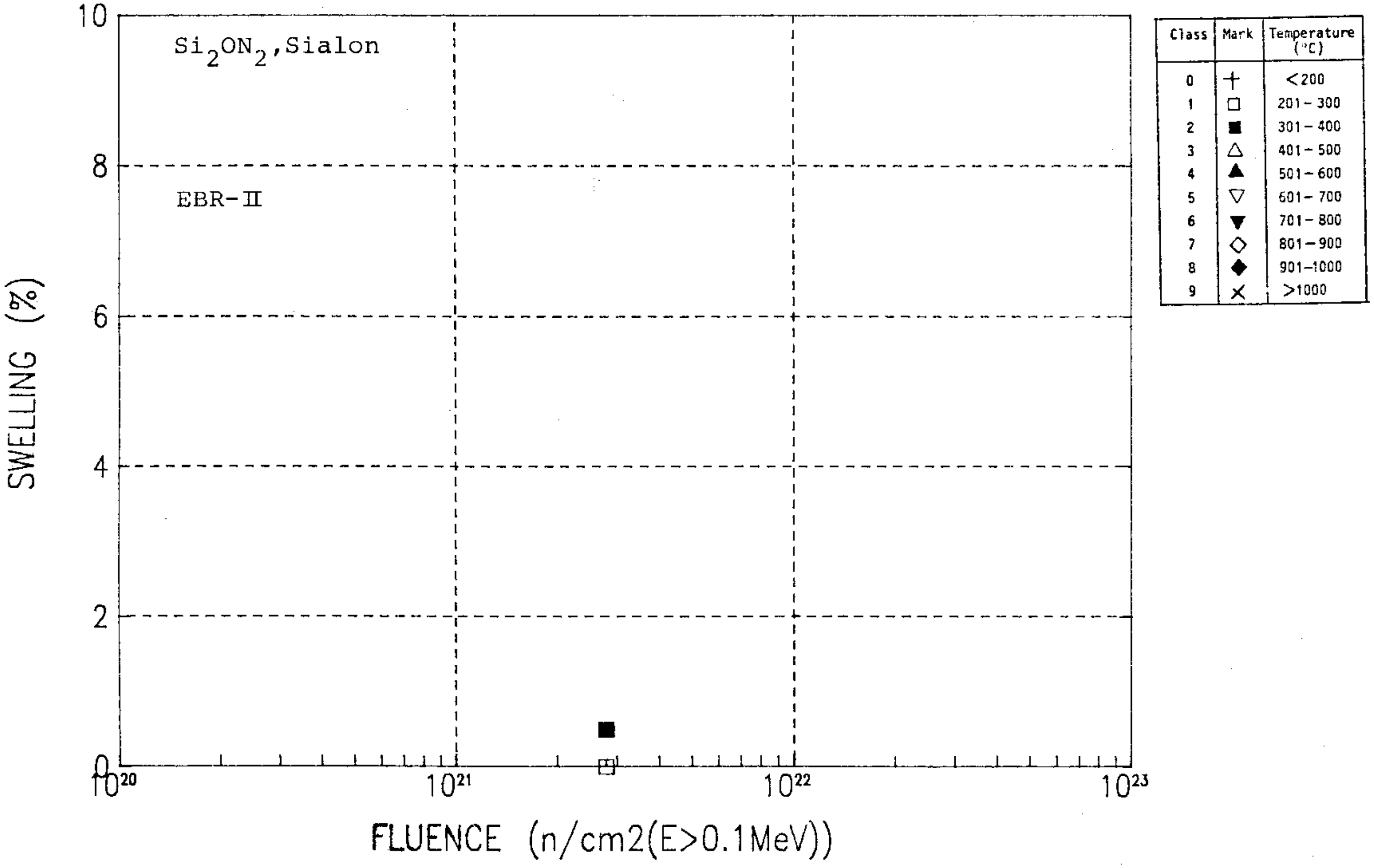


Fig. F-20 Si$_2$ON$_2$,Sialon : EBR-II

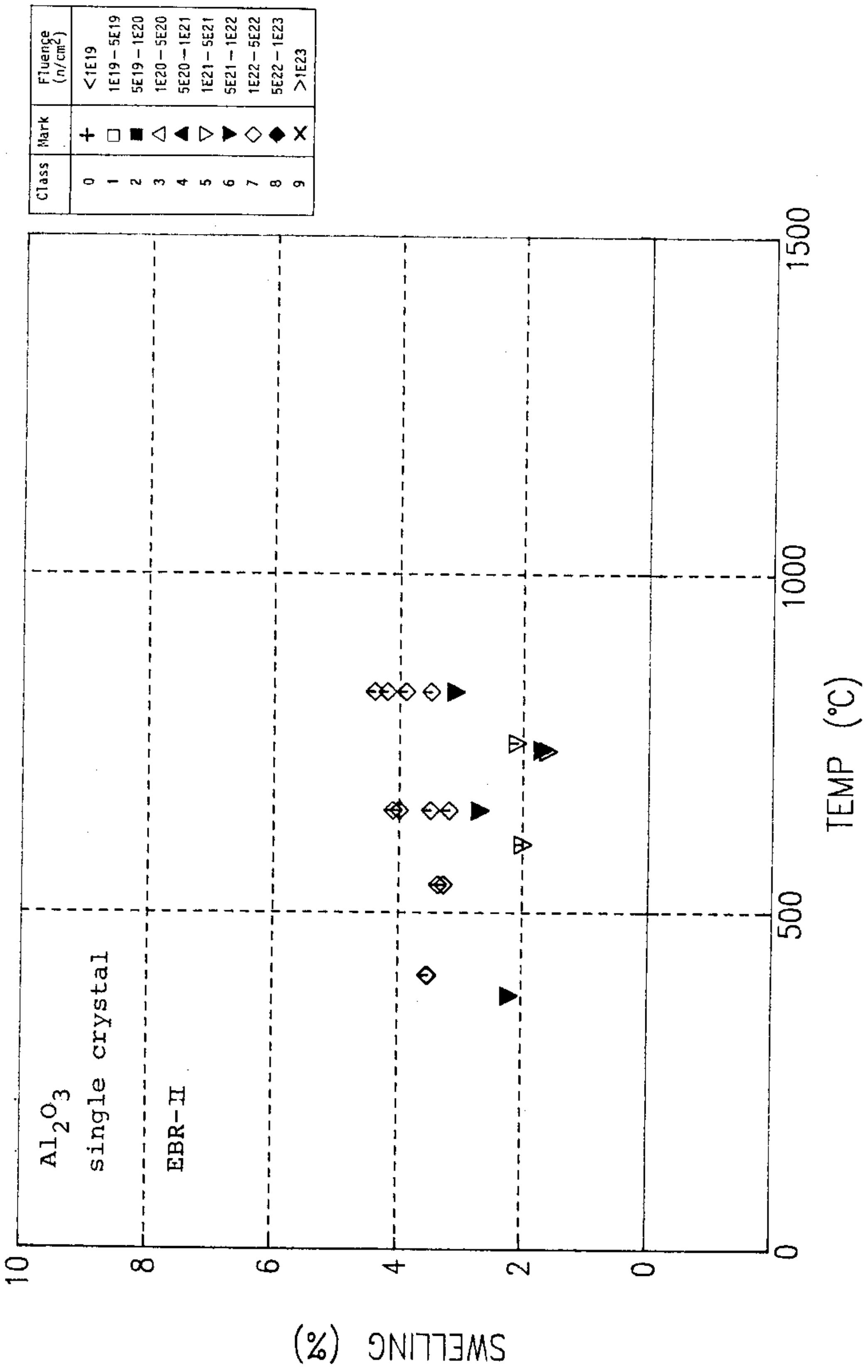


Fig. T-1 Al_2O_3 single crystal ; EBR-II

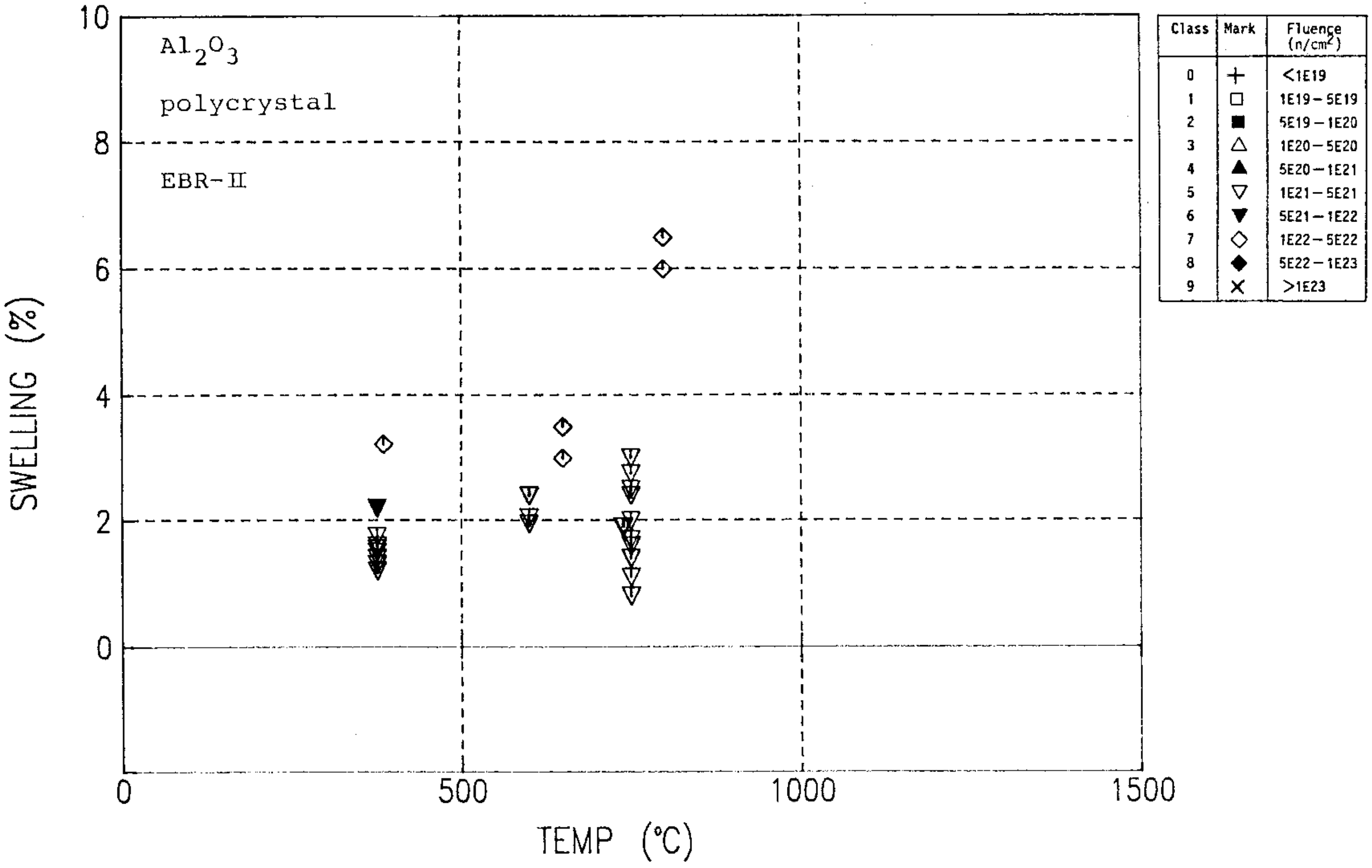


Fig. T-2 Al$_2$O$_3$ polycrystal : EBR-II

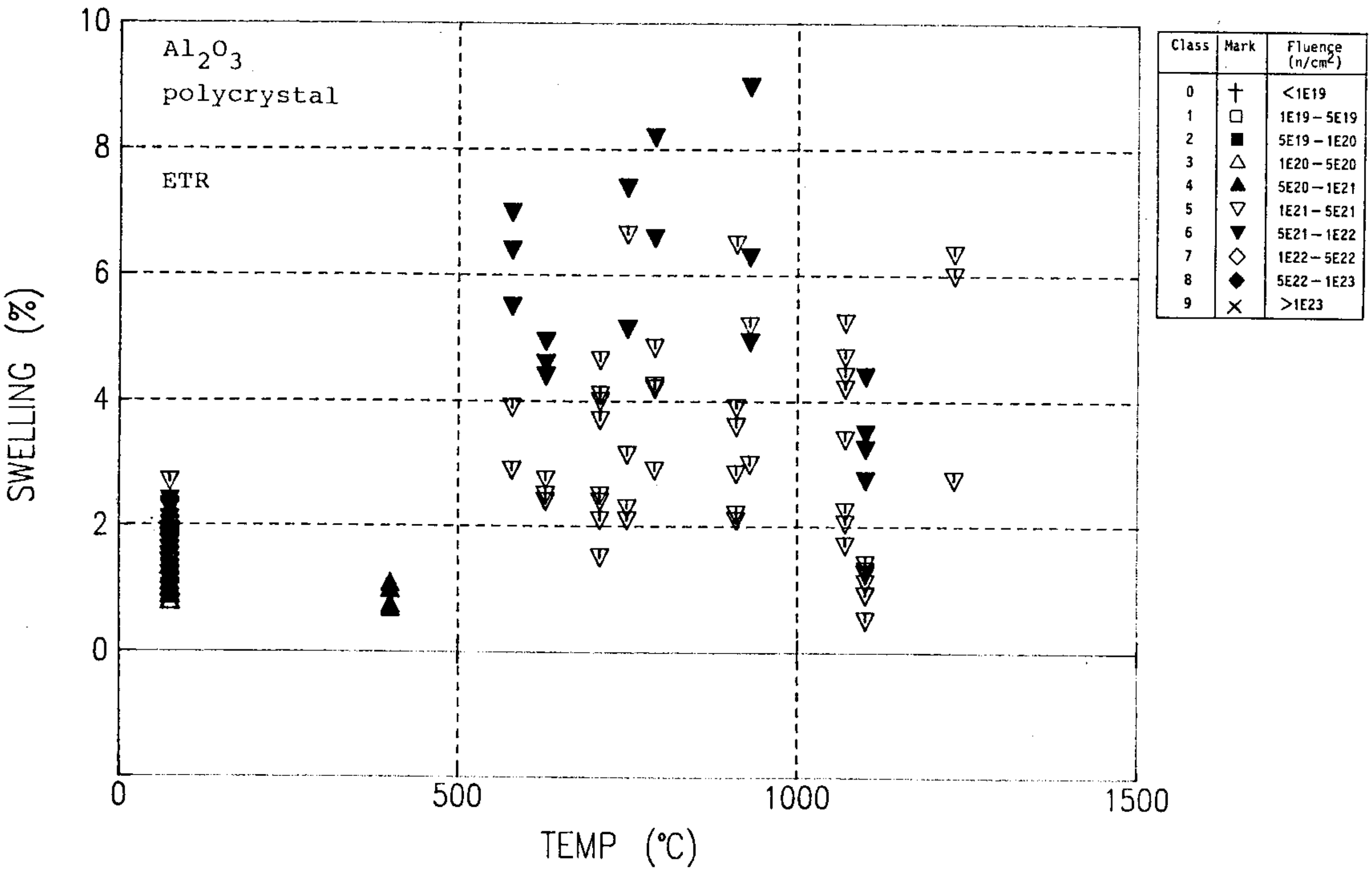


Fig. T-3 Al_2O_3 polycrystal ; ETR

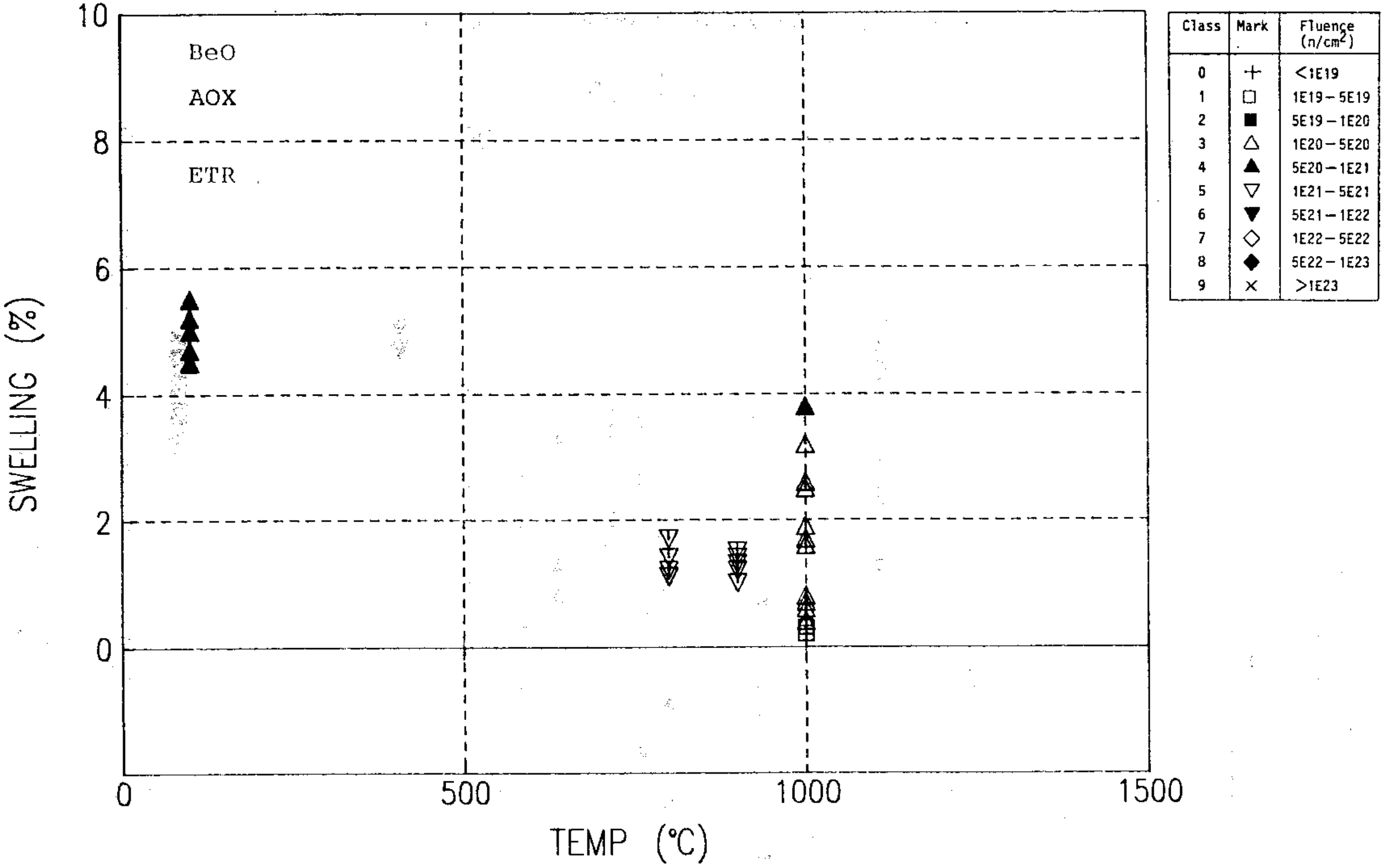


Fig. T-6 BeO AOX ; ETR

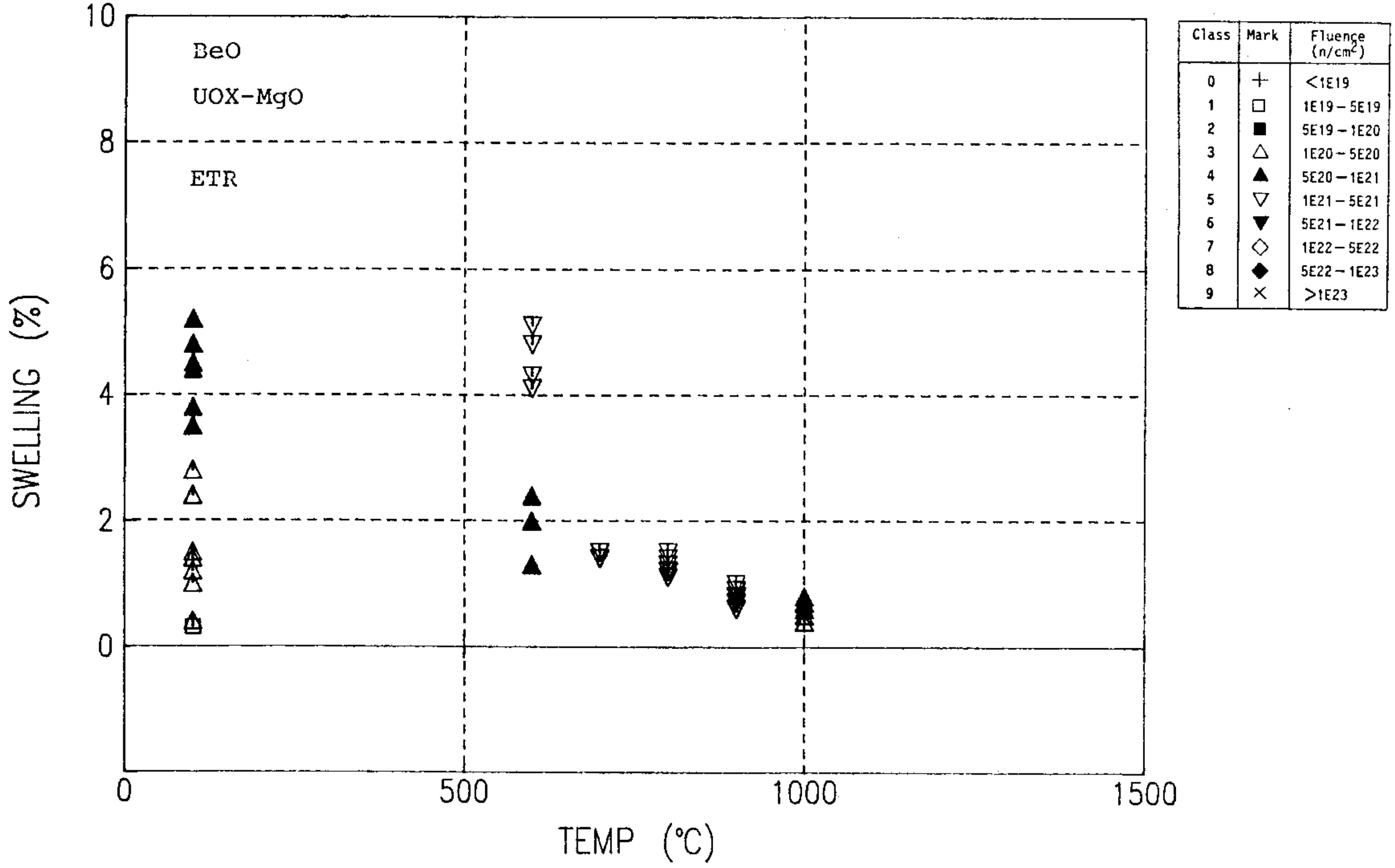


Fig. T-7 BeO UOX-MgO ; ETR

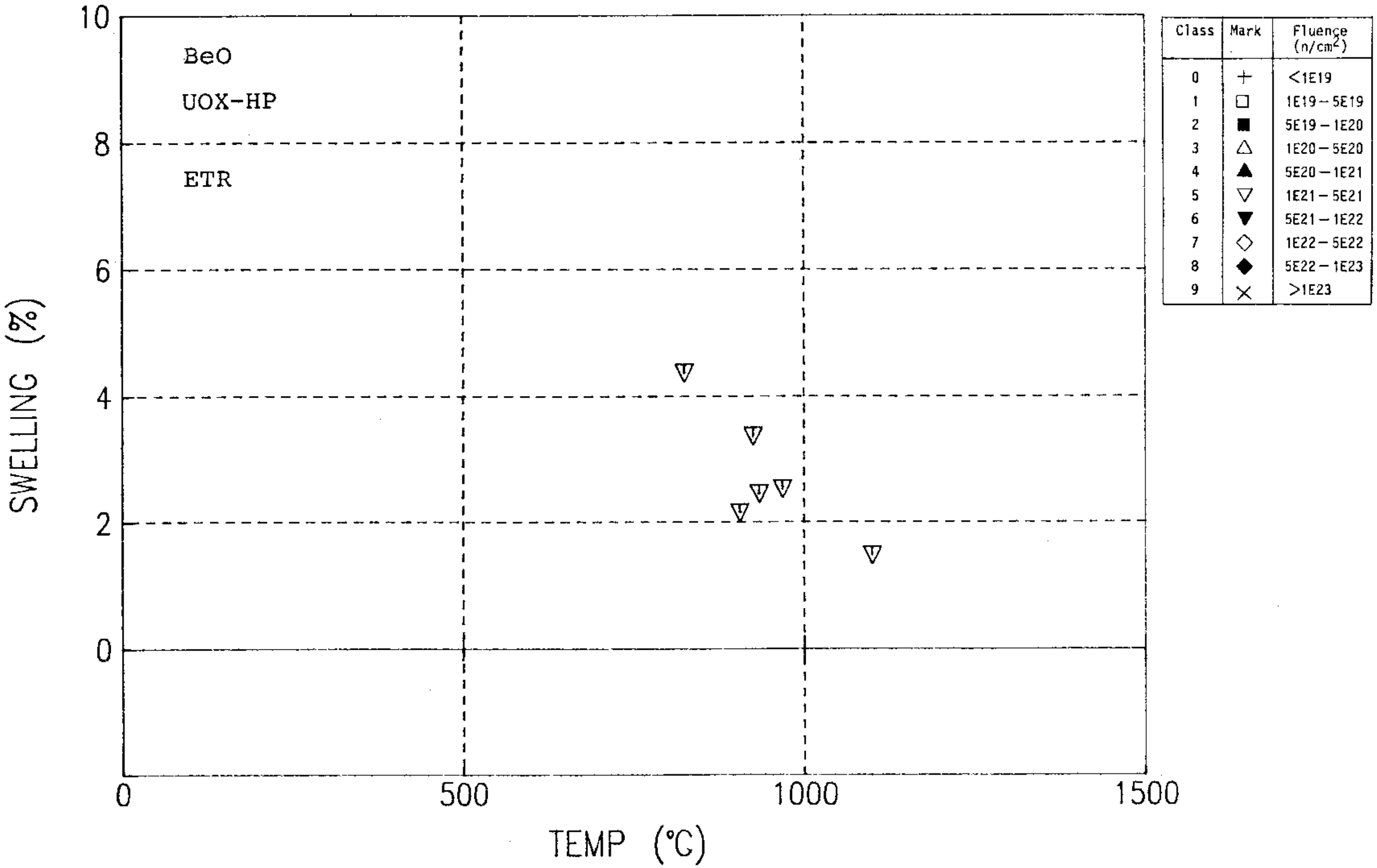


Fig. T-8 BeO UOX-HP ; ETR

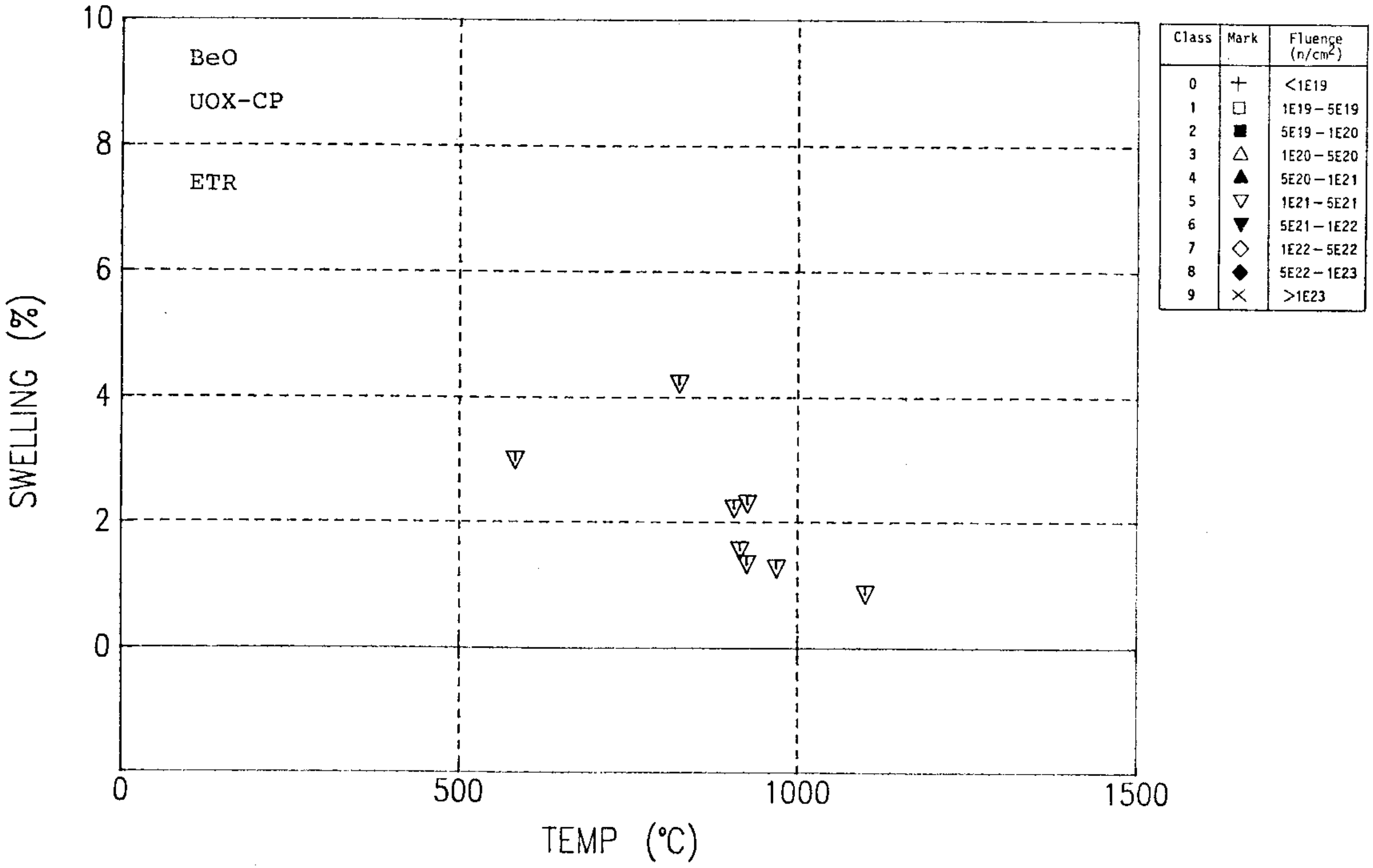


Fig. T-9 BeO UOX-CP ; ETR

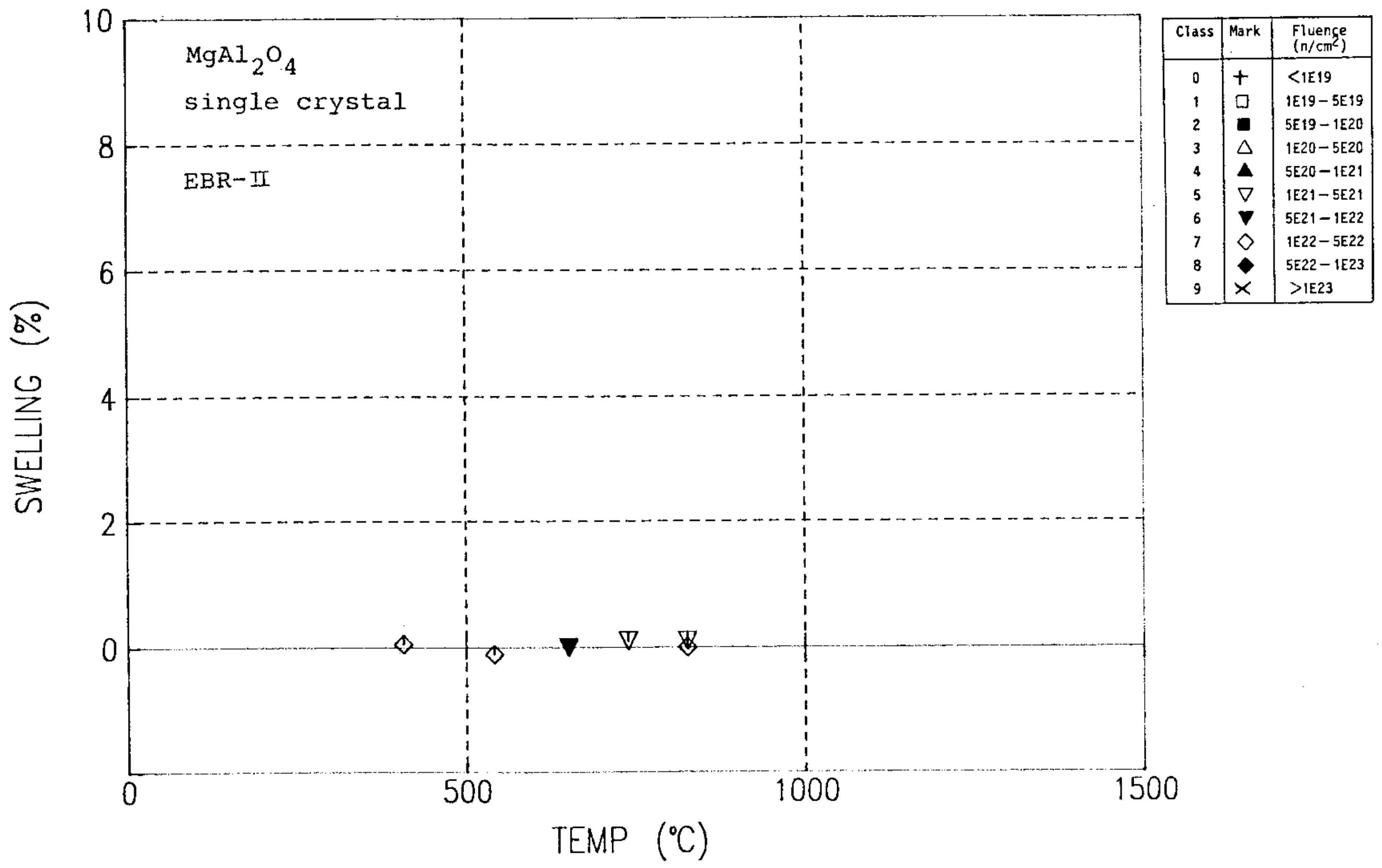


Fig. T-10 $MgAl_2O_4$ single crystal ; EBR-II

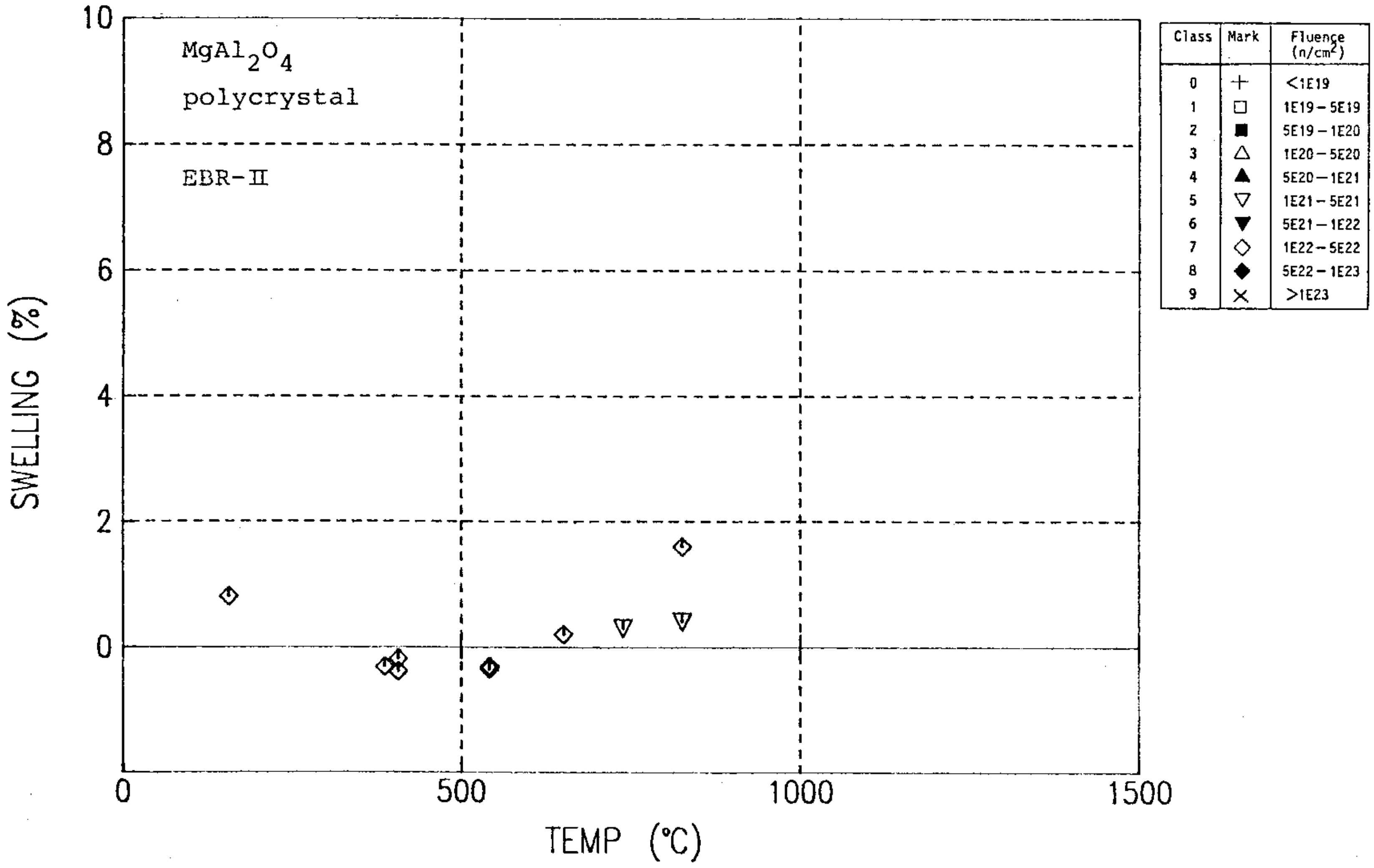


Fig. T-11 MgAl$_2$O$_4$ polycrystal ; EBR-II

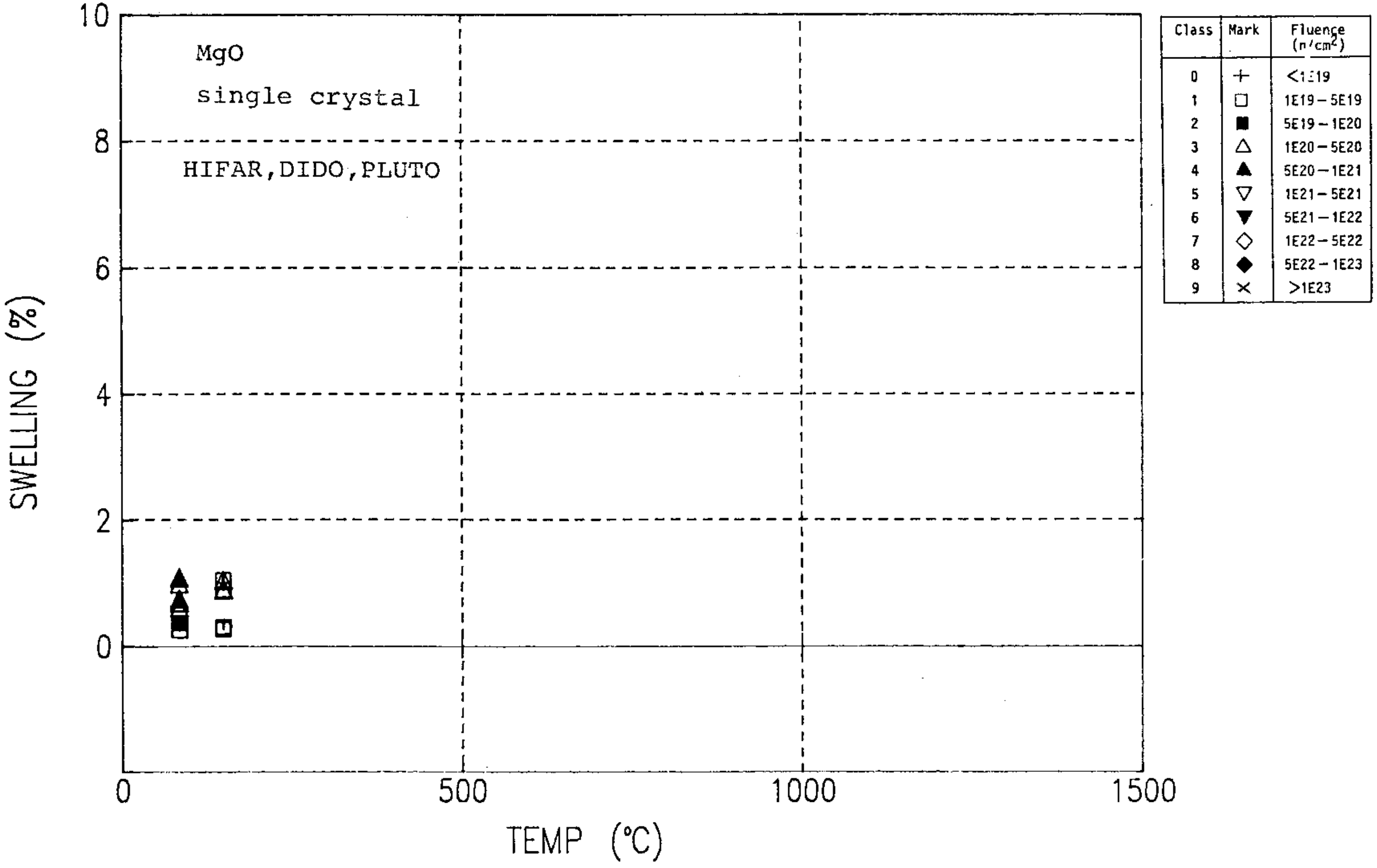


Fig. T-12 MgO single crystal ; HIFAR,DIDO,PLUTO

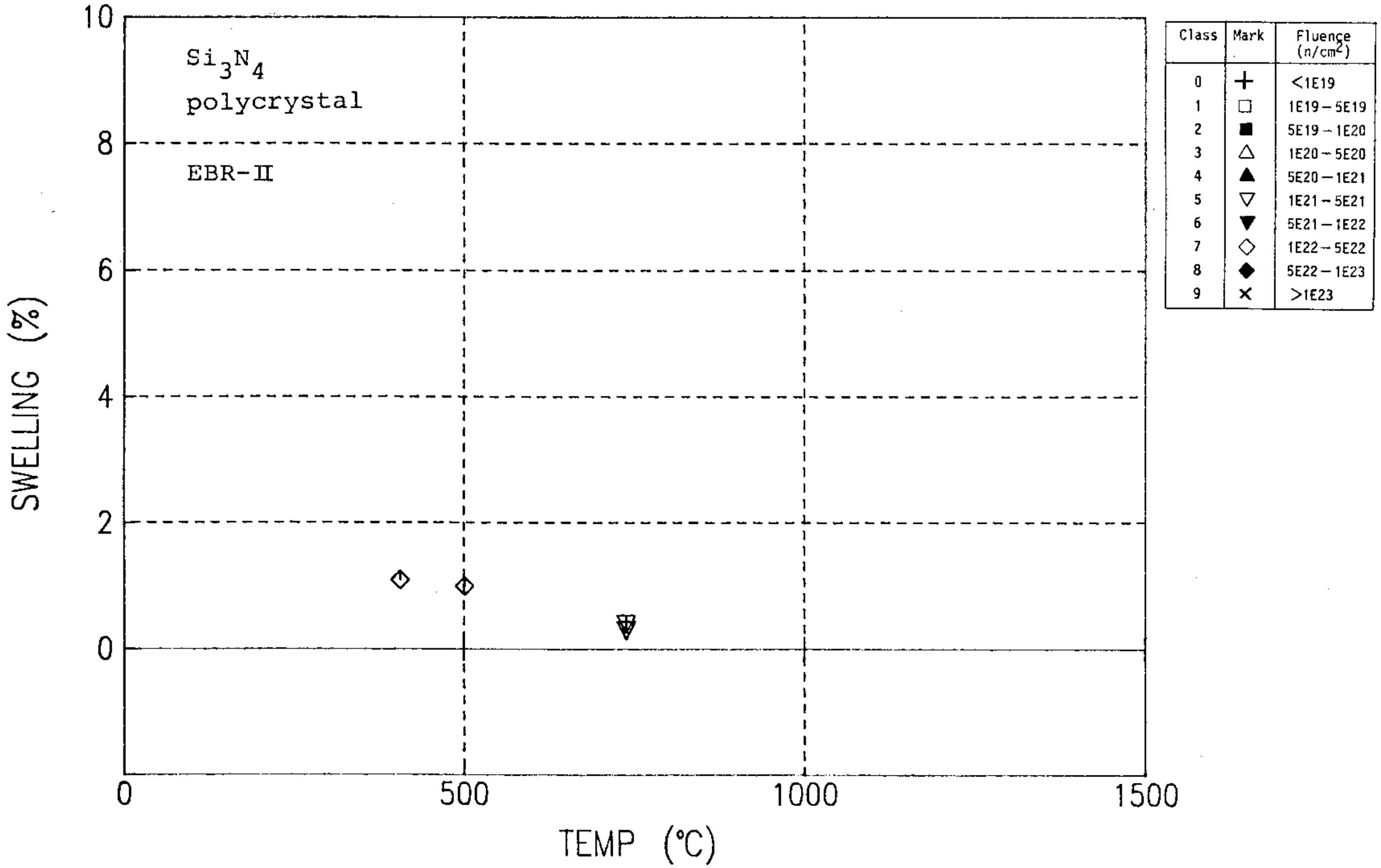


Fig. T-14 Si_3N_4 polycrystal ; EBR-II

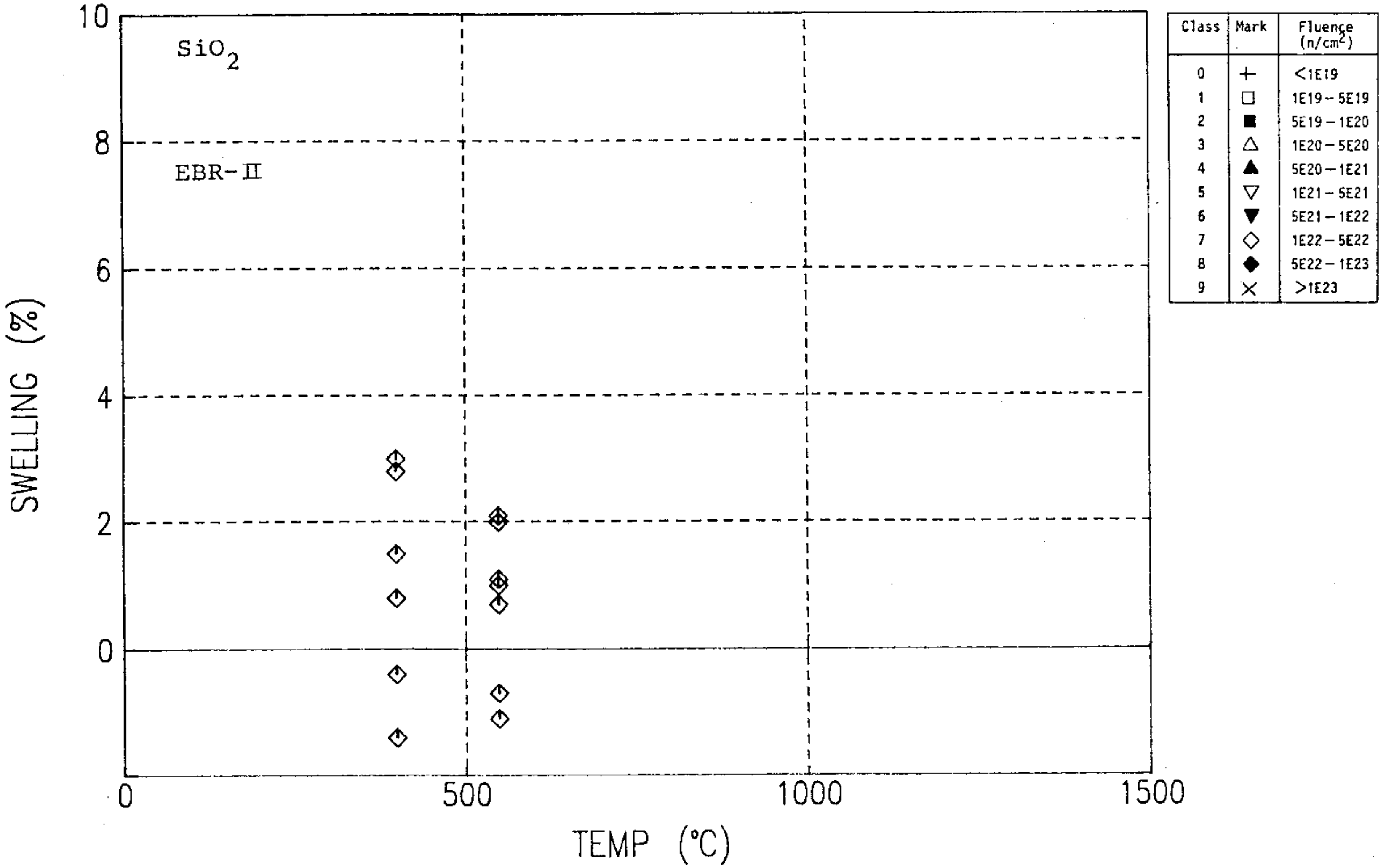


Fig. T-15 SiO$_2$; EBR-II

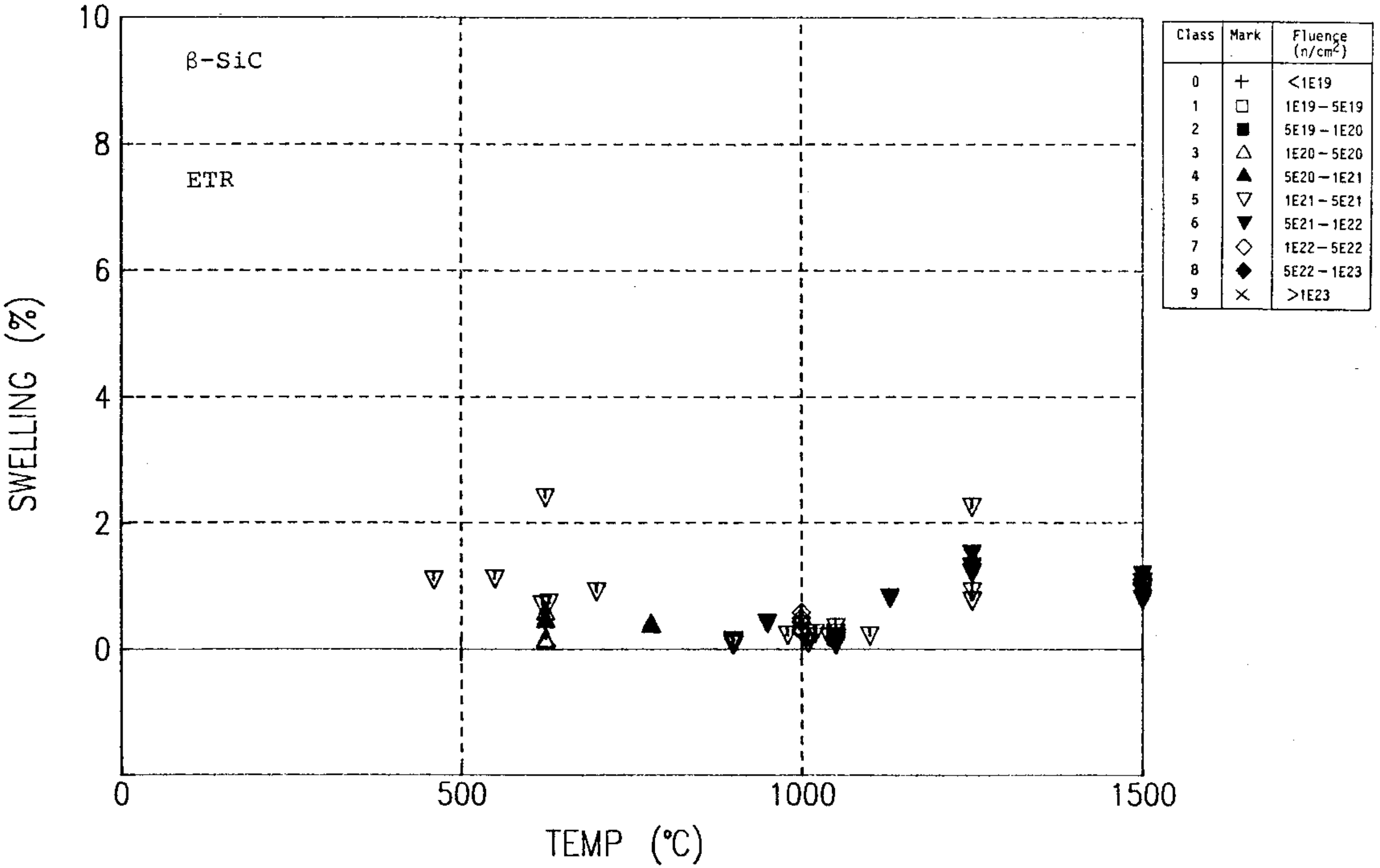


Fig. T-16 β-SiC ; ETR

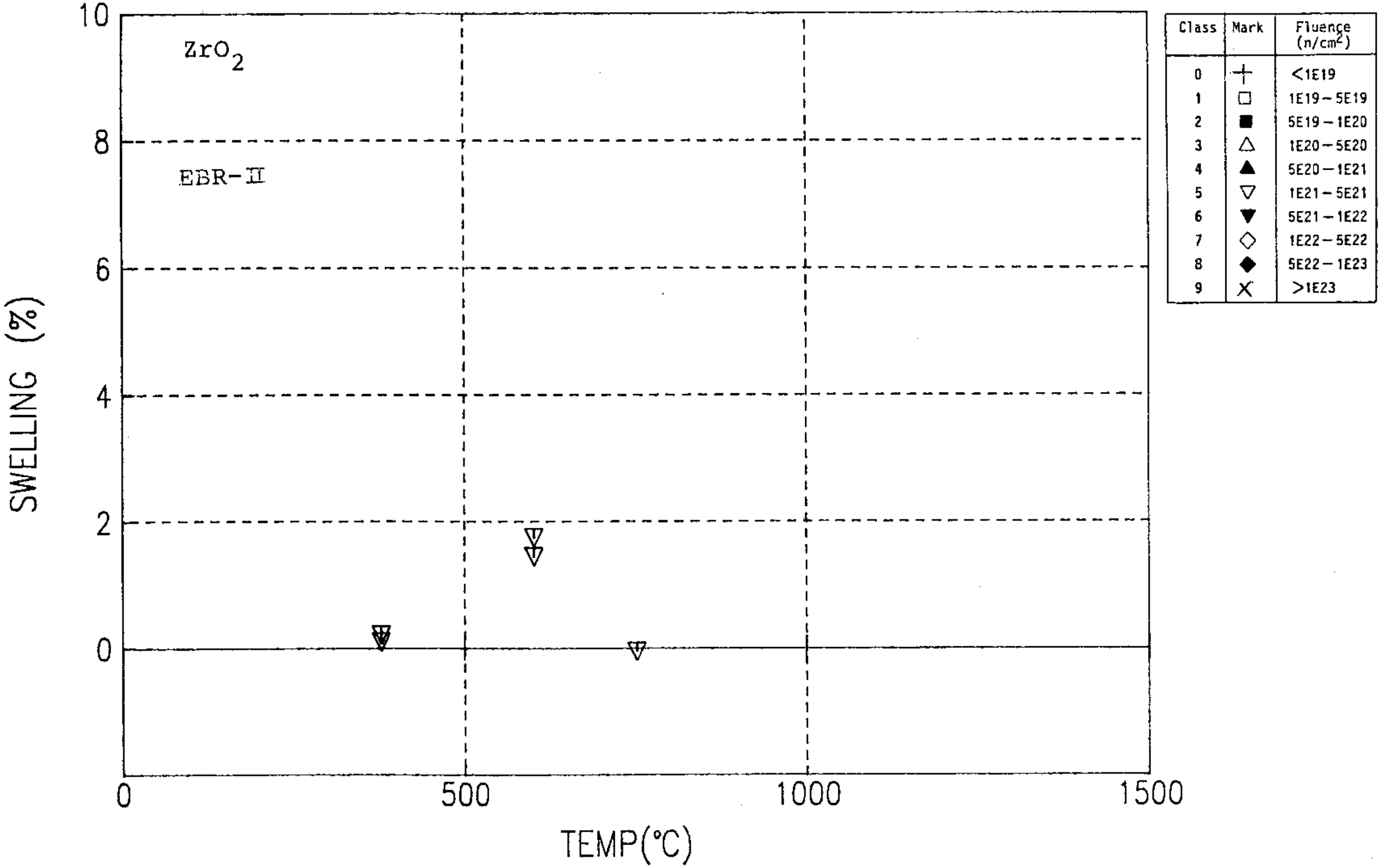


Fig. T-17 ZrO_2 ; EBR-II

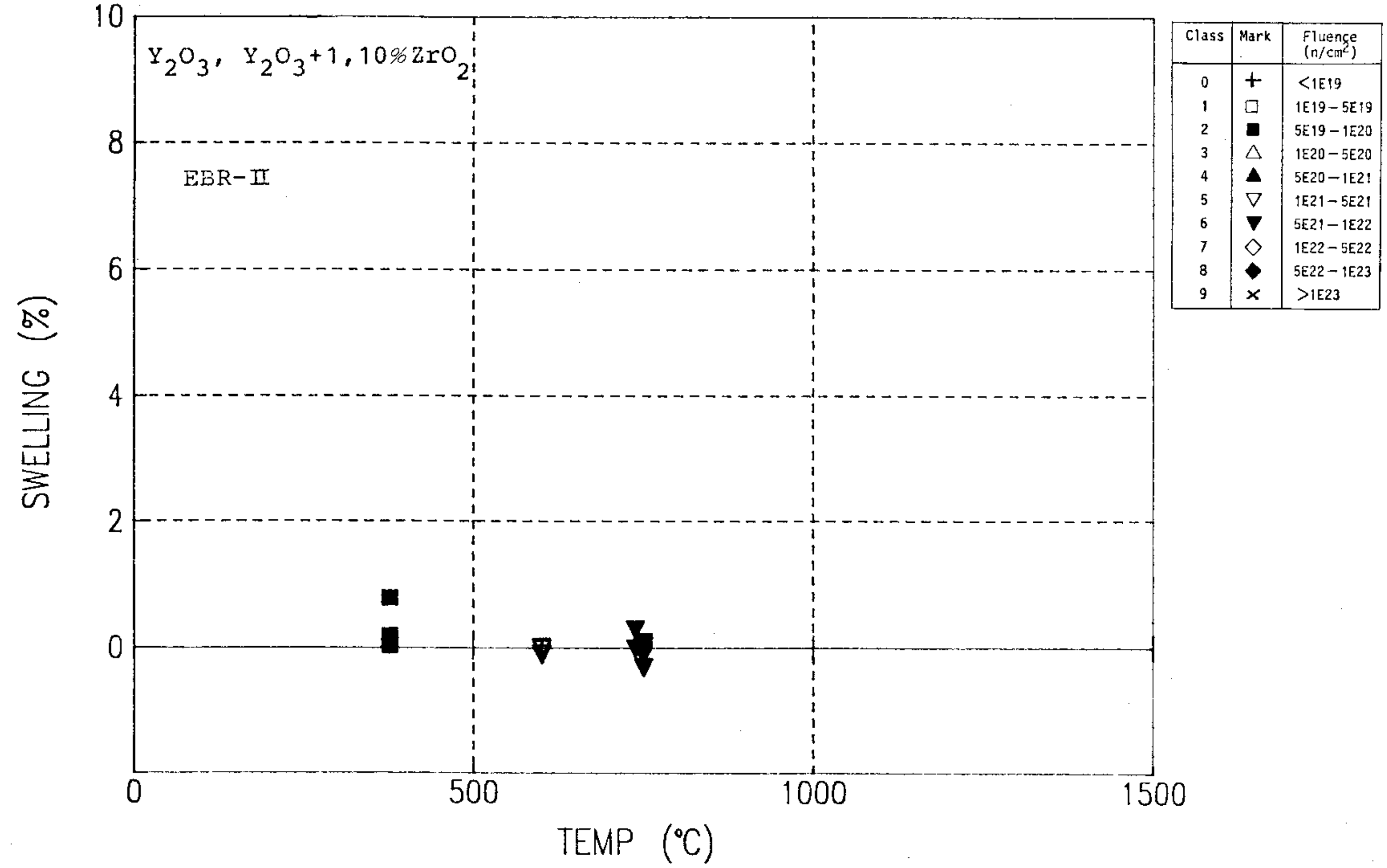
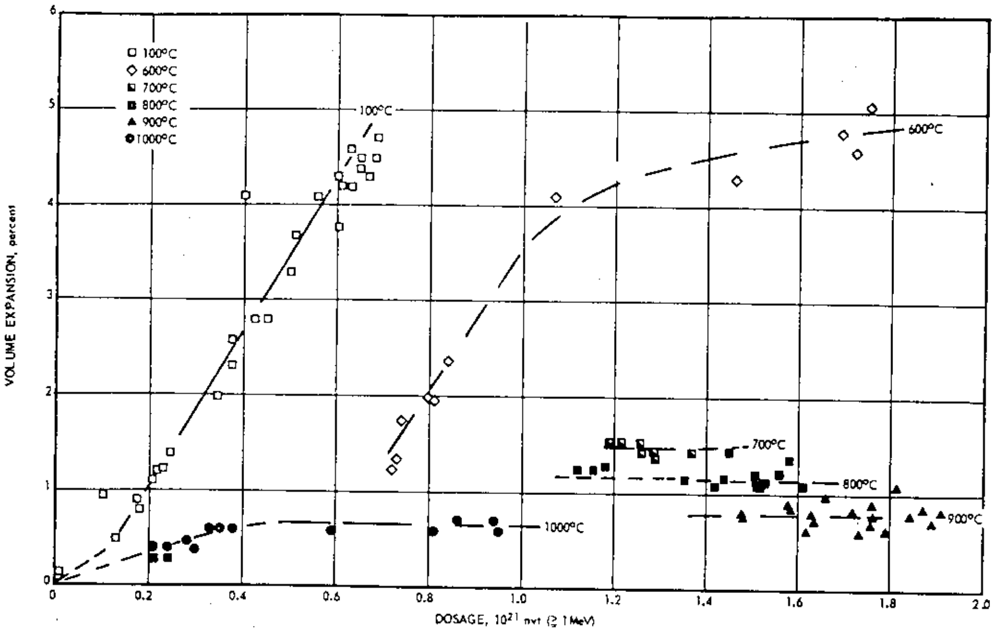


Fig. T-18 Y_2O_3, Y_2O_3+1,10% ZrO_2 ; EBR-II

5. Data Sheets

A-1

Material	BeO (sintered)	Property	Swelling	1/1
Irradiation Condition	$< 1.5 \times 10^{21}$ n/cm^2 (E > 1 MeV) ETR 100 ∿ 1200°C			



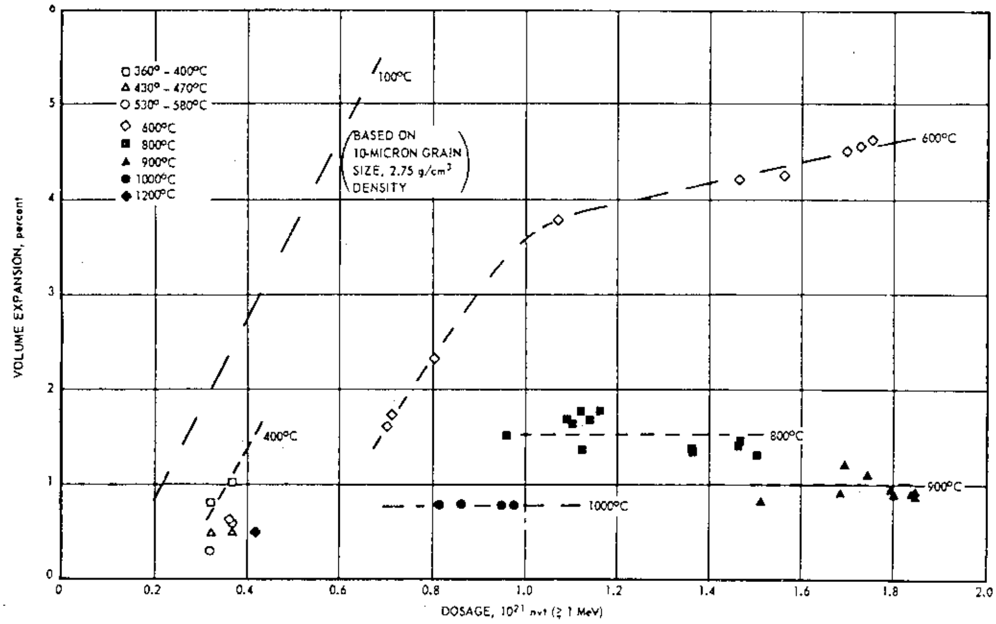
Volume expansion of UOX-0.5 wt % MgO composition of BeO of 20μ grain size 2.9 g/cm^3 density irradiated at elevated temperatures. This composition contained ~ 50 percent preferred orientation of the *c* axis along the longitudinal axis of the specimen.

Reference 5	Radiation Effects in BeO
	C. G. Collins
	J. Nucl. Mater. 14 (1964) 69-86

A-2

Material	BeO (sintered)	Property	Swelling	1/1

Irradiation Condition	< 1.5 x 10^{21} n/cm^2 (E > 1 MeV) ETR 100 ∿ 1200°C

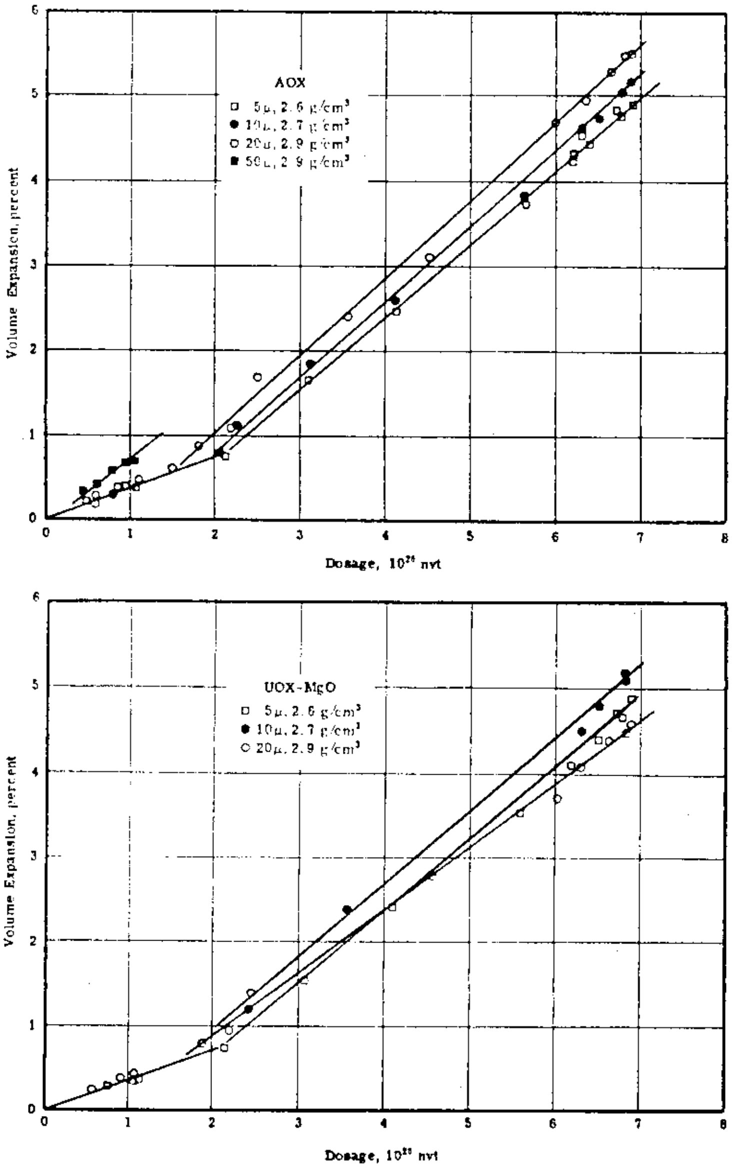


Volume expansion of UOX-0.5 wt % MgO composition of BeO of 10μ grain size and 2.8 g/cm^3 density irradiated at elevated temperatures. The data indicate the magnitude of the expansion under neutron fluxes of 1 to 3×10^{14} nv ($\geqq$ 1 MeV).

Reference 5	Radiation Effects in BeO C. G. Collins J. Nucl. Mater. 14 (1964) 69-86

A-3

Material	BeO (sintered)	Property	Swelling	1/1
Irradiation Condition	$< 1.5 \times 10^{21}$ n/cm^2 (E > 1 MeV) ETR 100 ∿ 1200°C			

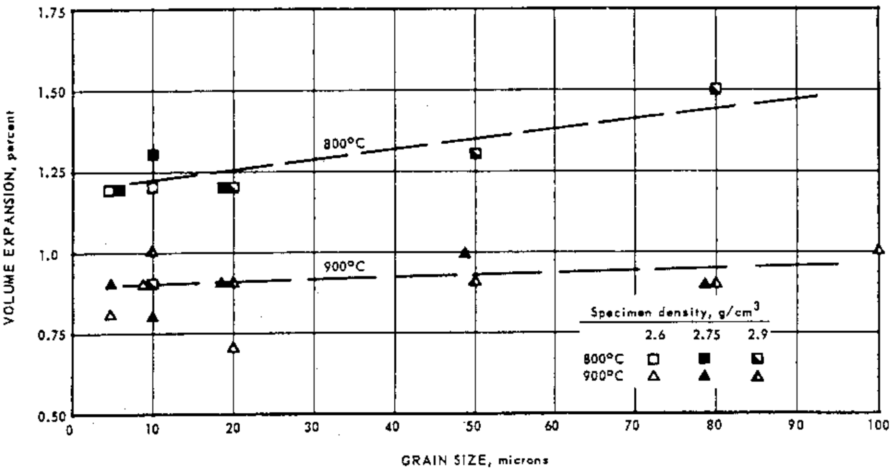


Volume expansion in different grain sizes and densities of AOX and UOX-0.5 wt % MgO compositions of BeO irradiated at 100°C.

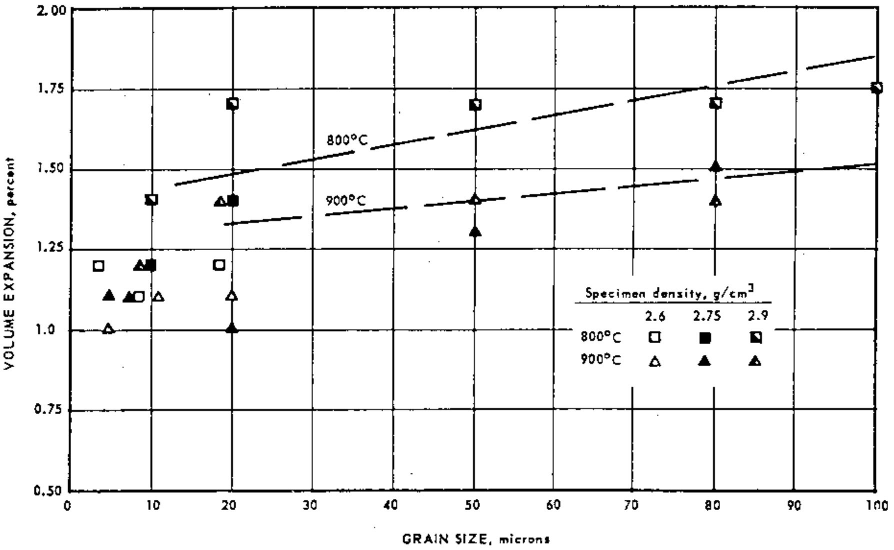
Reference	Radiation Effects in BeO
	C. G. Collins
5	J. Nucl. Mater. 14 (1964) 69-86

A-4

Material	BeO (sintered)	Property	Swelling	1/1
Irradiation Condition	$< 1.5 \times 10^{21}$ n/cm^2 (E > 1 MeV) ETR 100 ∿ 1200°C			



Volume expansion of UOX-0.5 wt % MgO of different grain sizes and densities after irradiation to 1.2 to 1.5×10^{21} nvt (≧ 1 MeV) at 800° to 900°C.

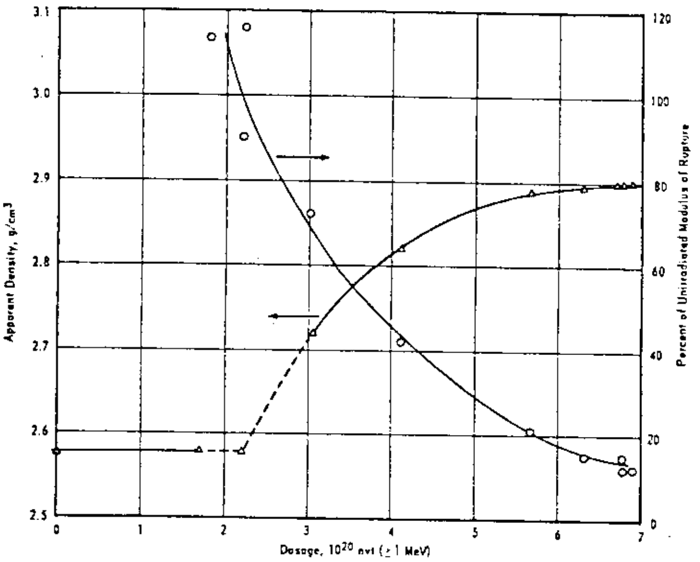


Volume expansion of AOX-grade BeO of different grain sizes and densities after irradiation to 1.2 to 1.5 × 10^{21} nvt (≧ 1 MeV) at 800° to 900°C.

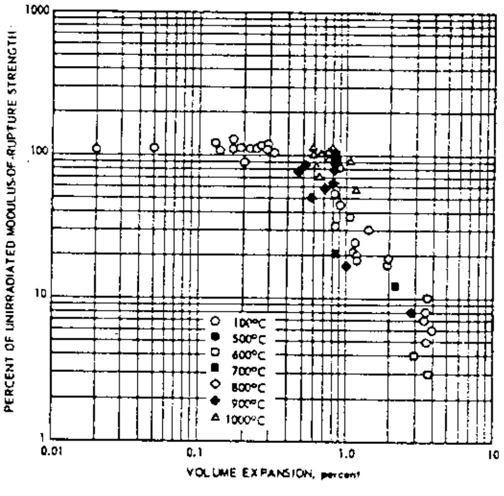
Reference 5	Radiation Effects in BeO
	C. G. Collins
	J. Nucl. Mater. 14 (1964) 69-86

A-5

Material	BeO (sintered)	Property	Swelling Rupture strength	1/1
Irradiation Condition	$< 1.5 \times 10^{21}$ n/cm^2 (E > 1 MeV) ETR 100 ∿ 1200°C			



Changes in the apparent density and the modulus-of-rupture of AOX grade BeO irradiated at ~ 100°C. The marked changes at ~ 2×10^{20} nvt result from microcracking. The specimens were 5μ grain size and 2.6 g/cm^3.



Strength changes in AOX-grade BeO of 20-micron grain size, 2.9 g/cm^3 density, after irradiation to dosages up to 1.5×10^{21} nvt ($\geq$ 1 MeV) at temperatures from 100°C to 1000°C.

Reference 5	Radiation Effects in BeO
	C. G. Collins
	J. Nucl. Mater. 14 (1964) 69-86

A-6

Material	BeO (sintered)	Property	Swelling, Lattice parameter	1/1

Irradiation Condition	< 1.5 x 10^{21} n/cm^2 (E > 1 MeV) ETR 100 ∿ 1200°C

Comparison of lattice and volume expansion in BeO irradiated at elevated temperatures

Sample			Irradiation Conditions			Lattice Expansion			Macroscopic Volume Increase, %
Composition	Grain Size, microns	Density, g/cm^3	Temperature, °C	Flux 10^{14} nv (≧ 1 MeV)	Dosage, 10^{20} nvt (≧ 1 MeV)	$\Delta a/a$, %	$\Delta c/c$, %	$\Delta V/V$, %	
AOX	13	2.88	1200	3.1	3.5	0	0.02	0.02	0.27
AOX	20	2.88	1040	1.5	3.6	0	0.11	0.11	0.58
AOX	20	2.88	1030	1.5	3.5	0	0.04	0.04	0.73
AOX	12	2.88	1000	2.0	2.4	0	0.04	0.04	0.63
UOX-MgO	20	2.88	950	2.0	4.7	0	0.05	0.05	0.68
UOX-MgO	20	2.94	840	2.5	3.0	0.02	0.18	0.22	0.35
AOX	7	2.76	660	0.61	2.8	0	0.30	0.30	0.64
UOX-MgO	11	2.88	530	2.8	3.2	0.04	0.23	0.31	0.32
UOX-MgO	11	2.88	430	2.8	3.2	0.07	0.21	0.35	0.47

Reference 5	Radiation Effects in BeO C. G. Collins J. Nucl. Mater. 14 (1964) 69-86

A-7

Material	BeO (sintered)	Property	Swelling, Lattice expansion	1/1

Irradiation Condition	< 1.5 x 10^{21} n/cm^2 (E > 1 MeV) ETR 100 ∿ 1200°C

Lattice expansion in BeO irradiated at 100°C

Specimen			Dosage, 10^{20} nvt (≧ 1 MeV)	Lattice Expansion, percent			Gravimetric[a]) Volume Increase, percent
Composition	Grain Size, microns	Density g/cm^3		*a* axis	*c* axis	volume	
UOX-MgO	18	2.9	0.08	0.015	0.04	0.07	—
UOX-MgO	9	2.9	0.5	0.05	0.07	0.17	—
AOX	45	2.9	1.1	0.04	0.17	0.25	—
AOX	4	2.6	1.2	0.05	0.22	0.32	—
AOX	45	2.9	1.2	0.05	0.25	0.35	—
AOX	45	2.9	1.5	0.04	0.25	0.33	—
AOX	45	2.9	1.5	0.06	0.38	0.50	—
AOX	45	2.9	1.8	0.06	0.52	0.64	0.6
AOX	45	2.9	2.2	0.06	0.58	0.70	—
UOX-MgO	18	2.9	2.2	0.08	0.57	0.74	—
AOX	45	2.9	2.5	0.06	0.57	0.69	—
AOX	42	2.7	2.6	0.06	0.59	0.71	—
UOX-MgO	17	2.9	2.8	0.08	0.57	0.73	—
AOX	19	2.9	5.3	0.12	1.3	1.56	1.7
UOX-MgO	18	2.9	5.6	0.11	1.6	1.8	—
UOX-MgO	17	2.9	6.3	0.15	1.7	2.0	—
UOX-MgO	18	2.9	6.8	0.15	—	—	2.2
UOX-MgO	18	2.9	8.1	0.15	2.1	2.4	—
				0.15	2.3	2.6	—
UOX-MgO	17	2.9	10.6	0.15	3.1	3.4	3.6
				0.16	3.4	3.7	—

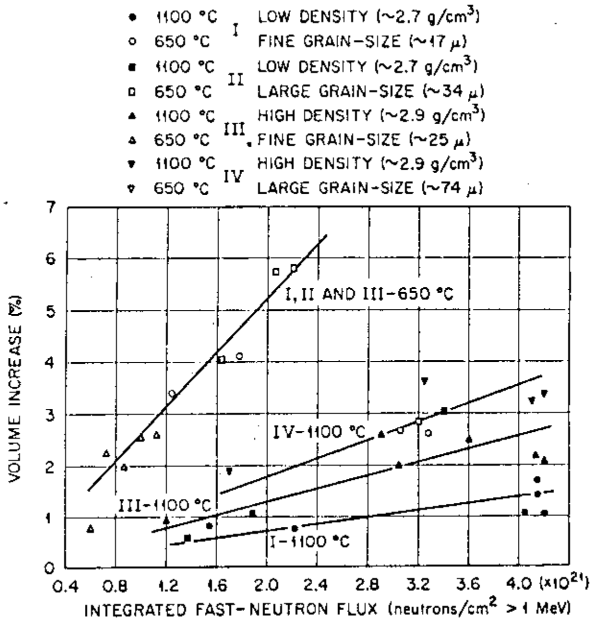
[a]) Volume increase determined from comparison of gravimetric densities of irradiated and non-irradiated specimens after crushing to less than 10 micron particle size.

Reference 5	Radiation Effects in BeO C. G. Collins J. Nucl. Mater. 14 (1964) 69-86

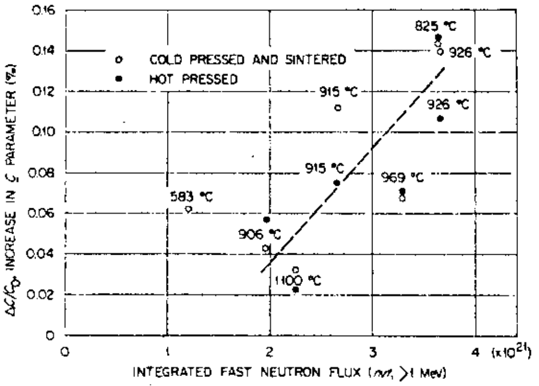
A-8

Material	BeO (sintered)	Property	Swelling, Lattice parameter	1/1

Irradiation Condition	$0.3 \sim 4.2 \times 10^{21}$ n/cm^2 (E > 1 MeV) ETR 100, 650, 1100°C



ORNL-DWG-63-1936, Volume increase of ½ in. (1.27 cm) BeO specimens vs integrated fast-neutron flux in experiment 41-9.



ORNL-LR-DWG-76727R, Increase in *c* parameter vs integrated fast-neutron flux in experiment 41-7.

Characteristics of beryllium oxide specimens

Type	Specimen size (in.)	Average bulk density (g/cm³)	Average grain Size (μ)
I (Low density, fine grain size)	0.25	2.7	24
	0.5	2.7	17
II (Low density, large grain size) . . .	0.25	2.7	60
	0.5	2.7	34
III (High density, fine grain size) . .	0.25	2.9	23
	0.5	2.9	25
IV (High density, large grain size) . .	0.25	2.9	71
	0.5	2.95	74

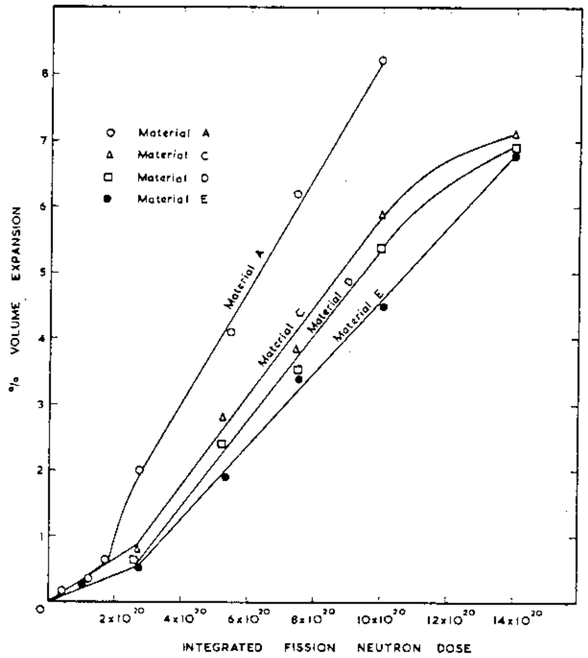
Reference 6	Behavior of BeO under Fast Irradiation
	G. W. Keilholtz, J. E. Lee, Jr., R. M. Moore and R. L. Homner
	J. Nucl. Mater. 14 (1964) 87

A-9

Material	BeO	Property	Swelling	1/1
Irradiation Condition	$2.5 \times 10^{20} \sim 1.4 \times 10^{21}$ n/cm² (nvt) HIFAR 75 ∿ 100°C, 500 ∿ 700°C			

Details of materials used in the investigation

Designation	Starting Material	Fabrication Route	Density per cent Theoretical	Grain-size	Dose at which microcracking is first observed	
					75–100° C	500–700° C
A	Pechiney Nuclear Grade	Hot pressed at 1750° C for ½-hour at 1 tsi	97–98	12–15μ	2.5×10^{20}	4.5 to 6.5×10^{20}
B	Berylco No. 1	Hot pressed at 1650° C for 4 hours at 2 tsi	99.5	25–30μ	2.5×10^{20}	4.5 to 6.5×10^{20}
C	Brush UOX (pre-ground)	Cold pressed at 20 tsi and sintered for one hour at 1550° C	96–98	8–12μ	5×10^{20}	9 to 12×10^{20}
D	Brush UOX (pre-ground)	Cold pressed at 20 tsi and sintered for one hour at 1500° C	91–94	1–2μ	1.4×10^{21}	Not observed up to 12×10^{20}
E	Brush UOX (pre-ground)	Cold pressed at 20 tsi and sintered for one hour at 1450° C	95–97	2–3μ	1.4×10^{21}	Not observed up to 12×10^{20}
F	Brush UOX	Cold pressed at 20 tsi and sintered for one hour at 1500° C	95–96	15–20μ	5×10^{20}	Not observed up to 12×10^{20}
G	Brush UOX	Cold pressed at 20 tsi and sintered for one hour at 1200° C	72–75	1μ	Not investigated	Not observed up to 4.5 to 6.5×10^{20}
H	Brush UOX	Hot pressed at 1500° C for ½-hour at 1 tsi	94–97	3–5μ	Not observed up to 3×10^{20}	Not investigated
J	Brush UOX	Hot pressed at 1700° C for ½-hour at 1 tsi	97–98	10–12μ	3×10^{20}	Not investigated



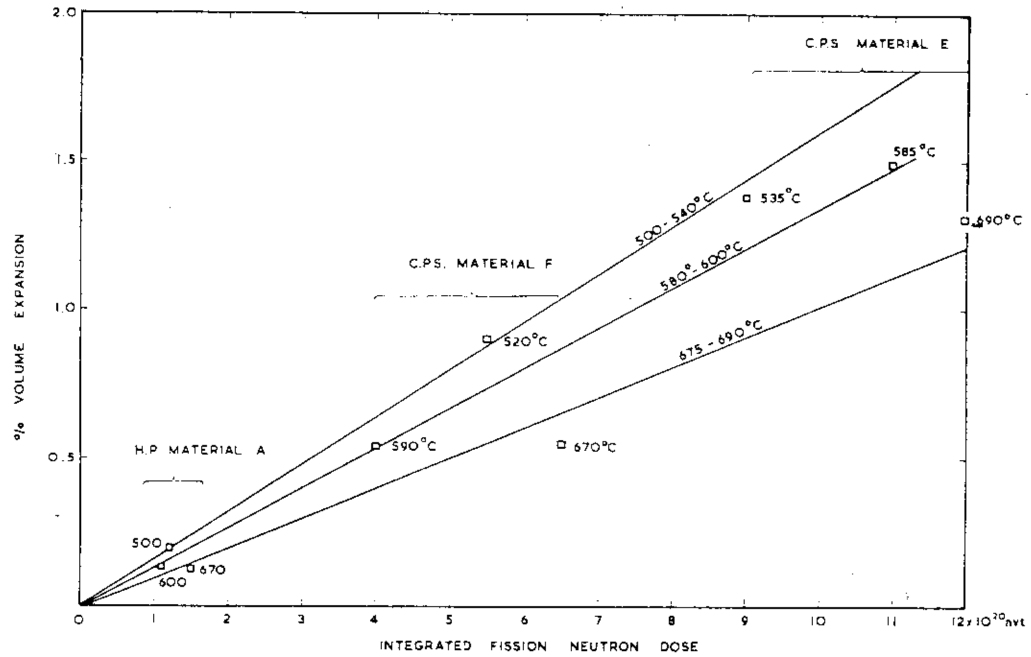
Volume changes after irradiation of various materials at 75–100° C.

Reference 7	
	The Effect on Neutron Irradiation on Beryllium Oxide
	B. S. Hickman and A. W. Pryor
	J. Nucl. Mater. 14 (1964) 96-110

A-10

Material	BeO	Property	Swelling	1/1

Irradiation Condition	$7.5 \times 10^{20} \sim 1.4 \times 10^{21}$ n/cm^2 (nvt) HIFAR 75 ∼ 100°C, 500 ∼ 700°C



Volume changes in material irradiated at 500–700° C which was considered to be free of microcracking.

Reference 7	The Effect on Neutron Irradiation on Beryllium Oxide
	B. S. Hickman and A. W. Pryor
	J. Nucl. Mater. 14 (1964) 96-110

A-11

Material	BeO	Property	Swelling	1/1

Irradiation Condition	$2.5 \times 10^{20} \sim 1.4 \times 10^{21}$ n/cm^2 (nvt) HIFAR 75 ∿ 100°C, 500 ∿ 700°C

Volume changes as calculated from dimensional changes

Material	Irradiation Temperature	Dose	$\Delta V/V$ %
A	510	1.2×10^{20}	0.2
	520	5.5×10^{20}	1.7
	535	9×10^{20}	Not measured owing to powdering
	600	1.1×10^{20}	0.14
	590	4.5×10^{20}	1.5
	585	1.1×10^{21}	3.0
	670	1.5×10^{20}	0.15
	670	6.5×10^{20}	1.3
	690	1.2×10^{21}	2.5
F	520	5.5×10^{20}	0.8
	590	4.5×10^{20}	0.6
	670	6.5×10^{20}	0.55
G	520	5.5×10^{20}	0.6
	590	4.5×10^{20}	0.6
	670	6.5×10^{20}	0.8
C	535	9×10^{20}	2.4
	585	1.1×10^{21}	1.9
	690	1.2×10^{21}	1.7
D	535	9×10^{20}	1.4
	585	1.1×10^{21}	1.3
	690	1.2×10^{21}	1.3
E	535	9×10^{20}	1.4
	585	1.1×10^{21}	1.4
	690	1.2×10^{21}	1.3

Details of materials used in the investigation

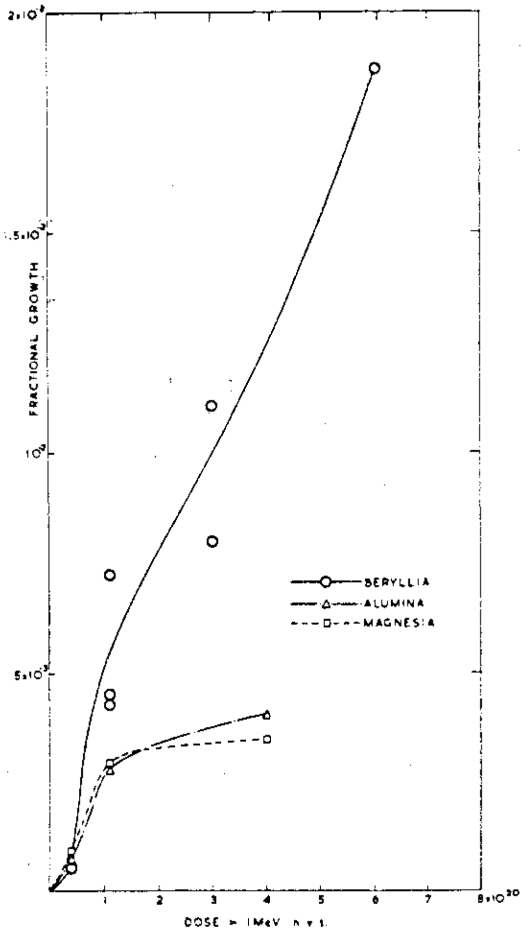
Designation	Starting Material	Fabrication Route	Density per cent Theoretical	Grain-size	Dose at which microcracking is first observed	
					75–100° C	500–700° C
A	Pechiney Nuclear Grade	Hot pressed at 1750° C for ½-hour at 1 tsi	97–98	12–15μ	2.5×10^{20}	4.5 to 6.5×10^{20}
B	Berylco No. 1	Hot pressed at 1650° C for 4 hours at 2 tsi	99.5	25–30μ	2.5×10^{20}	4.5 to 6.5×10^{20}
C	Brush UOX (pre-ground)	Cold pressed at 20 tsi and sintered for one hour at 1550° C	96–98	8–12μ	5×10^{20}	9 to 12×10^{20}
D	Brush UOX (pre-ground)	Cold pressed at 20 tsi and sintered for one hour at 1500° C	91–94	1–2μ	1.4×10^{21}	Not observed up to 12×10^{20}
E	Brush UOX (pre-ground)	Cold pressed at 20 tsi and sintered for one hour at 1450° C	95–97	2–3μ	1.4×10^{21}	Not observed up to 12×10^{20}
F	Brush UOX	Cold pressed at 20 tsi and sintered for one hour at 1600° C	95–96	15–20μ	5×10^{20}	Not observed up to 12×10^{20}
G	Brush UOX	Cold pressed at 20 tsi and sintered for one hour at 1200° C	72–75	1μ	Not investigated	Not observed up to 4.5 to 6.5×10^{20}
H	Brush UOX	Hot pressed at 1500° C for ½-hour at 1 tsi	94–97	3–5μ	Not observed up to 3×10^{20}	Not investigated
J	Brush UOX	Hot pressed at 1700° C for ½-hour at 1 tsi	97–98	10–12μ	3×10^{20}	Not investigated

Reference 7	The Effect on Neutron Irradiation on Beryllium Oxide
	B. S. Hickman and A. W. Pryor
	J. Nucl. Mater. 14 (1964) 96-110

A-12

Material	BeO(pc), MgO(sc), Al_2O_3(sc)	Property	Swelling	1/1

Irradiation Condition	$< 5 \times 10^{20}$ n/cm^2 (E > 1MeV) DIDO, PLUTO, BR2 < 150°C, 1000°C



Growth in beryllia, magnesia, and alumina on irradiation at about 150° C, as a function of dose.

Reference 8	Irradiation-Induced Growth in Oxides of Beryllium, Magnesium and Aluminium
	J. A. Desport and J. A. G. Smith
	J. Nucl. Mater. 14 (1964) 135-140

A-13

Material	BeO(pc), MgO(sc), Al_2O_3(sc)	Property	Swelling	1/1

Irradiation Condition	< 5 x 10^{20}n/cm^2 (E > 1MeV) DIDO, PLUTO, BR2 < 150°C, 1000°C

Growth of specimens irradiated at $< 150°$ C to a dose of approximately 3.5 to 4×10^{19} nvt > 1 MeV i.e. for 4 weeks. All beryllia specimens were of hot-pressed hydroxide-derived material.

Material	Density	Grain Size	Number of Specimens	Fractional Growth
BeO	> 2.98	40–45μ	4	$60 \times 10^{-5} \pm 5$
BeO	~ 2.92	15–20μ	5	$50 \times 10^{-5}\,{}^{+10}_{-6}$
BeO	~ 2.87	10–15μ	4	$50 \times 10^{-5}\,{}^{+8}_{-5}$
MgO	Single	crystal	2	$91 \times 10^{-5} \pm 4$
Al_2O_3	Single	crystal	5	$72 \times 10^{-5} \pm 7$

Growth of specimens irradiated at $< 150°$ C to a dose of approximately 1.1×10^{20} nvt > 1 MeV i.e. for 12 weeks. Of 20 beryllia specimens, only 7 survived irradiation and de-canning processes without breakage, but no powdering occurred. The first three sets of beryllia specimens were of hot-pressed hydroxide-derived material, the fourth of cold-pressed and sintered UOX material.

Material	Density	Grain Size	Number of Specimens	Fractional Growth
BeO	> 2.98	40–45μ	3	$720 \times 10^{-5} \pm 30$
BeO	~ 2.92	15–20μ	All broken	Not measured
BeO	~ 2.87	10–15μ	2	$450 \times 10^{-5} \pm 40$
BeO	~ 2.96	20–25μ	2	$430 \times 10^{-5} \pm 60$
MgO	Single	crystal	5	$295 \times 10^{-5} \pm 20$
Al_2O_3	Single	crystal	4	$287 \times 10^{-5} \pm 6$

Growth of magnesia and alumina single crystal specimens irradiated to a dose of approximately 4×10^{20} nvt > 1 MeV i.e. for 40 weeks. All beryllia specimens were of hot-pressed hydroxide-derived material of the same densities and grain sizes as in table 1 and were reduced to powder by this dose.

Material	Number of Specimens	Fractional Growth
MgO	2	$349 \times 10^{-5} \pm 1$
Al_2O_3	4	$406 \times 10^{-5} \pm 8$

Reference 8	Irradiation-Induced Growth in Oxides of Beryllium, Magnesium and Aluminium
	J. A. Desport and J. A. G. Smith
	J. Nucl. Mater. 14 (1964) 135-140

A-14

Material	BeO(pc), MgO(sc), Al_2O_3(sc)	Property	Swelling	1/1

Irradiation Condition	< 5 x 10^{20}n/cm^2(E > 1MeV) DIDO, PLUTO, BR2 < 150°C, 1000°C

Growth of beryllia specimens irradiated in BR2 (Mol) to doses of 3×10^{20} (first two sets) and 6×10^{20} nvt > 1 MeV (third set) in the space of 12 weeks. The higher density material became very fragile at the lower dose and disintegrated completely at the higher dose. All specimens were of cold-pressed and sintered UOX material.

Material	Density	Grain Size	Number of Specimens	Fractional Growth
BeO	~ 2.8	~ 2μ	5	$800\times10^{-5}\pm200$
BeO	> 2.95	~ 25μ	2	$1100\times10^{-5}\pm110$
BeO	~ 2.8	~ 2μ	5	$1870\times10^{-5}{}^{+240}_{-150}$

Growth of specimens irradiated at approximately 1000° C to a dose of about 4×10^{20} nvt > 1 MeV i.e. for 40 weeks. The beryllia specimens were of hot-pressed hydroxide-derived material.

Material	Density	Grain Size	Number of Specimens	Fractional Growth
BeO	> 2.98	40–45μ	5	$680\times10^{-5}\pm140$
MgO	Single	crystal	3	$3\times10^{-5}\pm2$
Al_2O_3	Single	crystal	3	$50\times10^{-5}\pm20$

Reference 8	Irradiation-Induced Growth in Oxides of Beryllium, Magnsium and Aluminium
	J. A. Desport and J. A. G. Smith
	J. Nucl. Mater. 14 (1964) 135-140

A-15

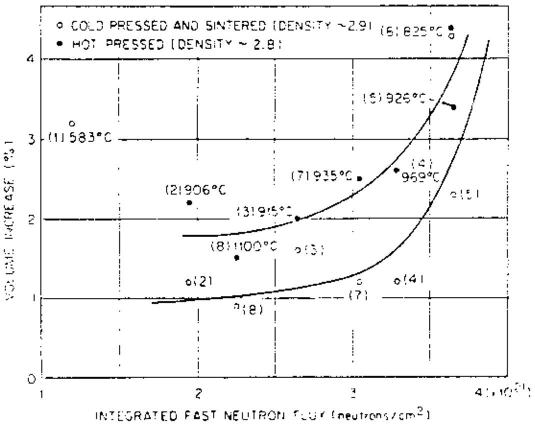
Material	BeO (hot-pressed, sintered)	Property	Swelling	1/1

Irradiation Condition	$1.2 \sim 3.65 \times 10^{21}$ n/cm^2 583 ∿ 1100°C

Summary of gross dimensional changes of BeO specimens

Capsule no. and BeO type †	Integrated flux (nvt)	Temperature (°C)	Diameter increase (%)	Length increase (%)	Gross anisotropic ratio (dia. increase/ length increase)	Volume increase (%)
	($\times 10^{21}$)					
1 CP	1.20	583	1.00	1.00	1.00	3.00
2 HP	1.95	906	0.68	0.80	0.85	2.16
CP			0.53	0.17	3.12	2.23
3 CP	2.65	915	0.61	0.34	1.79	1.56
4 HP	3.28	969	0.95	0.64	1.49	2.54
CP			0.51	0.25	2.04	1.27
5 HP	3.65	926	1.15	1.08	1.07	3.38
CP			0.90	0.51	1.77	2.31
6 HP	3.63	825	1.44	1.49	0.97	4.37
CP			1.62	0.98	1.66	4.22
7 HP	3.05	935	0.79	0.88	0.90	2.46
CP			0.57	0.20	2.86	1.34
8 HP	2.25	1100	0.64	0.20	3.20	1.48
CP			0.39	0.08	4.87	0.86

† HP = hot pressed; CP = cold pressed and sintered.



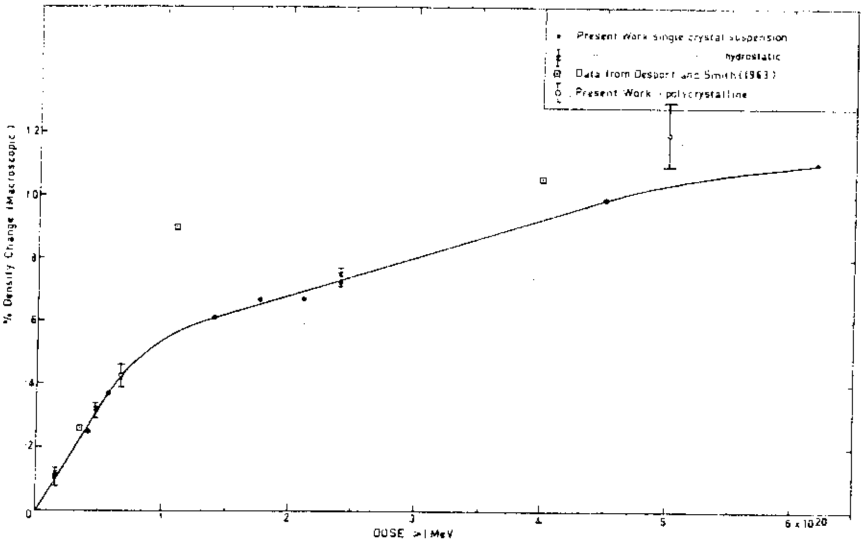
Percent volume increase of BeO specimens versus integrated fast-neutron flux in experiment 41–7.

Reference 12	The Effect of Fast-Neutron Irradiation on Beryllium Oxide Compacts at High Temperatures
	G. W. Keliholtz, J. E. Lee, Jr. and R. E. Moore
	J. Nucl. Mater. 11 (1964) 253

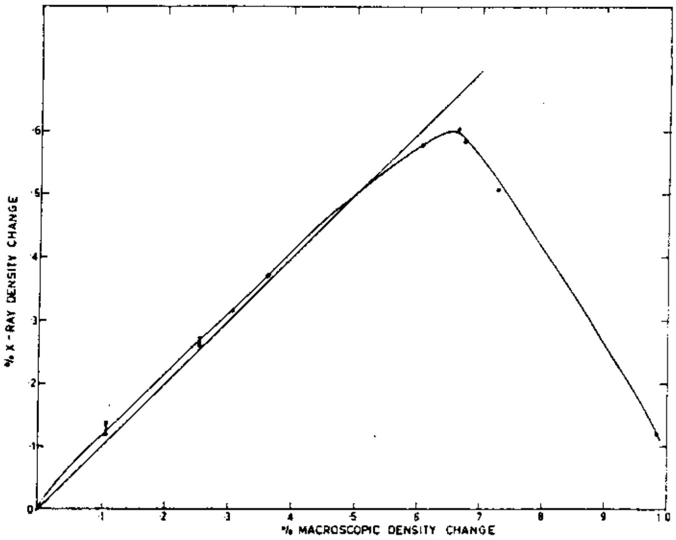
A-16

Material	MgO (sc, pc)	Property	Swelling	1/1

Irradiation Condition	$1.4 \times 10^{19} \sim 6.5 \times 10^{20}$ n/cm^2 (E > 1 MeV) HIFAR 75 ∼ 100°C



Variation in macroscopic density with dose. The results of Desport and Smith (1963) are included for comparison.

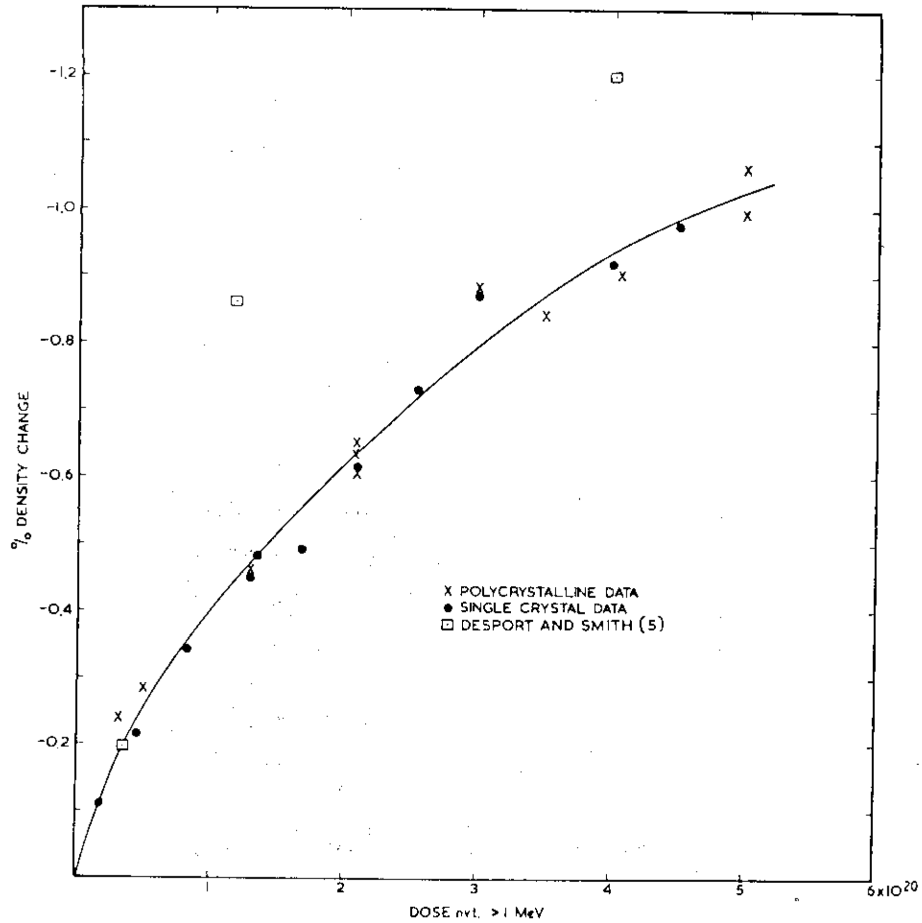


Comparison of the x-ray volume change and macroscopic density change.

Reference 13	Growth of Magnesium Oxide during Neutron Irradiation
	B. S. Hickman and D. G. Walker
	Phil. Mag. 11 (1965) 1101

A-17

Material	Al_2O_3 (sc, pc)	Property	Swelling	1/1
Irradiation Condition	< 5×10^{20} n/cm^2 (E > 1 MeV) HIFAR 75 ∿ 100°C, 500 ∿ 700°C			



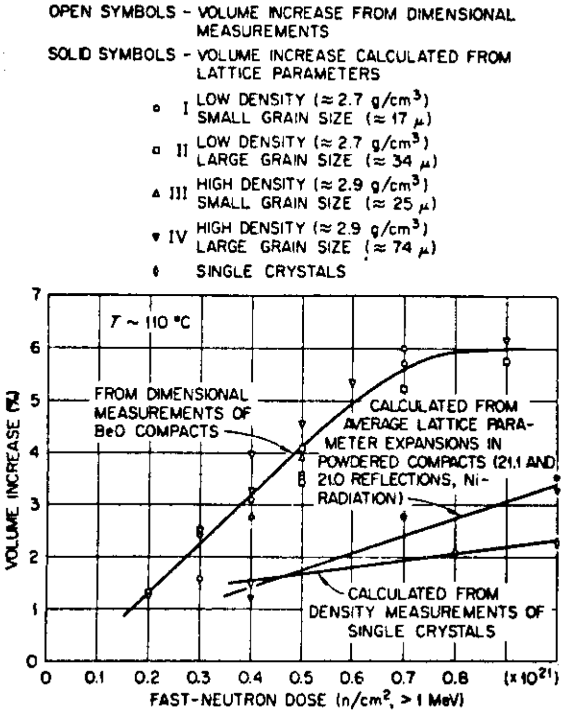
Macroscopic density changes in aluminium oxide after neutron irradiation at 75–100° C.

Reference 15	The Effect of Neutron Irradiation on Aluninium Oxide
	B. S. Hickman and D. G. Walker
	J. Nucl. Mater. 18 (1966) 197

A-18

Material	BeO (sintered)	Property	swelling	1/2

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

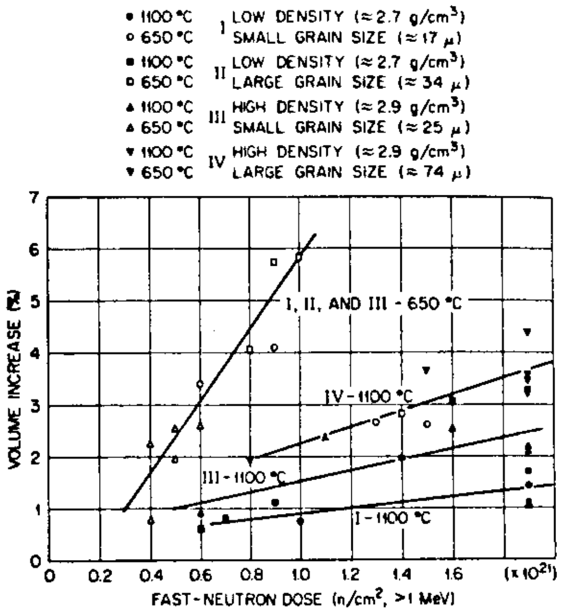


Volume increase of ½-in. BeO compacts and single crystals irradiated at 110°C vs fast-neutron dose.

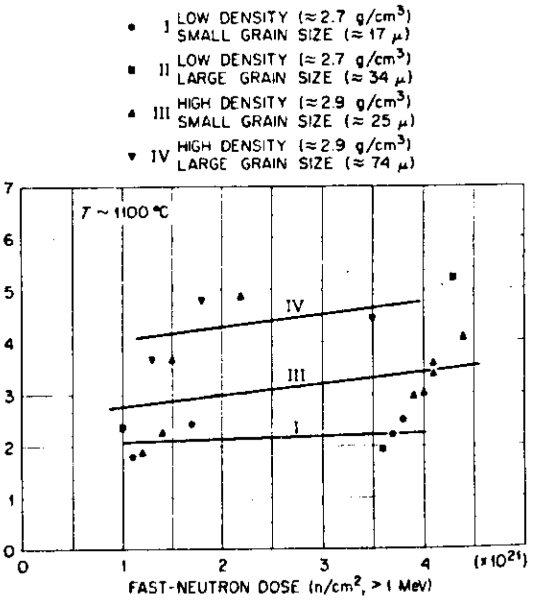
Reference 16	Irradiation Damage to Sintered Beryllium Oxide as a Function of Fast-Neutron Dose and Flux at 110, 650, and 1100°C
	G. W. Keilheltz, J. E. Lee, Jr. and R. E. Moore
	Nucl. Sci. and Eng. 26 (1966) 329

A-19

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



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



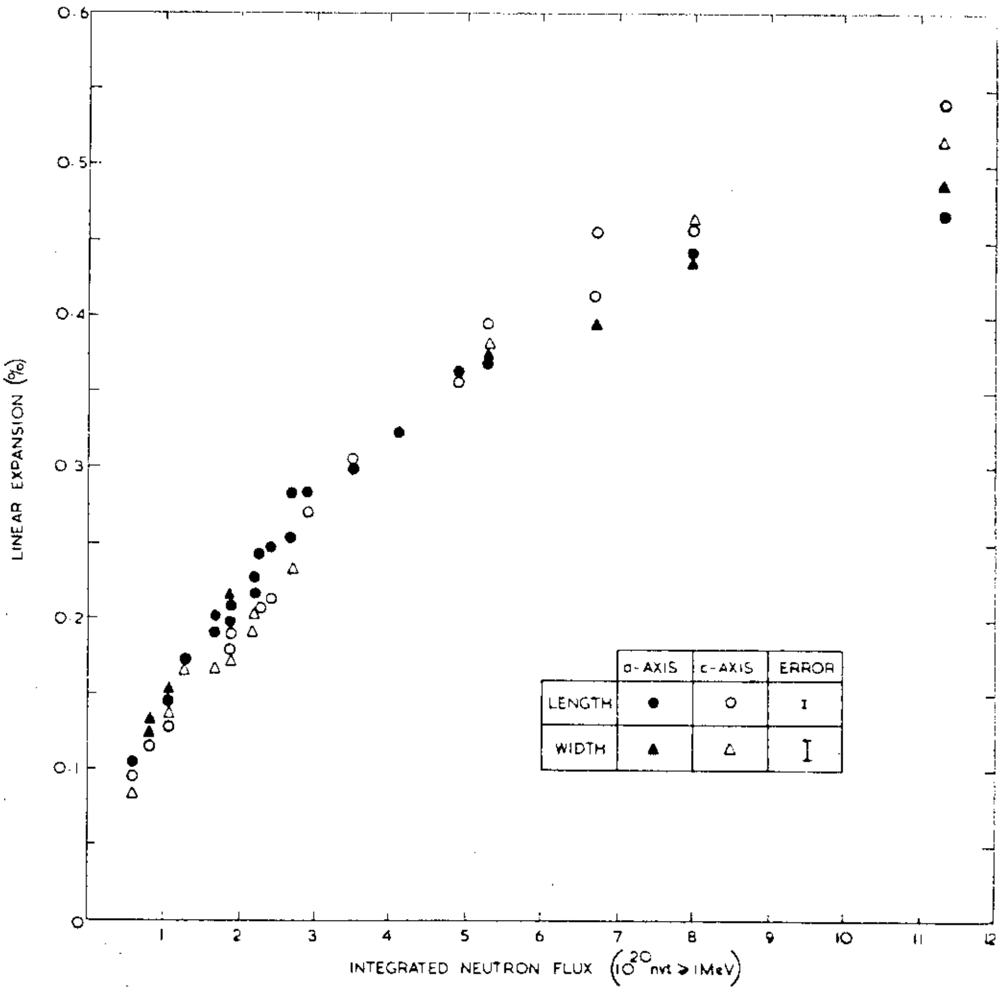
Volume increase of 1/2-in. BeO specimens irradiated at 1100°C in long-term experiment 41-8 (1.59 × 10^7 sec) vs fast-neutron dose.

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

A-20

Material	α-Al_2O_3(sc)	Property	Swelling	1/1

Irradiation Condition	$10^{18} \sim 1.1 \times 10^{21}$ n/cm^2 (E > 1 MeV) 150°C, 650°C



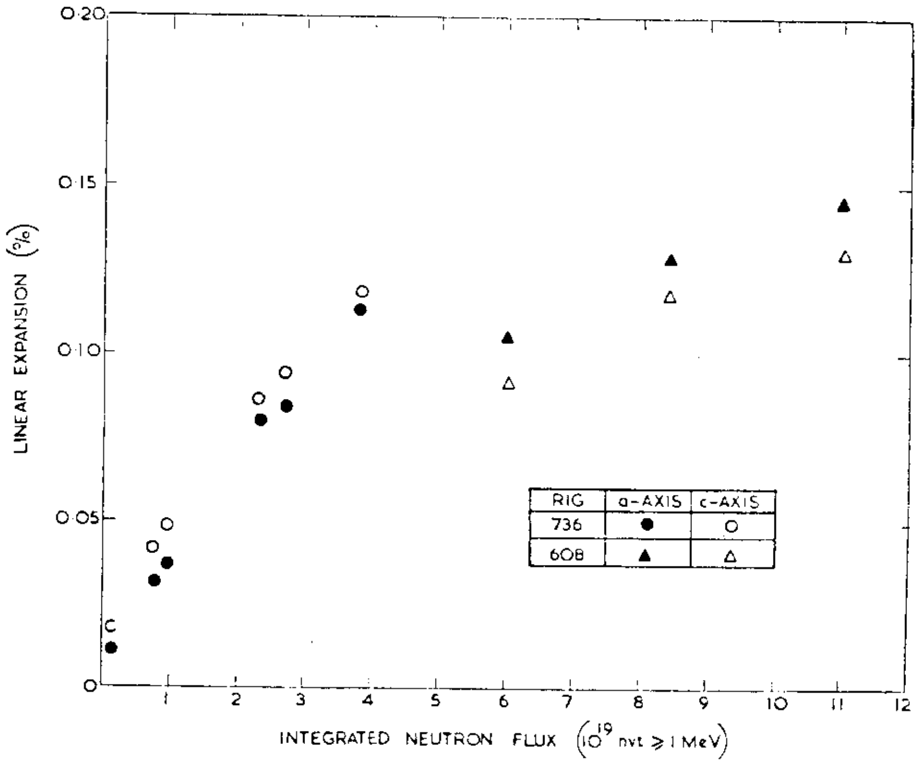
Macroscopic growth as a function of neutron dose at 150 C (608 rig).

Reference 17	The Irradiation-Induced Macroscopic Growth of α-Al_2O_3 Single Crystals
	R. S. Wilks, J. A. Dosport and J. A. G. Smith
	J. Nucl. Mater. 24 (1967) 80

A-21

Material	α-Al_2O_3(sc)	Property	Swelling	1/1

Irradiation Condition	$10^{18} \sim 1.1 \times 10^{21}$ n/cm^2 (E > 1 MeV) 150°C, 650°C



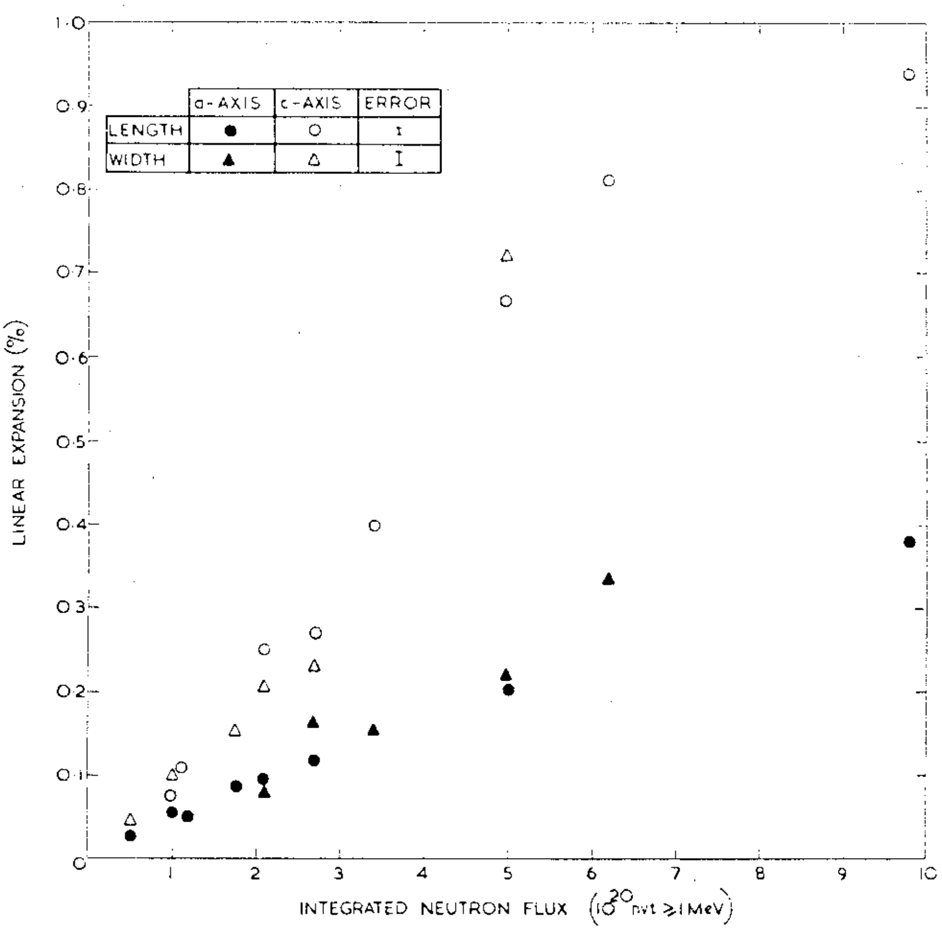
Macroscopic growth as a function of neutron dose at 150°C (736 rig).

Reference 17	The Irradiation-Induced Macroscopic Growth of α-Al_2O_3 Single Crystals
	R. S. Wilks, J. A. Desport and J. A. G. Smith
	J. Nucl. Mater. 24 (1967) 80

A-22

Material	α-Al_2O_3 (sc)	Property	Swelling	1/1

Irradiation Condition	$10^{18} \sim 1.1 \times 10^{21}$ n/cm^2 (E > 1 MeV) 150°C, 650°C



Macroscopic growth as a function of neutron dose at 650 C.

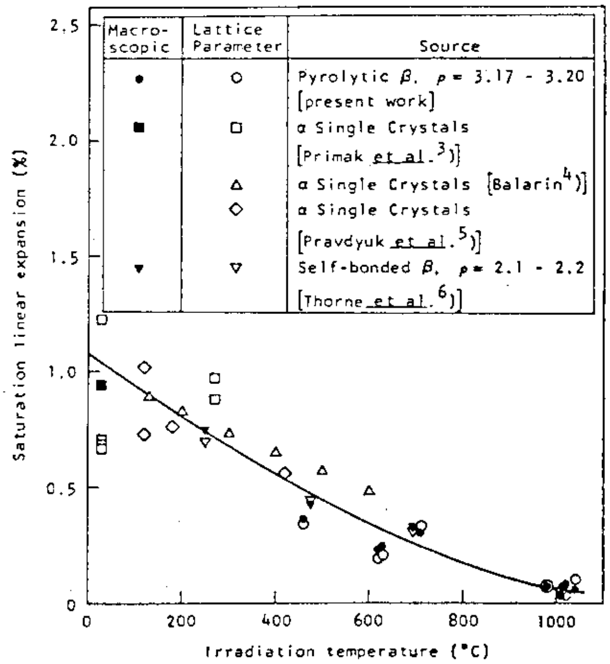
Reference 17	The Irradiation-Induced Macroscopic Growth of α-Al_2O_3 Single Crystals
	R. S. Wilks, J. A. Desport and J. A. G. Smith
	J. Nucl. Mater. 24 (1967) 80

A-23

Material	3-SiC (pyrolytic)	Property	Swelling Lattice parameter	1/1
Irradiation Condition	$2.0 \sim 4.2 \times 10^{21}$ n/cm^2 (E > 0.18 MeV) ETR 460°C, 1040°C			

Change in linear dimensions, lattice parameter and X-ray line-broadening of silicon carbide during irradiation

Irradiation conditions				Mean expansion, % (± S.D.)		Increase in RMS internal strain ($\times 10^4$)
Capsule no.	Cell no.	Neutron exposure (n/cm^2) (E>0.18 MeV)	Mean temperature (°C)	Linear dimensions	Lattice parameter	
P-13-F	1	2.8×10^{21}	630	0.24 ± 0.02	0.20 ± 0.02	5.0
	2	2.8×10^{21}	1020	0.08 ± 0.04	0.03 ± 0.02	4.0
	3	2.7×10^{21}	1010	0.06 ± 0.04	0.05 ± 0.02	3.0
P-13-H	1	3.8×10^{21}	700	0.30 ± 0.02	0.33 ± 0.02	3.5
	3	4.2×10^{21}	980	0.07 ± 0.05	0.07 ± 0.01	3.5
P-13-J	3	3.8×10^{21}	1040	0.06 ± 0.03	0.10 ± 0.04	7.0
	5	2.7×10^{21}	460	0.36 ± 0.03	0.34 ± 0.04	3.5
P-13-K	1	2.7×10^{21}	620	0.23 ± 0.03	0.19 ± 0.03	5.0
	5	2.0×10^{21}	1010	0.03 ± 0.04	0.05 ± 0.02	3.0



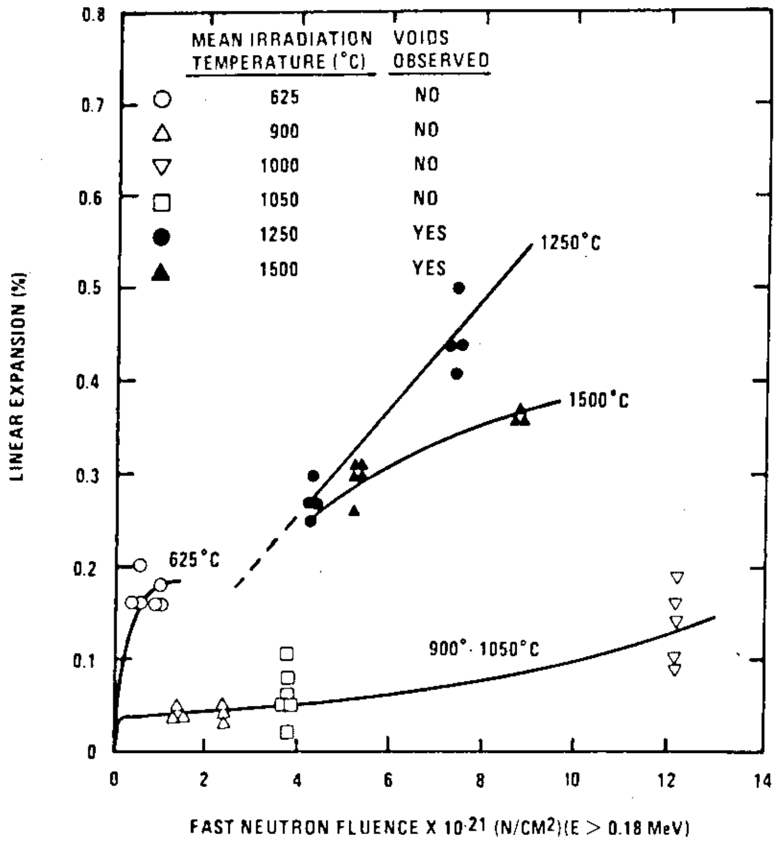
Saturation radiation-induced expansion of silicon carbide as a function of irradiation temperature (neutron exposures > 10^{20} nvt).

Reference 18	Effects of Fast-Neutron Irradiation on Pyrolitic Silicon Carbide
	R. J. Price
	J. Nucl. Mater. 33 (1969) 17

A-24

Material	β-SiC	Property	Swelling	1/1

Irradiation Condition	1.2×10^{22} n/cm^2 (E > 0.18 MeV) ETR (Idaho) 626°C, 1500°C



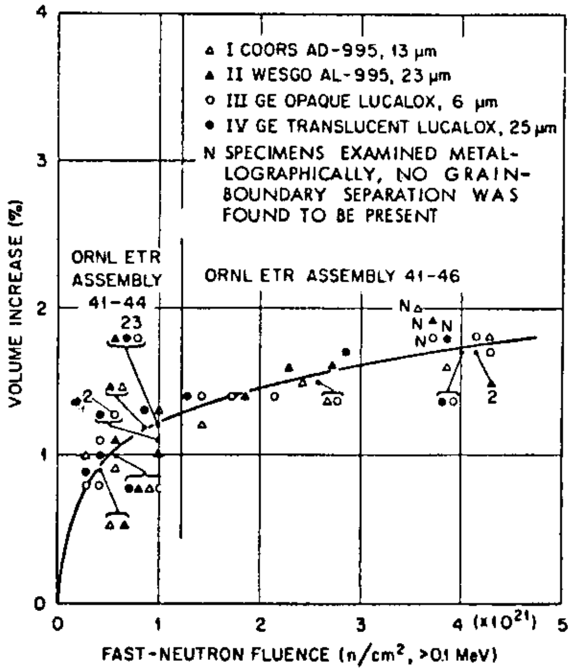
Expansion of β-silicon carbide as a function of fast neutron fluence at 625°C to 1500°C.

Reference 20	Neutron Irradiation-induced Voids in β-Silicon Carbide
	P. J. Price
	J. Nucl. Mater. 48 (1973) 47

A-25

Material	Al_2O_3 (pc)	Property	Swelling	1/1

Irradiation Condition	4.4×10^{21} n/cm^2 (E > 0.1 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[b] (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	0.03	0.007	0.01	Ni, 0.01
IV, GE translucent Lucalox	General Electric Co.	3.98	25	0.14	0.08	0.02	0.003	

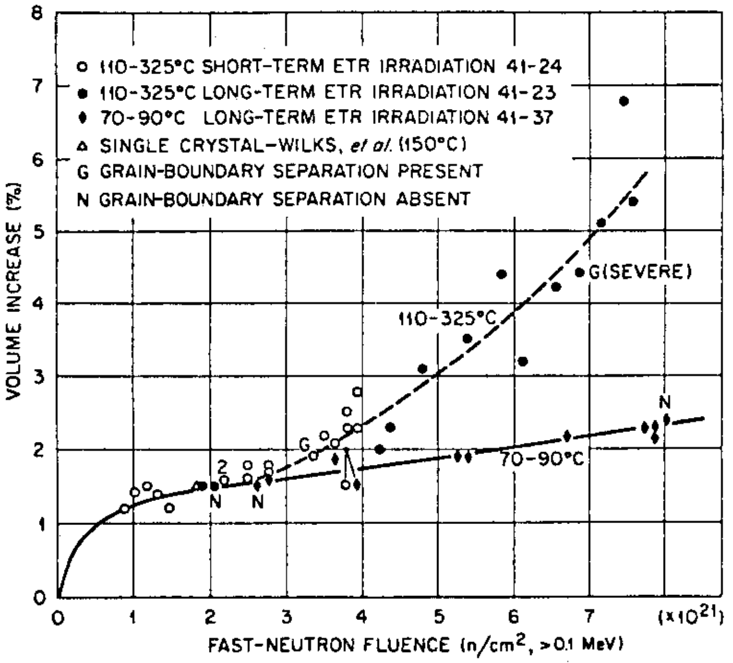
[a] All specimens of the same type used in the irradiation program were of the same batch.

[b] Summary of spectrographic analyses performed by C. Feldman and Anna M. Yoakum, Oak Ridge National Laboratory, Analytical Chemistry Division.

Reference 21	
	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

A-26

Material	Al_2O_3 (pc)	Property	Swelling	1/1
Irradiation Condition	8×10^{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.	3.86	13	0.42	0.1	0.06	0.06	Cu, 0.08 Cr, 0.1
II, Wesgo AL-995	Western Gold and Platinum Co.	3.85	33	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.	3.98	25	0.14	0.08	0.02	0.003	

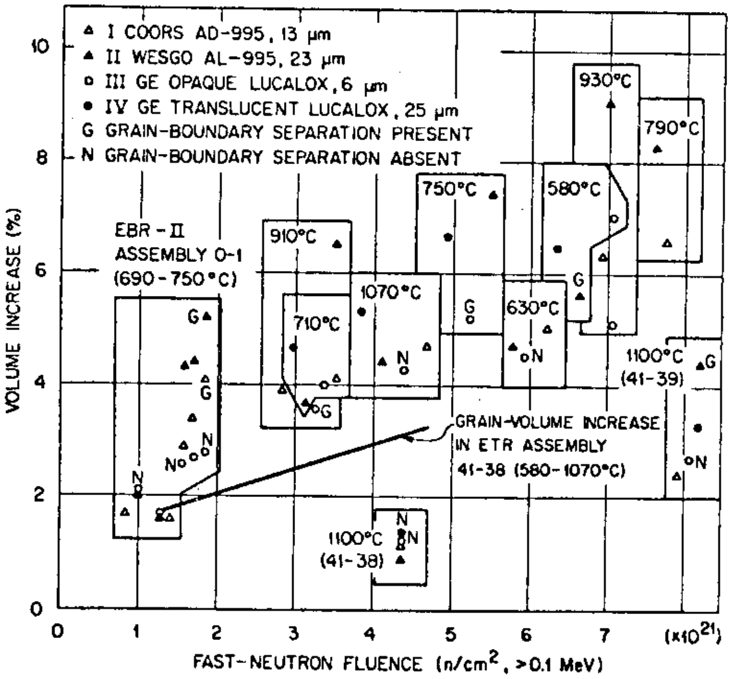
[a] All specimens of the same type used in the irradiation program were of the same batch.
[b] Summary of spectrographic analyses performed by C. Feldman and Anna M. Yoakum, Oak Ridge National Laboratory, Analytical Chemistry Division.

Reference 21	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

A-27

Material	Al_2O_3 (pc)	Property	Swelling	1/1

Irradiation Condition	8.2×10^{21} n/cm^2 (E > 0.1 MeV) EBR-II , ETR 690 ∿ 1100°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.	3.86	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.	3.98	25	0.14	0.08	0.02	0.003	

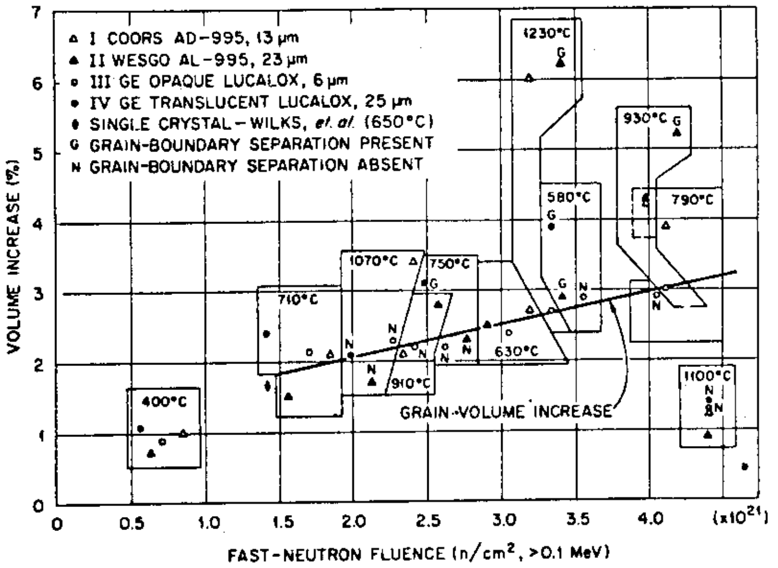
[a] All specimens of the same type used in the irradiation program were of the same batch.

[b] Summary of spectrographic analyses performed by C. Feldman and Anna M. Yoakum, Oak Ridge National Laboratory, Analytical Chemistry Division.

Reference 21	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

A-28

Material	Al_2O_3 (pc)	Property	Swelling	4/4
Irradiation Condition	4.2×10^{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[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.	3.86	13	0.42	0.1	0.06	0.06	Cu, 0.06 Cr, 0.1
II, Wesgo AL-995	Western Gold and Platinum Co.	3.85	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	

[a] All specimens of the same type used in the irradiation program were of the same batch.

[b] Summary of spectrographic analyses performed by C. Feldman and Anna M. Yoakum, Oak Ridge National Laboratory, Analytical Chemistry Division.

Reference 21	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

A-29

Material	Al_2O_3, Y_2O_3 Y_2O_3 - 10 % ZrO_2	Property	Swelling	1/1
Irradiation Condition	2 ∿ 6 x 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, ΔV/V, %
Al_2O_3 (Sapphire)	650	5.6 x 10^{21}	2.2
	875	4.3 x 10^{21}	2.0
	1025	4.4 x 10^{21}	2.1
Al_2O_3 (Lucalox)	650	4.1 x 10^{21}	1.5
	875	3.7 x 10^{21}	2.3
	1025	3.2 x 10^{21}	1.4
Al_2O_3 (AD-999x)	650	4.8 x 10^{21}	1.7
	875	4.0 x 10^{21}	2.1
	1025	4.1 x 10^{21}	2.4
Y_2O_3	650 (Moly. Corp.)	6.0 x 10^{21}	0.2
	875 (Moly. Corp.)	5.1 x 10^{21}	(-0.1)[a]
	1025 (Lindsey)	5.4 x 10^{21}	-0.3
Y_2O_3 - 10% ZrO_2 (Yttralox)	875	3.3 x 10^{21}	(0.0)[a]
	1025	3.9 x 10^{21}	(0.1)[a]

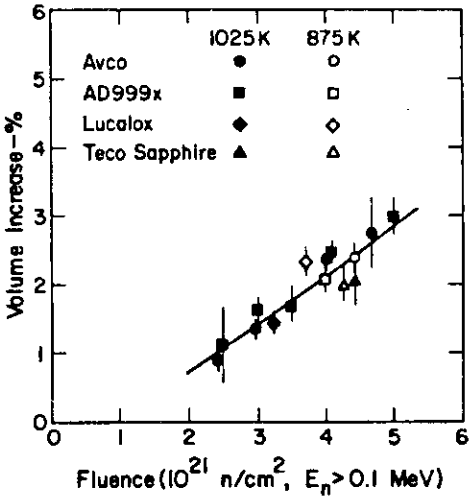
[a] Below level of significance.

Reference 23	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

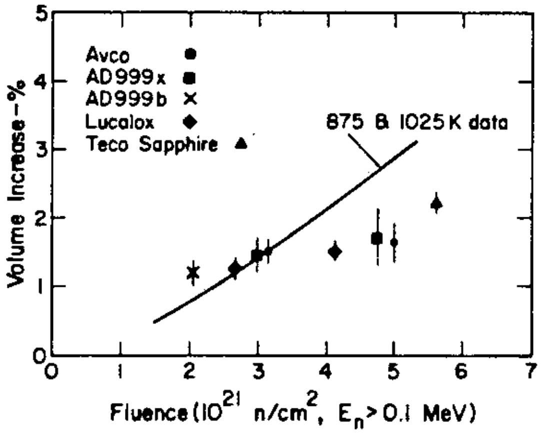
A-30

Material	Al_2O_3 (sc,pc)	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



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



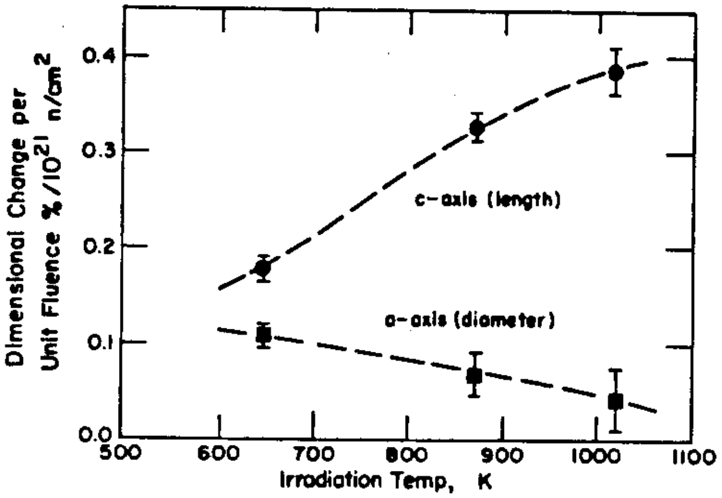
Volumetric Swelling of Al_2O_3 as a Function of Neutron Fluence at 650K. Data from Fig. 1 are Shown for Comparison.

Reference 23	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

A-31

Material	Al_2O_3 (sc)	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



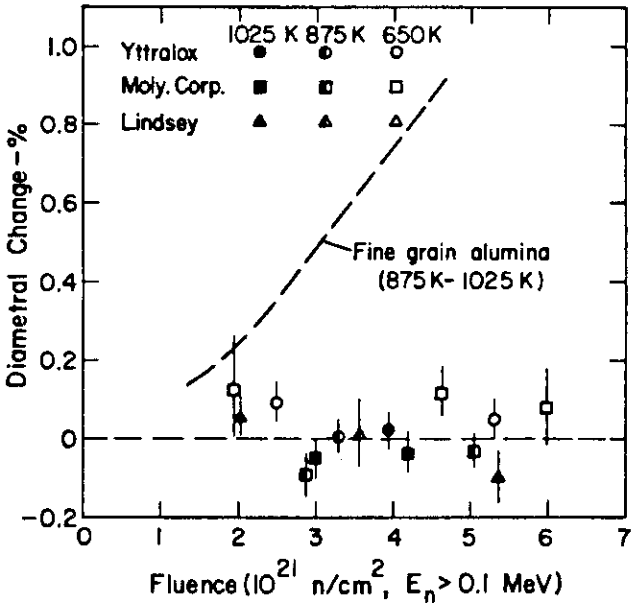
Dimensional Change per Unit Fluence versus Irradiation Temperature for Sapphire Irradiated to Neutron Fluences from 4.3 to 5.6×10^{21} n/cm^2 (E_n > 0.1 MeV).

Reference 23	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

A-32

Material	Y_2O_3 Y_2O_3 - 10 % ZrO_2	Property	Swelling	1/1

Irradiation Condition	2 ∿ 6 x 10^{21} n/cm^2 (E > 0.1 MeV) EBR-II 377°C, 602°C, 752°C



Diametral Change of Y_2O_3 Made from Moly. Corp. and Lindsey Powders and Y_2O_3-10% ZrO_2 (Yttralox) versus Neutron Fluence. Data from Fig. 1 are Shown for Comparison.

Reference 23	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

A-33

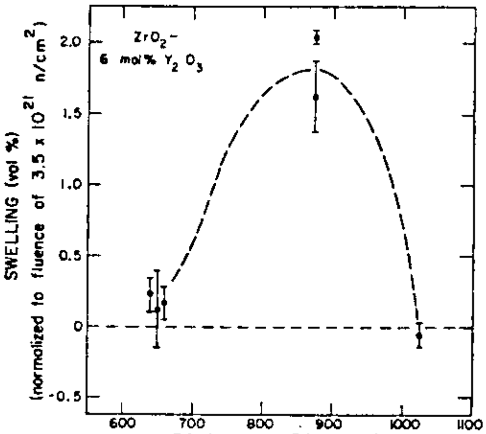
Material	ZrO_2 (stabilized)	Property	Swelling	1/1

Irradiation Condition	∿ 4.4×10^{21} n/cm^2 (E > 0.1 MeV) EBR-II 377°C, 602°C, 752°C

Irradiation Conditions and Swelling Values for Stabilized ZrO_2 Samples

Sample No.	Irradiation temp. (°K)	Fluence ($\times 10^{-21}$ 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. †$E_n > 0.1$ MeV.



Swelling of stabilized ZrO_2 after irradiation.

Reference 28	Neutron-Irradiation Damage in Stabilized ZrO_2 F. W. Clinard, Jr., D. L. Rohr and W. A. Ranken J. Am. Ceram. Soc. 60 (1979) 287

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Material	Al_2O_3, $MgAl_2O_4$, $Y_3Al_5O_{12}$ Y_2O_3, BeO, Si_3N_4, Sialon	Property	Swelling, Thermal diffusivity	1/1

Irradiation Condition	2.8×10^{21} n/cm^2 (E > 0.1 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 $(\bar{1}012)$	"	"
Al_2O_3 (Ad 995)	Polycrystal	1.9	53
$MgAl_2O_4$	Single crystal	0.1†	8
Spinel	Polycrystal	0.3	45
$Y_3Al_5O_{12}$	Single crystal	0.0	62
$Y_3Al_5O_{12}$	Polycrystal	0.2	54
Y_2O_3	Polycrystal	0.1†	24
Y_2O_3-$1ZrO_2$	Polycrystal	0.3	33
BeO-5SiC	Polycrystal	3.3	60‡
Niberlox	Polycrystal	"	"

*2.8×10^{21} n/cm^2 (E_n > 0.1 MeV) at 1015 K (740°C). †Below level of significance. ‡Estimated 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†	0.3	53
Sialon	0.5	31

*2.8×10^{21} n/cm^2 (E_n > 0.1 MeV) at 1015 K (740°C). †Approximate density 3.1.

Description of Materials Irradiated

Material	Description	Major impurities (ppm*)
Al_2O_3	Single crystal $(\bar{1}012)$†	60 Fe, 50 Nb, 40 Mo
Al_2O_3	Single crystal (0001)‡	80 Fe, 15 Ni, 100 Nb
Al_2O_3 (Ad-995)	Polycrystal§	2000 Mg, 2000 Si, 1000 Ca
$MgAl_2O_4$	Single crystal (111)‡	100 Si, 20 Fe, 1–10 Ca
$MgAl_2O_4$	Polycrystal‖	400 Si, 100 Ca, 80 Na
$Y_3Al_5O_{12}$	Single crystal (111)‡	10 Si, 10 Fe, 1–10 Ca
$Y_3Al_5O_{12}$	Polycrystal‖	2–6000 Si, 300 Ca, 300 Mg
Si_3N_4 (NC-132)	Polycrystal**	5300 WC, 6000 Mg, 2500 Fe, Al
Si_3N_4	Polycrystal††	2% Mg, 2000 Al, 1800 C
Sialon	$(2Si_3N_4:Al_2O_3:AlN)+5$ wt% Y_2O_3‡‡	400 Fe, 300 Mg, 200 Ca
Si_2ON_2	Porous polycrystal**	5000 Ca, 2000 Al, 2000 Fe
Y_2O_3	Polycrystal††	<500 Zr
Y_2O_3-$1ZrO_2$	Polycrystal††	9000 Zr, 80 Al, 50 Si
BeO-5SiC	Polycrystal-dispersed SiC††	5.1% SiC, 5000 Al, 400 B
Niberlox	BeO polycrystal-dispersed second phase§§	2.39% Al, 2.9% Si, 1000 Mg

*Measured by LASL Analytical Chemistry Group. †Tyco Laboratories, Inc., N.H. ‡Linde Div., Union Carbide Corp., New York, N.Y. §Coors Porcelain Co., Golden, Colo. ‖Los Alamos Scientific Lab, Los Alamos, N.M. **Norton Co., Worcester, Mass. ††Ceradyne, Inc., Santa Ana, Calif. ‡‡J. M. Wimmer, Air Force Materials Lab, Wright-Patterson AFB, Ohio. §§ National Beryllia Corp., Haskell, N.J.

Reference 30	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	MACOR	Property	Density	1/1

Irradiation Condition	10^{16}, 10^{18} 14 MeV n/cm^2 RTNS-II room temperature

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 32	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. 103 & 104 (1981) 755

A-36

Material	MgO, $MgAl_2O_4$	Property	Swelling, Mechanical properties	1/1

Irradiation Condition	2.1×10^{22} n/cm^2 (E > 0.2 MeV) 4.6×10^{22} n/cm^2 (thermal) HFIR 157°C

Strength of MgO and $MgAl_2O_4$ by Diametral Compression Tests.

Samples Irradiated to 2.1×10^{26} n/m^2 $E_n > 0.2$ 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)
$MgAl_2O_4$	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
$MgAl_2O_4$-1	American Lava	94	.01Fe, .01Ca, .04Si	10 μm

Material	Vol. Swelling,%
MgO-1	2.6
MgO-2	3.0
$MgAl_2O_4$	0.8

Reference 33	Structural Properties of MgO and $MgAl_2O_4$ 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

				A-37
Material	SiO_2 SiO_2-based Glass Ceramic	Property	Swelling, Hardness	1/1
Irradiation Condition	~ 2.7×10^{22} n/cm^2 (E > 0.1 MeV) EBR-II 400°C, 550°C			

Swelling and Hardness Results

Sample	T_{irr}(°C)	ϕt(10^{22} n/cm^2), E>0.1 MeV	$\Delta V/Vo$ (%)	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.

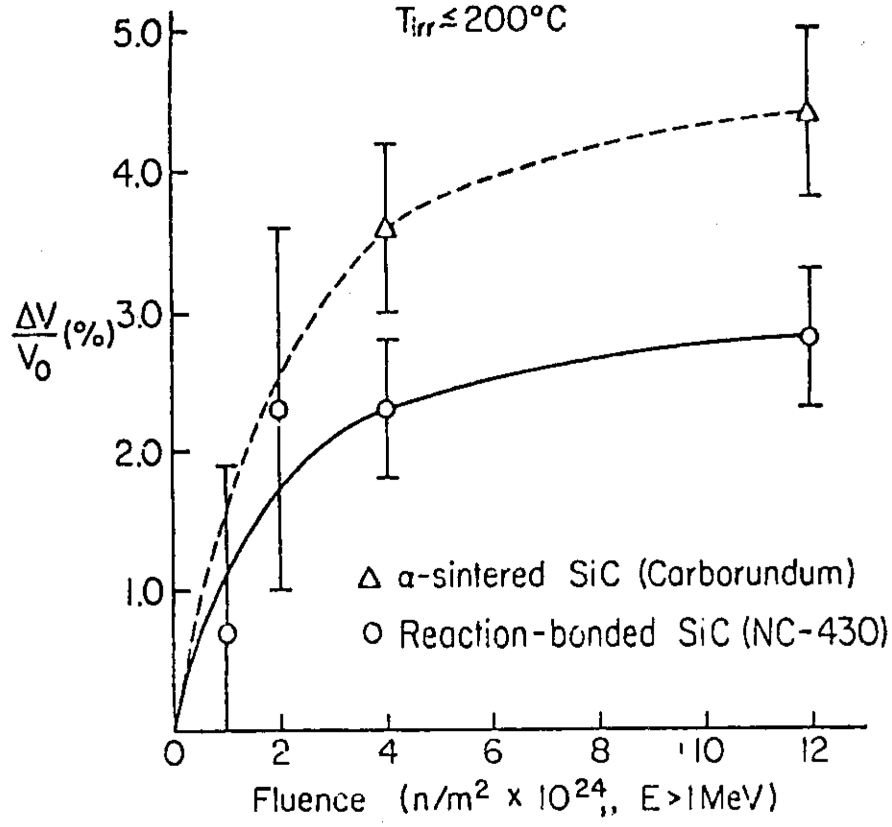
Ceramic Compositions, wt.%

Sample	SiO_2	Al_2O_3	MgO	As_2O_5	B_2O_3	ZrO_2	K_2O	MgF_2	Li_2O	P_2O_5	CoO	ZnO	BaO	Na_2O
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 34	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. 103 & 104 (1981) 767

				A-38
Material	α-SiC, SiC(NC-430)	Property	Swelling	1/1
Irradiation Condition	1.2×10^{21} n/cm^2 (E > 1 MeV) HFBR (BNL)			

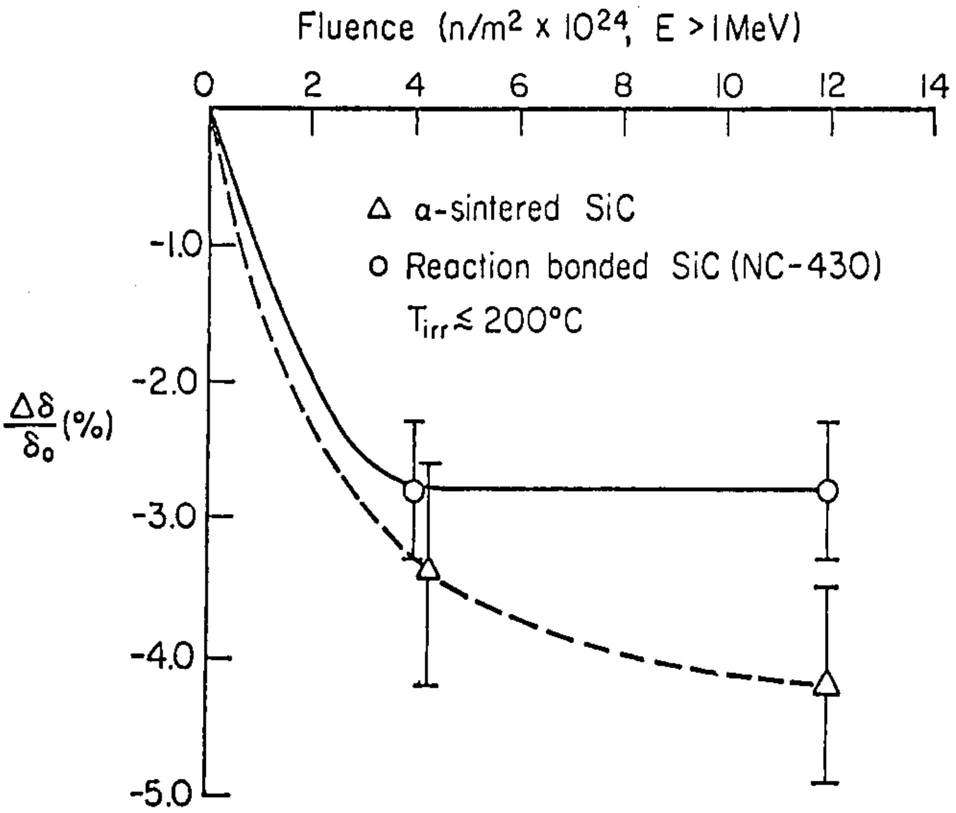


Swelling, $\frac{\Delta V}{V_0}$, vs Fluence for NC-430 SiC and Sintered α-SiC

Reference 36	Ceramic Materials for Fusion Reactors
	G. Hopkins, G. C. Trantina and J. Corelli
	AP-1702, EPRI Research Project 992, Interim Report, February 1981

A-39

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



Density changes $\frac{\Delta\delta}{\delta_o}$ vs fluence for NC-430 SiC and sintered α-SiC

Reference 36	Ceramic Materials for Fusion Reactors
	G. Hopkins, G. C. Trantina and J. Corelli
	AP-1702, EPRI Research Project 992, Interim Report, February 1981

A-40

Material	MgO, Al_2O_3, $MgAl_2O_4$	Property	Swelling	1/1

Irradiation Condition	2.3×10^{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 [a]	30	430	0.14	2.6
pc MgO (2)	2.1 [a]	30	430	0.14	3.0
sc Al_2O_3	0.03 [a]	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_2O_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 $MgAl_2O_4$	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 $MgAl_2O_4$ (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 $MgAl_2O_4$ (2)	2.1 [a]	30	430	0.18	0.8

[a] >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	8000 Al	3000 Fe		14, 28 [a]	0.75 [b]
pc MgO (2)	Honeywell, Inc.	3000 Ca	800 Fe	800 Si	300 Al		14, 28 [a]	0.79 [b]
sc Al_2O_3	Linde Division Union Carbide Corp.	60 Fe	50 Nb	40 Mo				
sc Al_2O_3	Tyco Laboratories, Inc.	100 Nb	80 Fe	15 Ni				
pc Al_2O_3	Coors Porcelain Co Ad 995	2000 Mg	2000 Si	1000 Ca			2	0.97
sc $MgAl_2O_4$	Linde Division Union Carbide	100 Si	20 Fe	8 B	5 Ca			
pc $MgAl_2O_4$ (1)	Reaction sintered	400 Si	100 Ca	80 Na	35 B	20 Fe	0.5	>0.99
pc $MgAl_2O_4$ (2)	American Lava Corp.	400 Si	100 Fe	100 Ca			10	0.94

[a] Bimodal grain size distribution.

[b] Density deliberately kept low for another study.

sc = single crystal, pc = polycrystal.

Reference 39	Neutron Irradaition Damage in MgO, Al_2O_3 and $MgAl_2O_4$ Ceramics
	F. W. Clinard, G. F. Hurley and L. W. Hobbs
	J. Nucl. Mater. 108 & 109 (1982) 655

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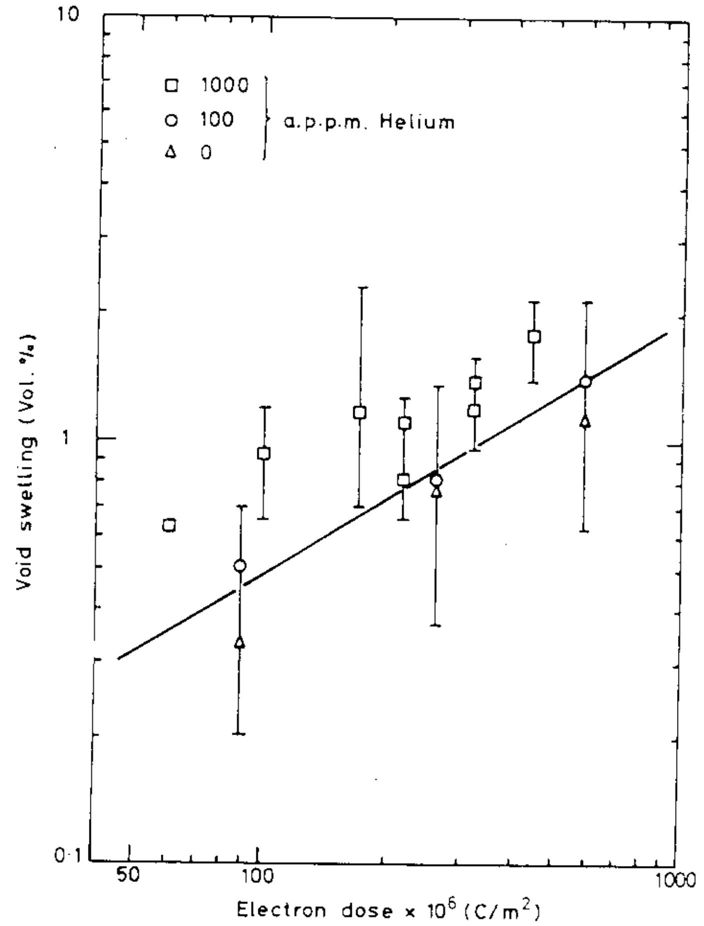
Material	α-Al_2O_3	Property	Swelling	1/1

Irradiation Condition	< 500 MC/m^2 1 MeV electron (HVEM) 607 ∿ 857°C



Volume fraction of voids as a function of 1 MV electron fluence for pure α-Al_2O_3 and for α-Al_2O_3 doped with 100 and 1000 a.p.p.m. helium. The solid line has a slope of 0·6.

Reference 41	Radiation Damage in Pure and Helium-Doped α-Al_2O_3 in the HVEM
	G. P. Pells and T. Shikama
	Phil. Mag. A48 (1983) 779-794

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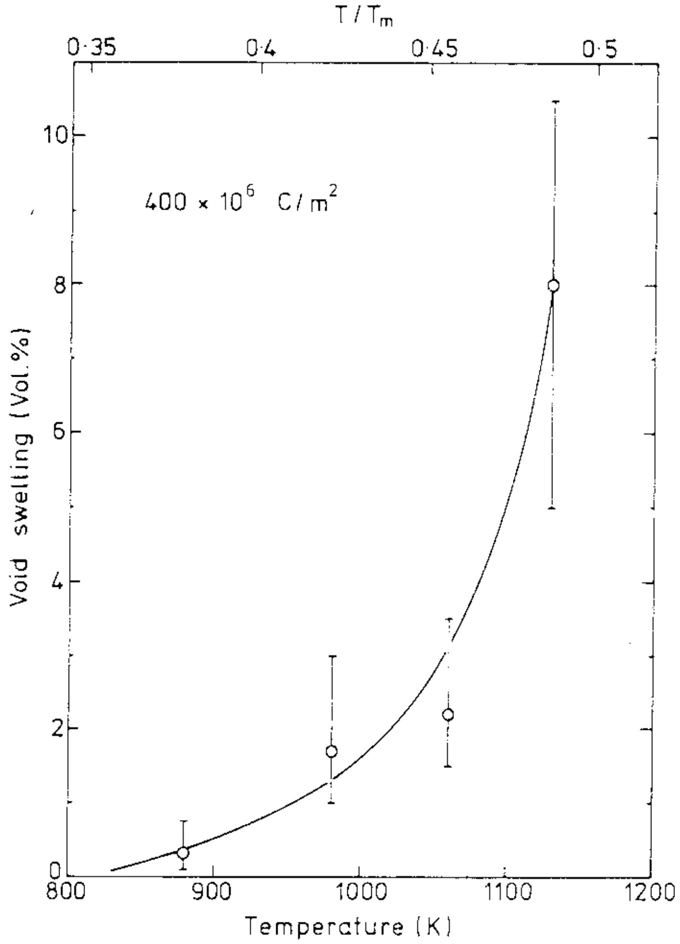
Material	α-Al_2O_3	Property	Swelling	1/1

Irradiation Condition	< 500 MC/m^2 1 MeV electron (HVEM) 607 ∿ 857°C



Void swelling of α-Al_2O_3 doped with 1000 a.p.p.m. helium as a function of temperature at a displacement dose of ~20 d.p.a.

Reference 46	Radiation Damage in Pure and Helium-Doped α-Al_2O_3 in the HVEM
	G. P. Pells and T. Shikama
	Phil. Mag. A48 (1983) 779-794

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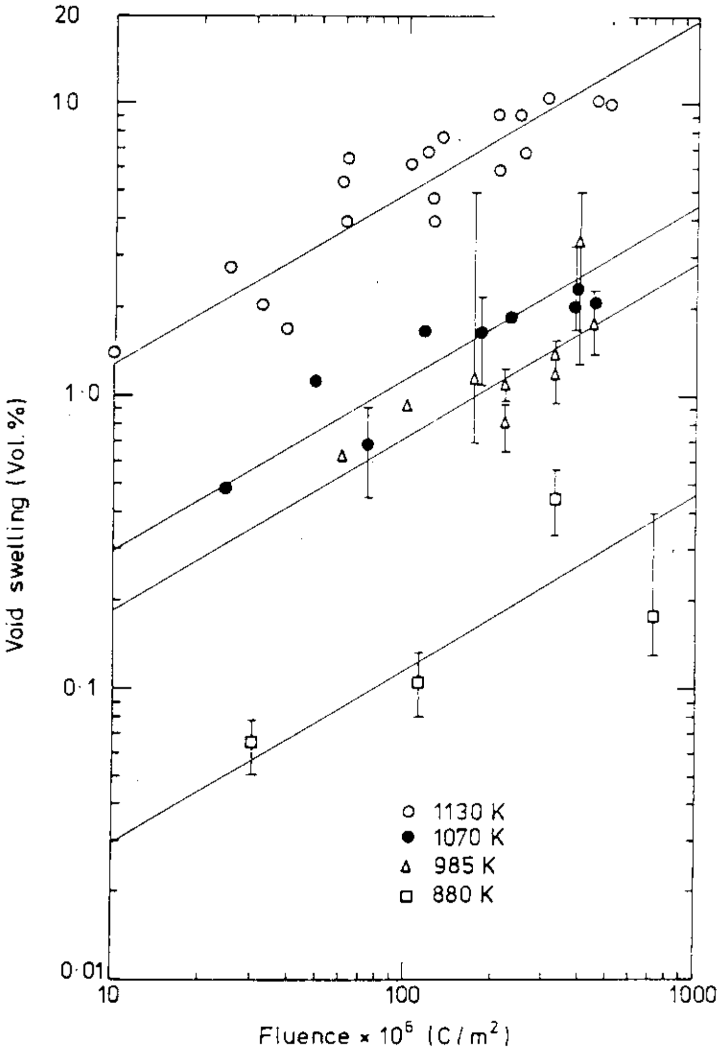
Material	α-Al_2O_3 (sc)	Property	Swelling	1/1
Irradiation Condition	< 500 MC/m^2 1 MeV electron (HVEM) 607 ∿ 857°C			



Volume fraction of voids in 1000 a.p.p.m. helium-doped α-Al_2O_3 as a function of 1 MV electron fluence. The solid lines are for a slope of 0·6.

Reference 46	Radiation Damage in Pure and Helium-Doped α-Al_2O_3 in the HVEM
	G. P. Pells and T. Shikama
	Phil. Mag. A48 (1983) 779-794

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Material	$MgAl_2O_4$, Al_2O_3, Si_3N_4	Property	Swelling, Strength	1/1
Irradiation Condition	$2.2 \pm 0.4 \times 10^{22}$ n/cm^2 (E > 0.1 MeV) EBR-II 407°C, 542°C			

Swelling and strength changes after irradiation to $2.2 \pm 0.4 \times 10^{26}$ n/m^2 (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, %
$MgAl_2O_4$ 1)	control	--	5	145 [18]	--
(sc)††	680	0.05	4	279 [28]	+92
	815	-0.11	4	254 [20]	+75
$MgAl_2O_4$ 2)	control	--	3	129 [2]	--
(pc)††	680	-0.19	6	178 [14]	+38
	815	-0.35	4	173 [16]	+34
$MgAl_2O_4$ 3)	control	--	5	112 [12]	--
(pc)	680	-0.39	3	156 [12]	+39
	815	-0.31	3	137 [17]	+22
Al_2O_3 4)	control	--	8	273 [80]	--
(sc)	680	3.54	4	290 [43]	+ 6
	815	3.37	4	333 [40]	+22
Al_2O_3 5)	control	--	7	302 [68]	--
(sc)	680	3.52	4	330 [22]	+ 9
	815	3.28	4	286 [124]	- 5
Si_3N_4 6)	control	--	7	234 [20]	--
(pc)	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% Al_2O_3-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 Al_2O_3 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 48	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. 122 & 123 (1984) 1386

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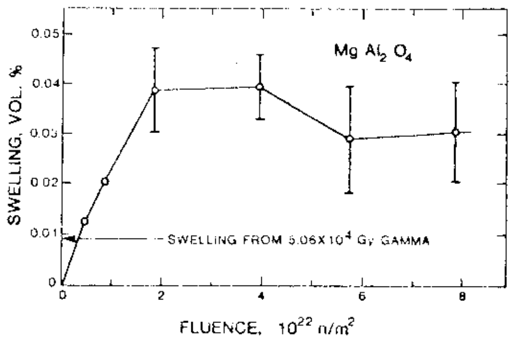
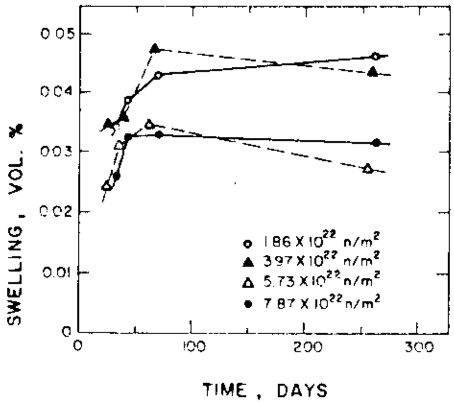
Material	$MgAl_2O_4$	Property	Swelling	1/1

Irradiation Condition	$4.7 \times 10^{17} \sim 7.9 \times 10^{18}$ n/cm^2 ($E > 0.1$ MeV) OWR $\sim$ 50°C



Swelling of single-crystal $MgAl_2O_4$ spinel after irradiation in OWR at ≈ 50°C.



Swelling as a function of storage time after removal from the reactor for four fluences.

Reference 53	Swelling of Spinel after Low-Dose Neutron Irradiation
	W. A. Coghman, F. W. Clinard, Jr., N. Itoh and L. R. Greenwood
	J. Nucl. Mater. 141-143 (1986) 382

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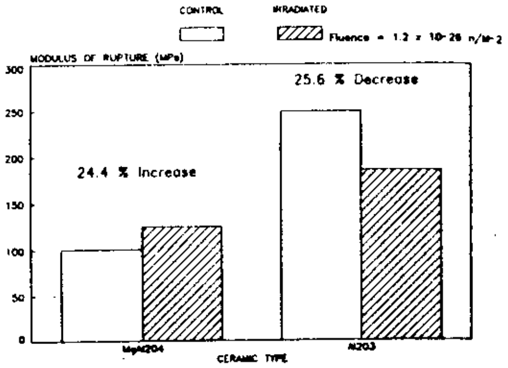
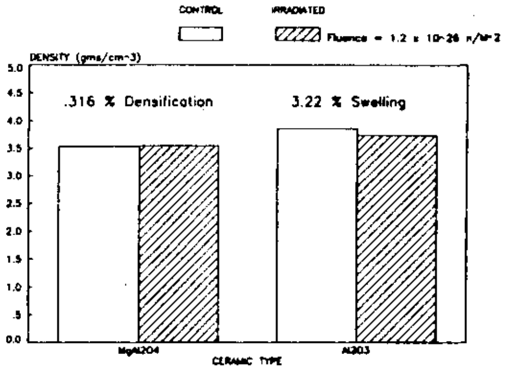
Material	$MgAl_2O_4$, Al_2O_3	Property	Swelling Tensile strength	1/1

Irradiation Condition	2×10^{22} n/cm^2 (E > 0.1 MeV) EBR-II 387°C

Material	Source	Impurities (wppm)
$MgAl_2O_4$	Ceradyne, Inc.	1000 Li 200 Fe 70 Ga 60 Ca
Al_2O_3	Coors Porcelain Co.	1500 Li 150 Fe 40 Si 30 Ca



. Change in tensile strength after irradiation for $MgAl_2O_4$ and Al_2O_3; irradiation temp. = 660 K.



Density changes after irradiation for $MgAl_2O_4$ and Al_2O_3; irradiation temp. = 660 K.

Reference 54	Effects of Neutron-Irradiation on $MgAl_2O_4$ and Al_2O_3
	D. S. Tucker, T. Zocco, C. D. Kise and J. C. Kennedy
	J. Nucl. Mater. 141-143 (1986) 401

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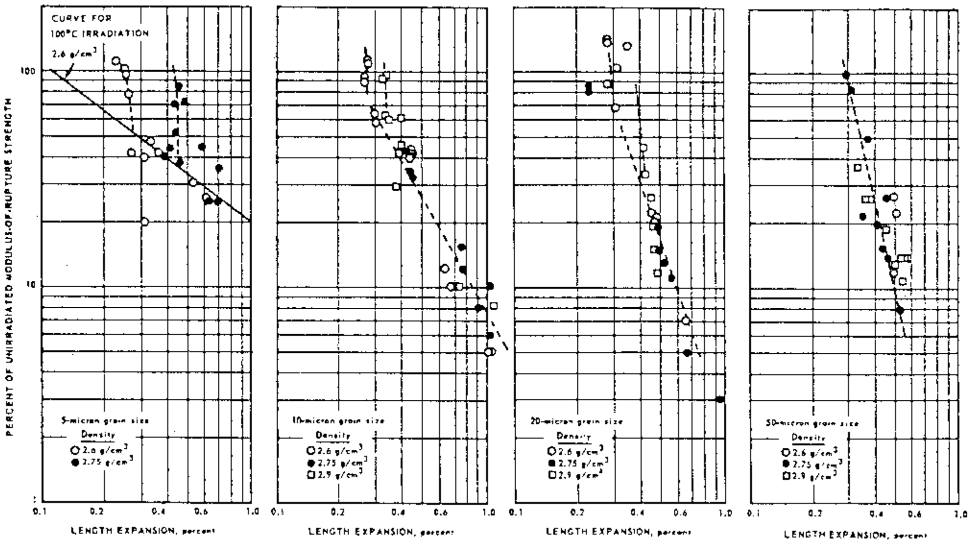
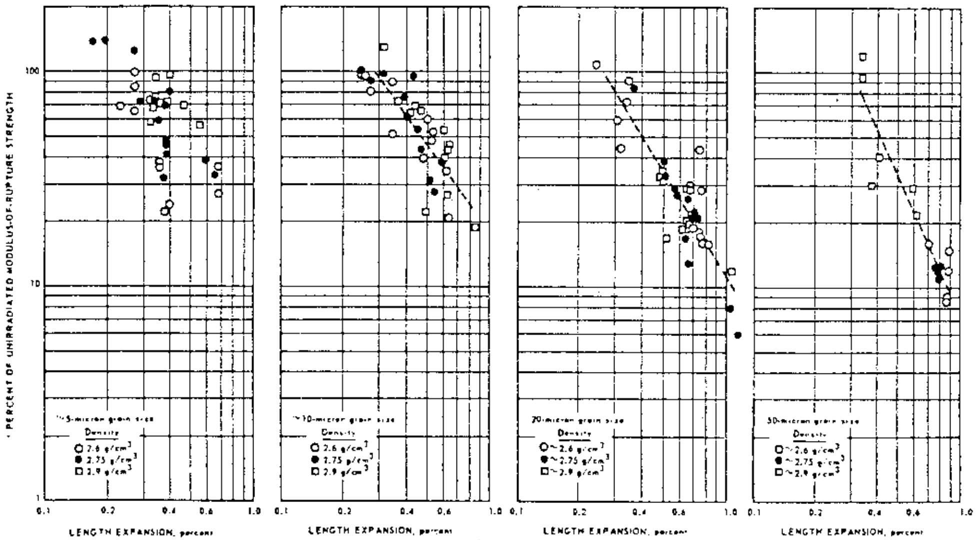
Material	BeO (sintered)	Property	Rupture strength	1/1
Irradiation Condition	$< 1.5 \times 10^{21}$ n/cm^2 (E > 1 MeV) ETR 100 ∿ 1200°C			



Modulus-of-rupture strength of randomly oriented AOX-grade BeO irradiated at 600°C to 950°C to dosages of 0.5 to 1.2×10^{21} nvt (≧ 1 MeV) as a function of length expansion.



Modulus-of-rupture strength of UOX+0.5 wt % MgO composition of BeO irradiated at 600°C to 950°C to dosages of 0.5 to 1.2×10^{21} nvt (≧ 1 MeV) as a function of length expansion.

Reference 5	Radiation Effects in BeO
	C. G. Collins
	J. Nucl. Mater. 14 (1964) 69-86

A-48

Material	Al_2O_3(sc, pc)	Property	Fracture strength	1/1

Irradiation Condition	< 5×10^{20} n/cm^2 (E > 1 MeV) HIFAR 75 ∿ 100°C, 500 ∿ 700°C

Results of mechanical property measurements

Material	Dose (nvt)	σ_i/σ_u
Fine grain. . . . . (Material B)	1.3×10^{20}	0.8
	1.7×10^{20}	1.3
	2.1×10^{20}	1.5–1.7
	3.5×10^{20}	1.0–1.6
	5.0×10^{20}	1.6
Coarse grain . . . . . . (Material C)	2.1×10^{20}	1.1–1.2
	4.2×10^{20}	1.3
	5.0×10^{20}	1.2–1.3

Reference 15	The Effect of Neutron Irradiation on Aluminium Oxide
	B. S. Hickman and D. G. Walker
	J. Nucl. Mater. 18 (1966) 197

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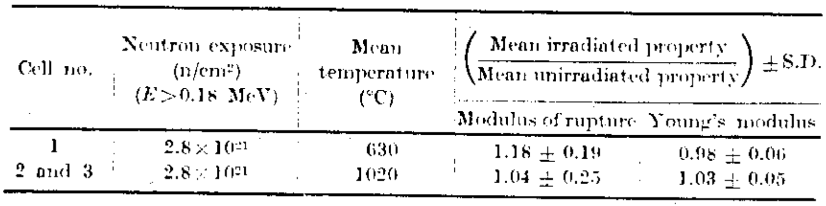
Material	β-SiC (pyrolytic)	Property	Rupture strength	1/1

Irradiation Condition	$2.0 \sim 4.2 \times 10^{21}$ nvt ($E > 0.18$ MeV) ETR 460°C, 1040°C

Mechanical property changes in irradiated pyrolytic silicon carbide



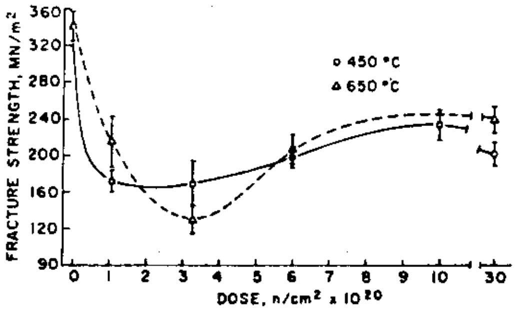
Cell no.	Neutron exposure (n/cm²) ($E > 0.18$ MeV)	Mean temperature (°C)	$\left(\frac{\text{Mean irradiated property}}{\text{Mean unirradiated property}}\right) \pm$ S.D.	
			Modulus of rupture	Young's modulus
1	2.8×10^{21}	630	1.18 ± 0.19	0.98 ± 0.06
2 and 3	2.8×10^{21}	1020	1.04 ± 0.25	1.03 ± 0.05

Reference 18	Effects of Fast-Neutron Irradiation on Pyrolitic Silicon Carbide
	R. J. Price
	J. Nucl. Mater. 33 (1969) 17

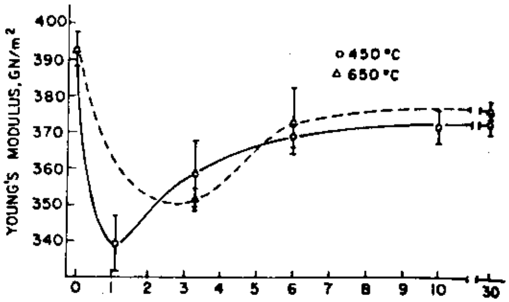
A-50

Material	SiC (reaction-bond SiC)	Property	Fracture strength Young's modulus	1/1

Irradiation Condition	3×10^{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.

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

[a] n = number of samples.

Reference 22	Irradiation Damage in Reaction-Bonded Silicon Carbide
	R. B. Mattews
	J. Nucl. Mater. 51 (1974) 203

A-51

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
Flux = $2.3 \times 10^{17} e/m^2 \cdot s$

Mean fracture strength = 266 MPa (38.6 ksi)
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 27	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

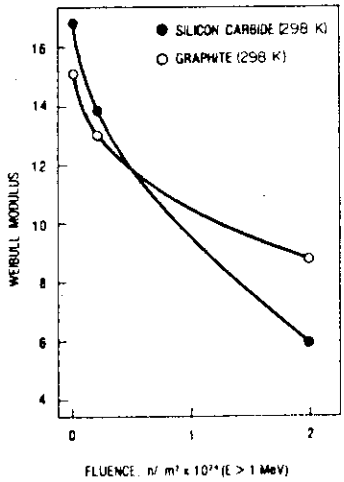
A-52

Material	SiC (self-bonded SiC, Norton NC-430)	Property	Fracture strength	1/1

Irradiation Condition	2 x 10^{19}, 2 x 10^{20} n/m^2 (E > 1 MeV) HFBR (BNL)

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

Dose	*T* = 298 K				*T* = 1473 K					Average sample width	
	Time-to--failure (s)	Mean fracture strength		Weibull modulus	Time-to--failure (s)	Mean fracture strength		Weibull modulus	Strength degradation exponent	(in.)	(m) x 10^2
		(MPa)	(ksi)			(MPa)	(ksi)				
Unirradiated	19.2	268	38.9	16.8	1164	270	39.2	14.1	217	0.1000	0.2540
					4.8	281	40.2	11.2			
2 x 10^{23} n/m^2 (*E* > 1 MeV)	17.9	250	36.2	14.0	1188	276	40.1	14.1	242	0.1002	0.2545
					4.8	270	39.2	10.2			
2 x 10^{24} n/m^2 (*E* > 1 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 27	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

A-53

Material	MACOR	Property	Flexture strength	1/1

Irradiation Condition	10^{16}, 10^{18} 14 MeV n/cm^2 RTNS-II room temperature

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_o
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 32	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. 103 & 104 (1981) 755

A-54

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_2O_3	MgO	As_2O_5	B_2O_3	ZrO_2	K_2O	MgF_2	Li_2O	P_2O_5	CoO	ZnO	BaO	Na_2O
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	---	---	---	---

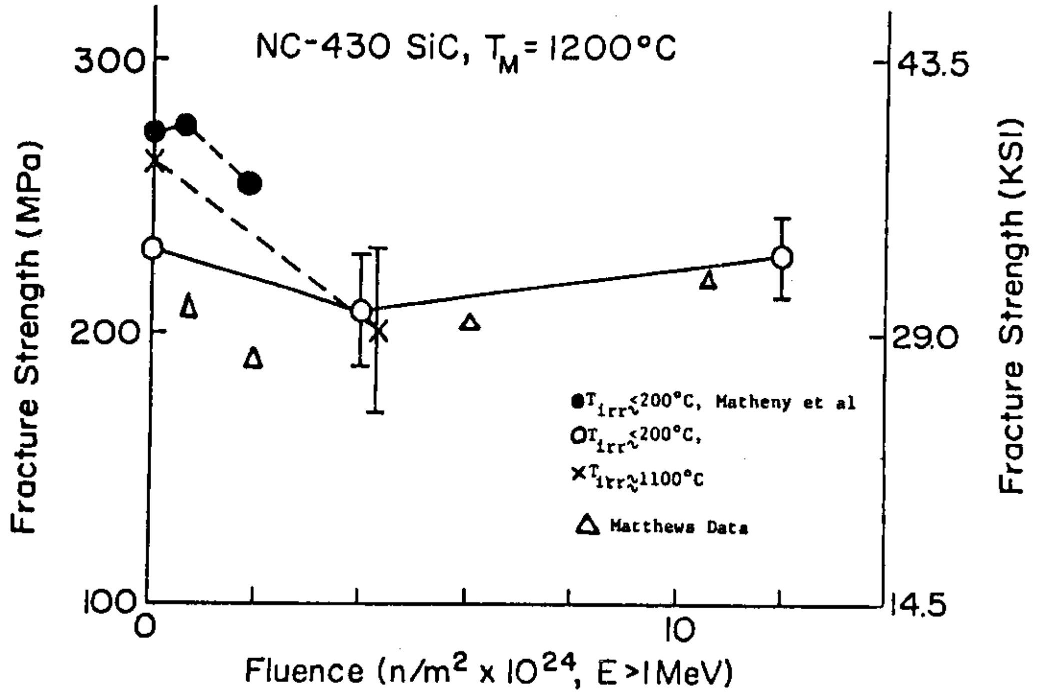
* Fluorine is added at 6.3 wt.% to substitute with oxygen.

Reference 34	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

A-55

Material	SiC (NC-430)	Property	Fracture strength	1/3

Irradiation Condition	1.2×10^{21} n/cm^2 (E > 1 MeV) HFBR (BNL)



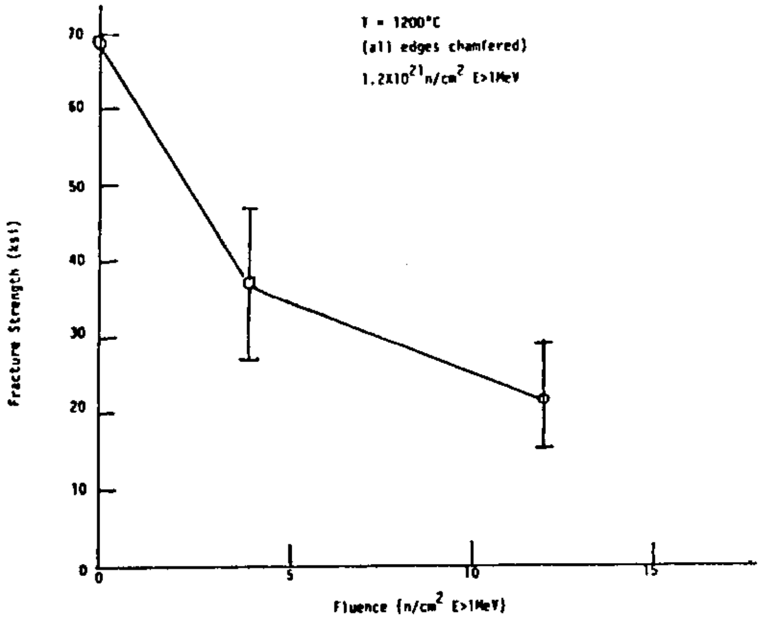
Mean fracture strength vs fluence of NC-430 SiC at 1200°C. Also included is data by Matheny et al

Reference 36	Ceramic Materials for Fusion Reactors
	G. Hopkins, G. C. Trantina and J. Corelli
	AP-1702, EPRI Research Project 992, Interim Report, February 1981

A-56

Material	α-SiC	Property	Fracture strength	2/3

Irradiation Condition	1.2×10^{21} n/cm^2 (E > 1 MeV) HFBR (BNL)

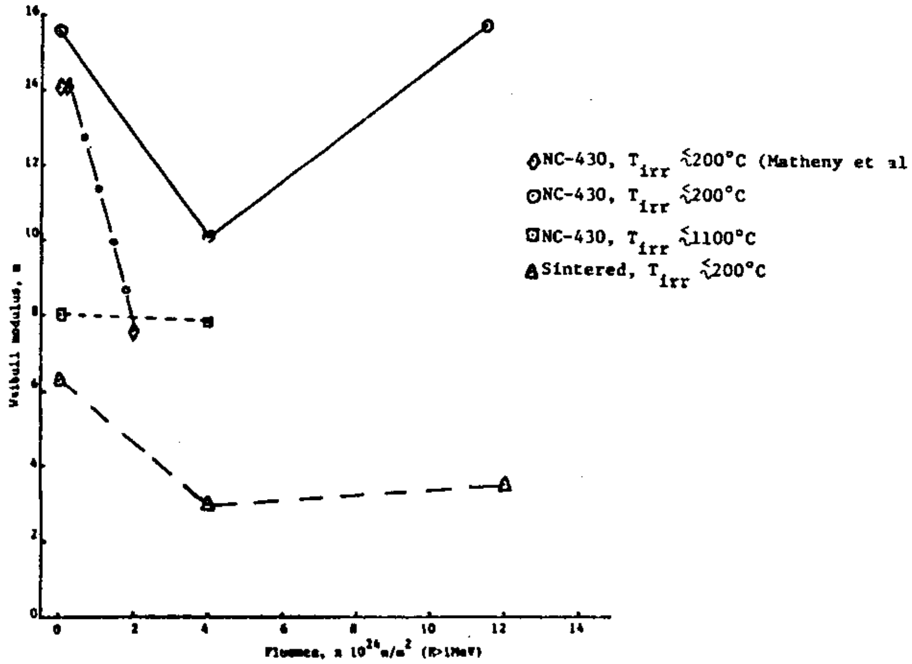


Mean fracture strength vs fluence of sintered α-SiC at 1200°C

Reference 36	Ceramic Materials for Fusion Reactors
	G. Hopkins, G. C. Trantina and J. Corelli
	AP-1702, EPRI Research Project 992, Interim Report, February 1981

A-57

Material	α-SiC, SiC (NC-430)	Property	Fracture strength (Weibull modulus)	3/3
Irradiation Condition	1.2×10^{21} n/cm^2 (E > 1 MeV) HFBR (BNL)			

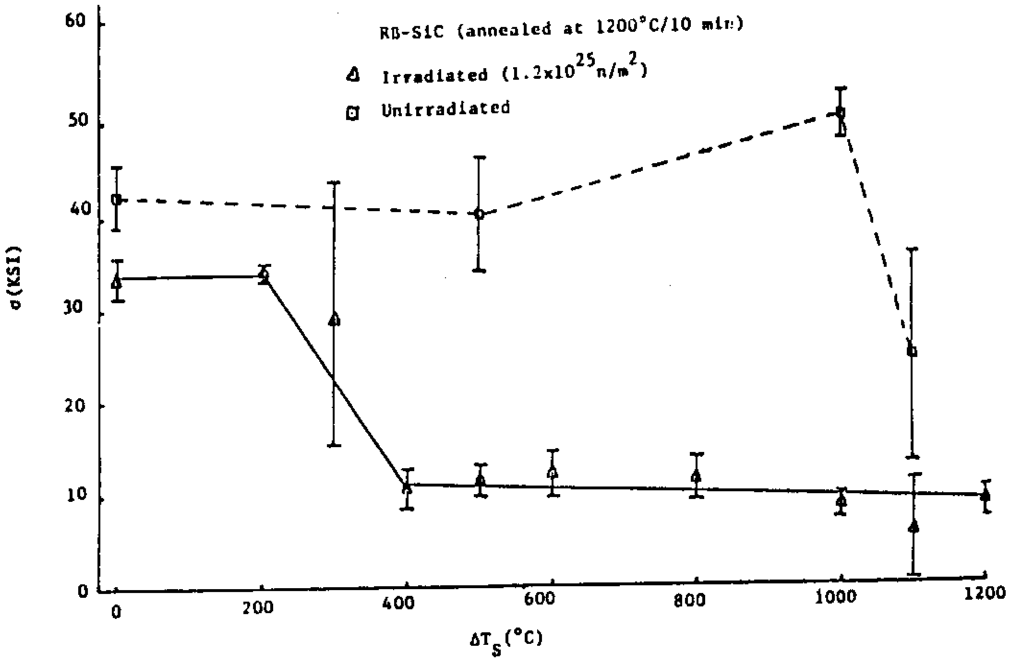


Weibull Modulus vs Fluence for NC-430 SiC and sintered α-SiC

Reference 36	
	Ceramic Materials for Fusion Reactors
	G. Hopkins, G. C. Trantina and J. Corelli
	AP-1702, EPRI Research Project 992, Interim Report, February 1981

A-58

Material	SiC (NC-430)	Property	Fracture strength	1/1
Irradiation Condition	1.2×10^{21} n/cm^2 (E > 1 MeV) HFBR (BNC)			



Mean fracture strength (measured at 23°C) vs thermal shock temperature of Irradiated (1.2×10^{25} n/m^2 E>1MeV) and Unirradiated NC-430 SiC

Reference 36	Ceramic Materials for Fusion Reactors
	G. Hopkins, G. C. Trantina and J. Corelli
	AP-1702, EPRI Research Project 992, Interim Report, February 1981

A-59

Material	SiC (NC-430), α-SiC	Property	Fracture strength	1/1

Irradiation Condition	1.2×10^{21} n/cm^2 (E > 1 MeV) HFBR (BNL) $\lesssim$ 147°C 8.1×10^{21} n/cm^2 (E > 1 MeV) HFIR (ORNL) $\sim$ 730°C

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

Fluence (10^{24} n/m^2) (E>1 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[†]		1473	231±17	15.6	12
0[‡]		1473	257±20	8.0	14
4[†]	≤ 473	1473	208±21	10.1	14
4[‡]	1373	1473	201±14	7.8	15
12[†]	≤ 473	1473	229±16	15.7	14
0[§]		1473	234±14	17.7	13
3.6[§]	413	1473	228±34	6.20	11
7.6[§]	413	1473	200±14	11.7	11
0[¶]		296	279±19	9.54	20
93[¶]	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. [†] These samples had three machined surfaces and one as-fired surface. [‡] These samples had four machined surfaces. [§] These samples were made of reaction-bonded SiC with ≈0.3 wt% natural boron dopant. [¶] Data of Ref. 11.

Summary of Fracture Strength Results for Sintered Alpha Silicon Carbide[*]

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

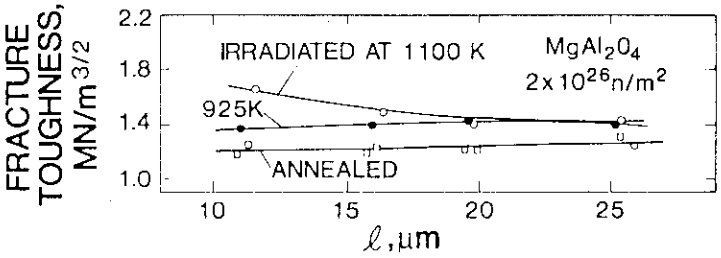
[*] Carborundum Co., Niagara Falls, NY. [†] These samples had three machined surfaces and one as-fired surface. [‡] These samples were commercially available and were sintered with ≈0.5 wt% natural boron. [§] Data of Ref. 11.

Reference 45	Mechanical, Thermal, and Microstructural Properties of Neutron-Irradiated SiC
	J. C. Corelli, J. Hoole, J. Lazzaro and C. W. Lee
	J. Am. Ceram. Soc. 66 (1983) 529

A-60

Material	$MgAl_2O_4$	Property	Fracture toughness	1/1

Irradiation Condition	∿ $1\text{-}2 \times 10^{22}$ n/cm^2 (E > 0.1 MeV) EBR-II 652, 742, 827°C



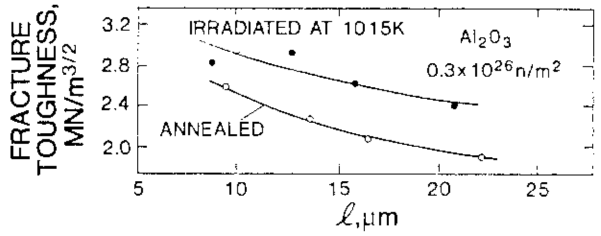
Fracture toughness of $MgAl_2O_4$ as a function of diagonal dimension of indentation, as annealed and after irradiation to 2×10^{26} n/m^2. Results from material annealed at 925 and 1100 K are not differentiated. The slight dependence of toughness on indentation size may be related to surface effects.

Reference 49	The Effect of Elevated-Temperature Neutron Irradiation on Fracture Toughness of Ceramics
	F. W. Clinard, Jr., G. F. Hurley, R. A. Youngman and L.W.Hobbs
	J. Nucl. Mater. 133 & 134 (1985) 701

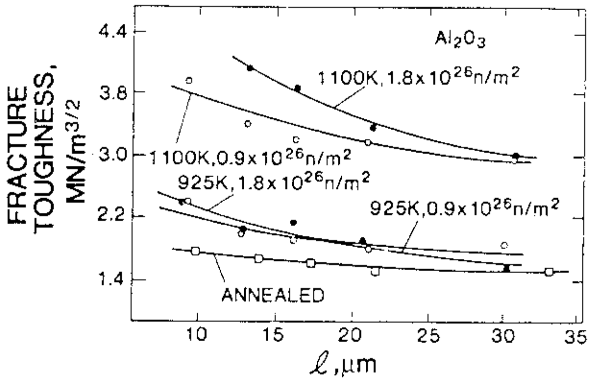
A-61

Material	Al_2O_3	Property	Fracture toughness	1/1

Irradiation Condition	∿ 1-2 x 10^{22} n/cm^2 (E > 0.1 MeV) EBR-II 652, 742, 827°C



Fracture toughness of Al_2O_3 as a function of diagonal dimension of indentation, as annealed and after irradiation at 1015 K.



Fracture toughness of Al_2O_3 as a function of diagonal dimension of indentation, as annealed and after irradiation to 0.9 and 1.8×10^{26} n/m^2. Results from material annealed at 925 and 1100 K are not differentiated.

Comparison of observed toughening ($K_c$irrad/$K_c$contr) and predicted toughening ($\sigma_{irrad}/\sigma_{contr}$) in Al_2O_3. Other symbols are defined in the text. Measured values of fracture toughness were taken in the range of indentation sizes deemed to give the most reliable results

Irrad. T (K)	$K_c$irrad/ $K_c$contr	$2r_0$	$2C$	$2C/2r_0$	σ_{irrad}/ σ_{contr}
925	1.2	3.6	18	5.0	1.2
1015	1.3	5.2	24	4.6	1.3
1100	2.1	9.0	21	2.3	1.7

Reference 49	The Effect of Elevated-Temperature Neutron Irradiation on Fracture Toughness of Ceramics
	F. W. Clinard, Jr., G. F. Hurley, R. A. Youngman and L.W.Hobbs
	J. Nucl. Mater. 133 & 134 (1985) 701

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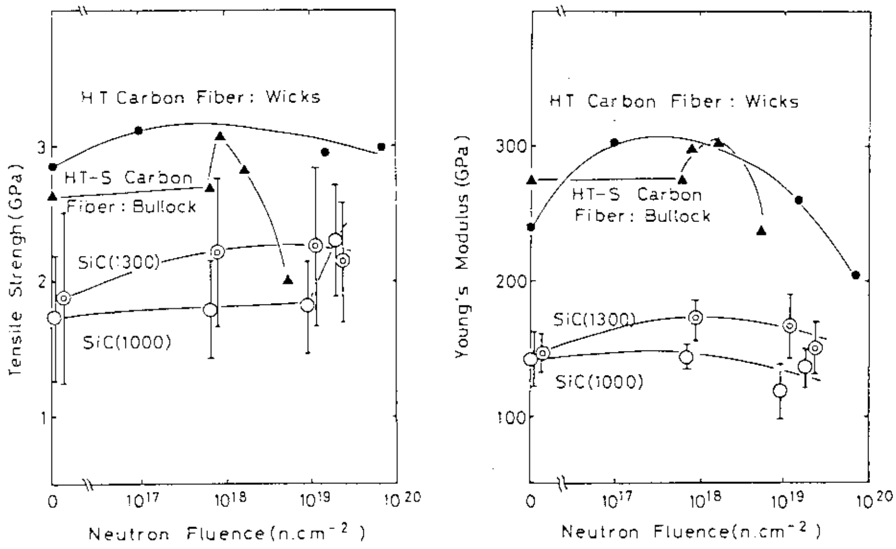
Material	SiC Fiber (SiC(1000),SiC(1300))	Property	Tensile strength, Young's modulus	1/1

Irradiation Condition	7.7 x 10^{17}, 1 x 10^{19}, 2 x 10^{19} n/cm^2 (E > 1MeV), JMTR, < 300°C 4 x 10^{17} n/cm^2 (E > 14 MeV), RTNS-II, RT

Density, tensile strength and Young's modulus of the SiC fibers before and after neutron irradiation

Fiber	Reactor	Fluence (n/cm^2)	Density (g/cm^3)	Tensile strength (GPa)	Young's modulus (GPa)
SiC (1000)		unirrad.	2.34	1.73 ± 0.48	139 ± 20
	JMTR (E > 1 MeV)	7.7 × 10^{17}	2.37	1.76 ± 0.37	144 ± 9
		1.0 × 10^{19}	2.35	1.80 ± 0.35	118 ± 20
		2.0 × 10^{19}	2.42	2.26 ± 0.42	135 ± 16
	RTNS-II (E = 14 MeV)	~ 4 × 10^{17}	2.33	1.72 ± 0.38	151 ± 9
SiC (1300)		unirrad.	2.60	1.87 ± 0.64	148 ± 15
	JMTR (E > 1 MeV)	7.7 × 10^{17}	2.60	2.20 ± 0.56	173 ± 14
		1.0 × 10^{19}	2.60	2.24 ± 0.60	168 ± 24
		2.0 × 10^{19}	2.59	2.12 ± 0.46	153 ± 18
	RTNS-II (E = 14 MeV)	~ 4 × 10^{17}	2.60	1.81 ± 0.42	139 ± 12



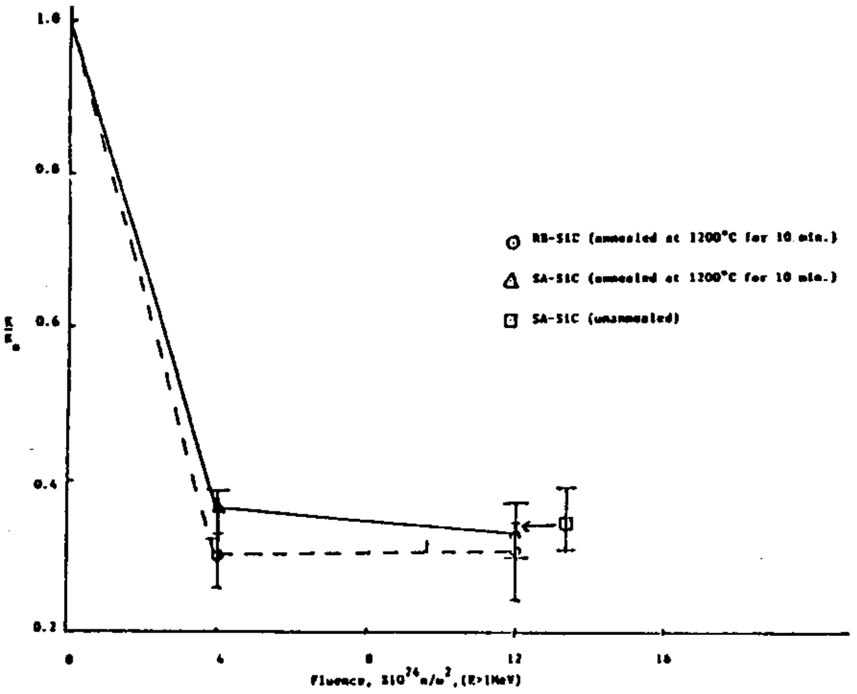
Effects of neutron irradiation on tensile strength and Young's modulus of the SiC fibers and the PAN based carbon fibers [5,6]. ○, SiC(1000) fiber; ◎, SiC(1300) fiber; ▲, HT-S carbon fiber by Bullock [5]; ●, HT carbon fiber by Wicks [6].

Reference 50	Effects of Neutron Irradiation on SiC Fiber
	K.Okamura, T.Matsuzawa, M.Sato, Y.Higashiguchi and S.Morozumi
	J. Nucl. Mater. 133 & 134 (1985) 705-708

A-63

Material	α-SiC, SiC (NC-430)	Property	Thermal conductivity	1/1

Irradiation Condition	1.2×10^{21} n/cm^2 (E > 1 MeV) HFBR (BNL)



Relative thermal conductivity, $\frac{K}{K_o}$, (measured at $T \approx 23$ C) vs fluence for NC-430 SiC and Sintered α-SiC

Reference 36	Ceramic Materials for Fusion Reactors
	G. Hopkins, G. C. Trantina and J. Corelli
	AP-1702, EPRI Research Project 992, Interim Report, February 1981

A-64

Material	MACOR	Property	Thermal diffusivity	1/1

Irradiation Condition	10^{16}, 10^{18} 14 MeV n/cm^2 RTNS-II room temperature

Thermal diffusivity changes in MACOR.

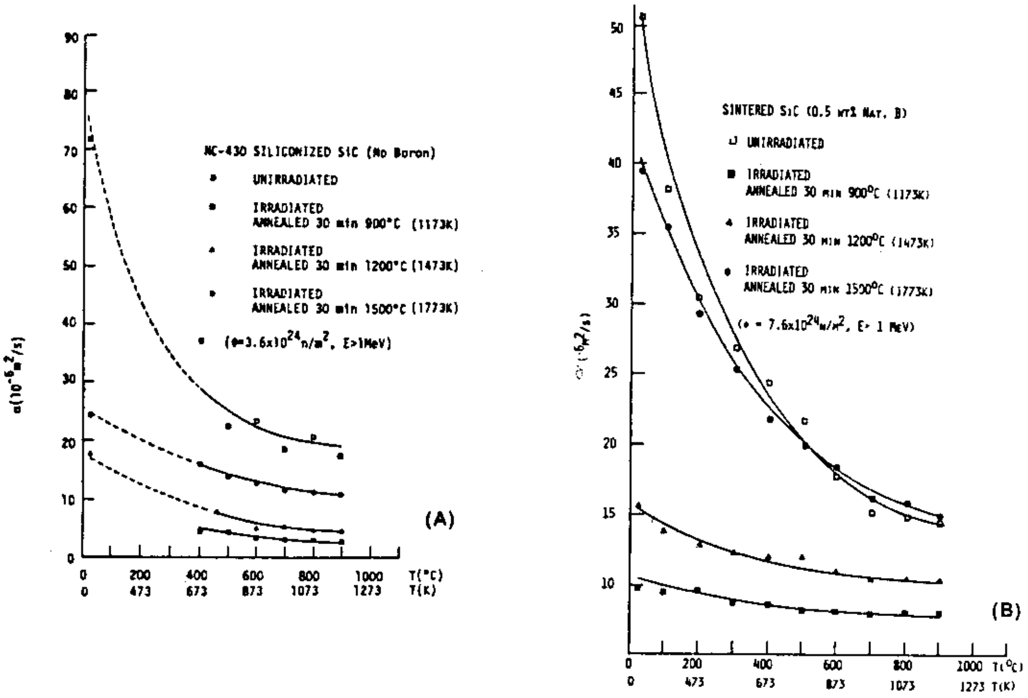
Sample fluence (n/m^2)	Number of samples	Thermal diffusivity (normalized)
Control	5	1 (4.5×10^{-7} m^2/s)
10^{20}	4	0.998
10^{22}	2	0.978

Reference 32	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. 103 & 104 (1981) 755

A-65

Material	SiC (NC-430), α-SiC	Property	Thermal diffusivity	1/1

Irradiation Condition	1.2×10^{21} n/cm^2 (E > 1 MeV) HFBR (BNL) $\lesssim$ 147°C 8.1×10^{21} n/cm^2 (E > 1 MeV) HFIR (ORNL) $\sim$ 730°C

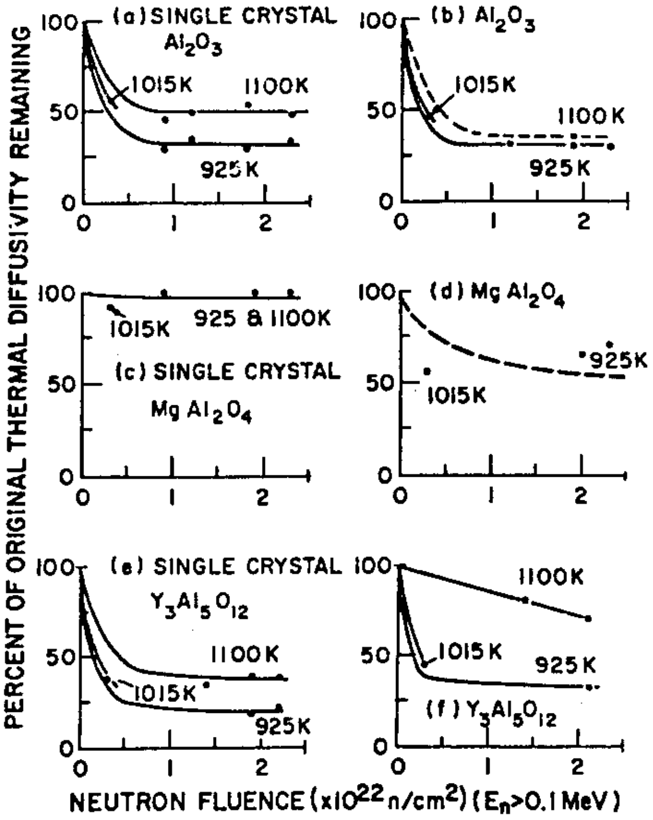


Thermal diffusivity vs temperature for (*A*) siliconized SiC, (*B*) sintered α-SiC sintered with 0.5 wt% natural boron, and (*C*) siliconized SiC doped with 0.3 wt% ^{10}B, showing effect of annealing.

Reference 45	Mechanical, Thermal, and Microstructural Properties of Neutron-Irradiated SiC
	J. C. Corelli, J. Hoole, J. Lazzaro and C. W. Lee
	J. Am. Ceram. Soc. 66 (1983) 529

A-66

Material	Al_2O_3, $MgAl_2O_4$, $Y_2Al_5O_{12}$	Property	Thermal diffusivity	1/1
Irradiation Condition	∼ 2.5 x 10^{22} n/cm^2 (E > 0.1 MeV) EBR-II < 827°C			



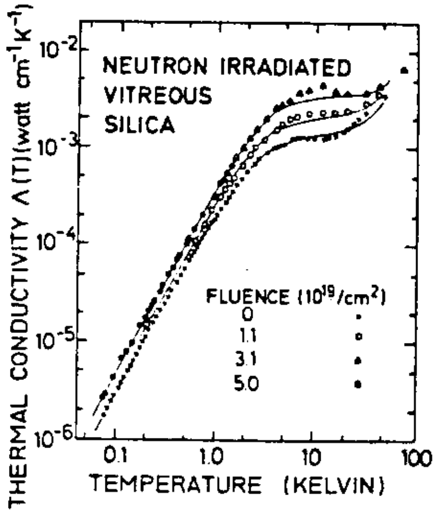
Decrease in RT thermal diffusivity (approximately proportional to thermal conductivity) as a function of irradiation temperature and fission neutron fluence for several ceramics.

Reference 37	The Inorganic Insulator Program at LASL
	F. W. Clinard, Jr. and D. M. Parkin
	USDOE Report No. CONF-801237, 1981, P17-1

A-67

Material	Silica	Property	Thermal conductivity	1/1

Irradiation Condition	5×10^{19} n/cm^2 (E > 1 MeV)



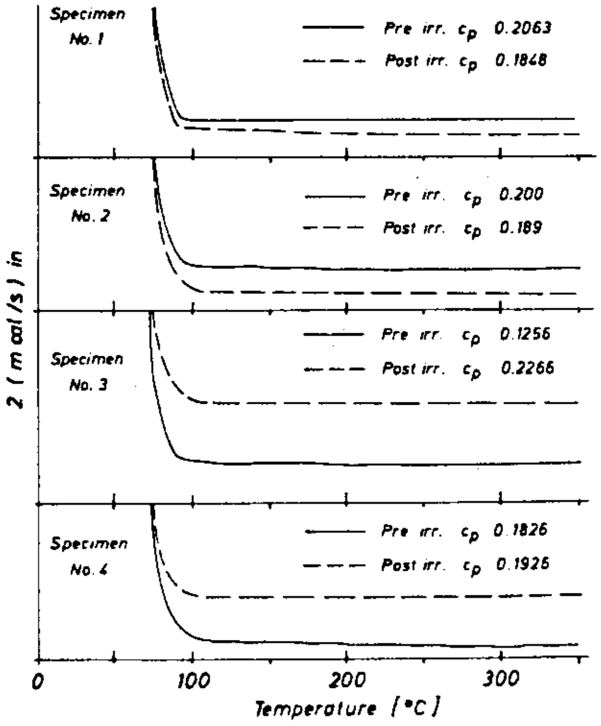
Thermal conductivity of neutron irradiated silica.

Reference 40	Thermal Conductivity of Neutron-Irradiated Silica
	A. K. Raychandhuri and R. O. Pohl
	Solid State Communication 44 (1982) 711

A-68

Material	Porcelain	Property	Specific heat	1/1

Irradiation Condition	14.3 MeV n (Neutron Generator) 8.4, 16.8, 21.0 x 10^{10} n/cm^2



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

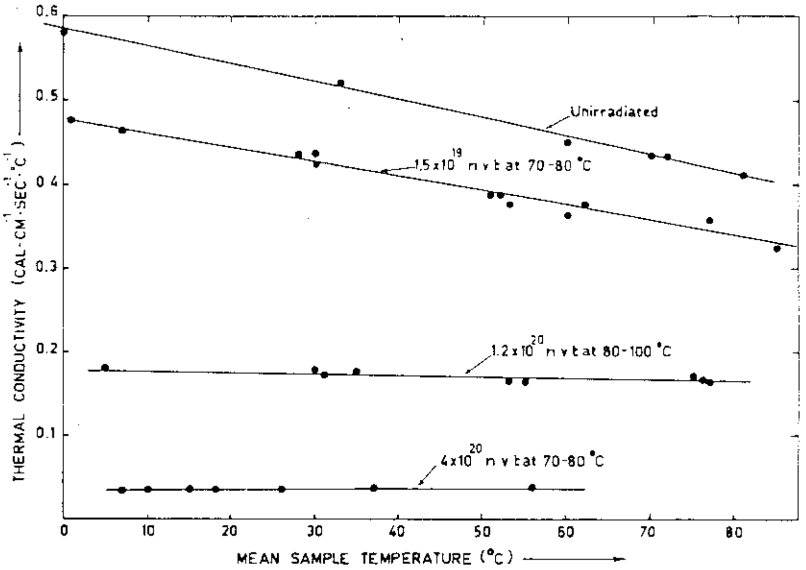
Composition of the prepared porcelain bodies

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

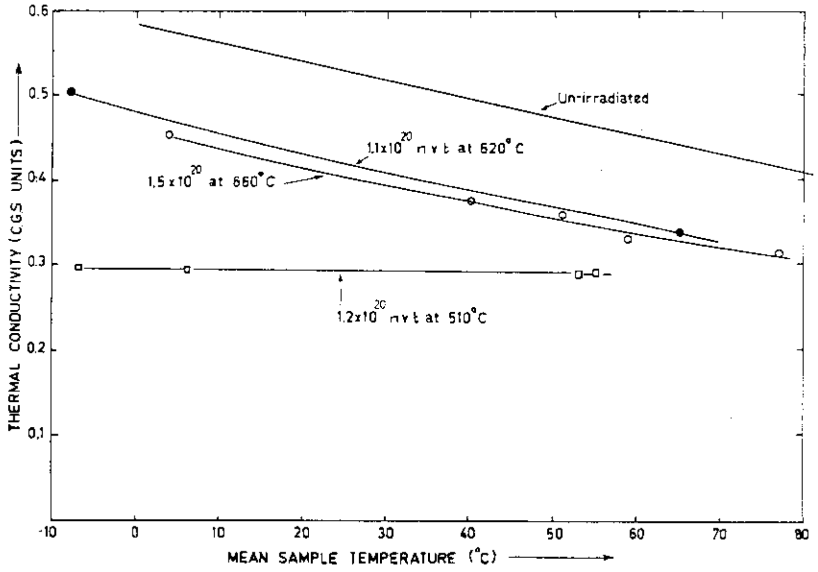
Reference 43	Investigations on Porcelain and Fast Neutron Effects
	W. A. Fattach and D. S. El-Alousi
	Sprechsaal <u>115</u> (1982) 1113

A-69

Material	BeO (hot-pressed)	Property	Thermal conductivity	1/1
Irradiation Condition	$< 4 \times 10^{20}$ n/cm^2 HIFAR 70 ∿ 100°C, 510 ∿ 660°C			



Thermal conductivity of unirradiated and irradiated beryllium oxide.



Thermal conductivity of beryllium oxide irradiated at high temperature.

Reference 1	The Effect of Neutron Irradiation on the Thermal Conductivity of Beryllium Oxide
	M. K. Cooper, A. R. Palmer and G. Z. A. Stolarski
	J. Nucl. Mater. 9 (1963) 320

A-70

Material	BeO (hot-pressed, sintered)	Property	Thermal conductivity	1/1

Irradiation Condition	$1.2 \sim 365 \times 10^{21}$ n/cm^2 ETR $583 \sim 1100$°C

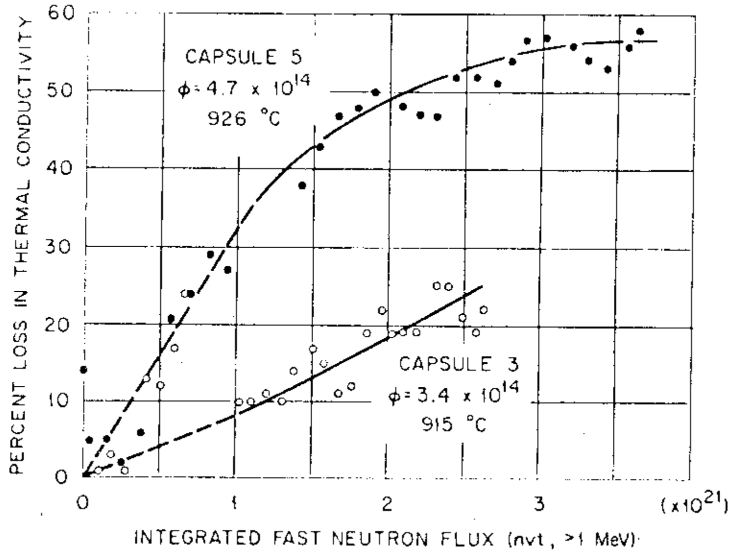


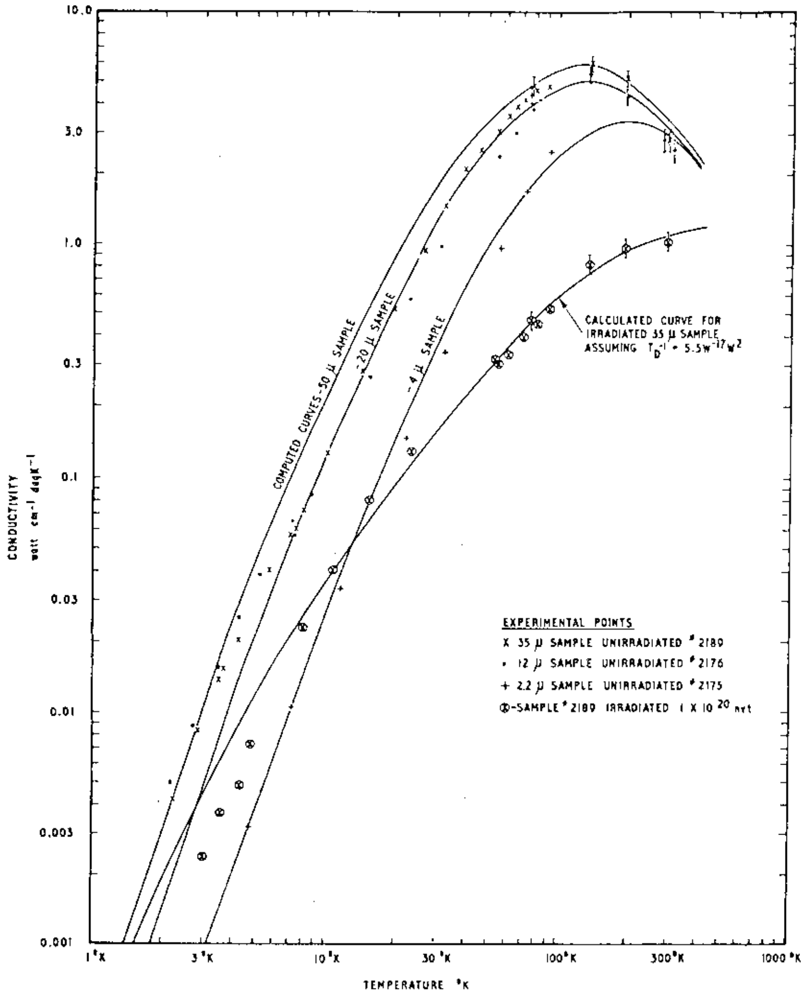
Fig. 5. Percent loss in thermal conductivity of BeO versus integrated fast-neutron flux in experiment 41–7.

Reference 12	The Effect of Fast-neutron Irradiation on Beryllium Oxide Compacts at High Temperature
	G. W. Keilholtz, J. E. Lee, Jr. and R. E. Moore
	J. Nucl. Mater. 14 (1964) 253

A-71

Material	BeO (sintered)	Property	Thermal conductivity	1/1

Irradiation Condition	1 x 10^{21} n/cm^2 HIFAR ∿ 75°C

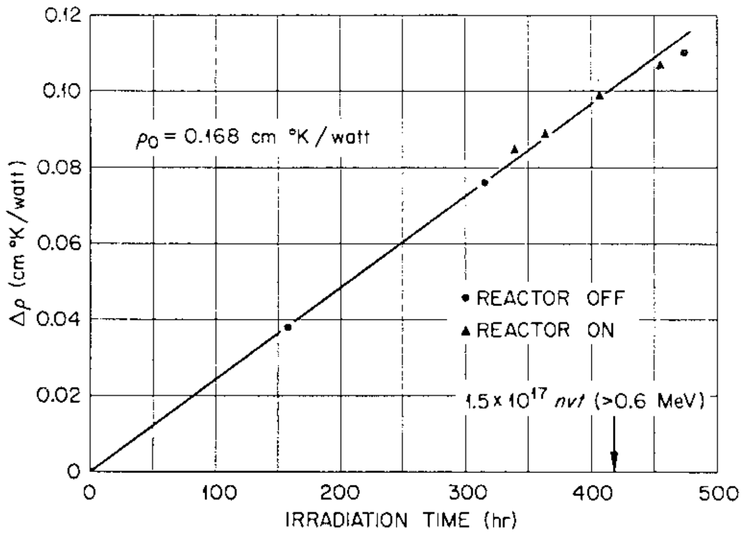


Experimental values for three unirradiated samples are shown with curves calculated from the Callaway Integral formula [19]). Also shown are the experimental points for an irradiated sample and a calculated curve assuming an ω^2-dependence for the defect scattering. Points with error bars were determined in the first cryostat (77°–298° K) described.

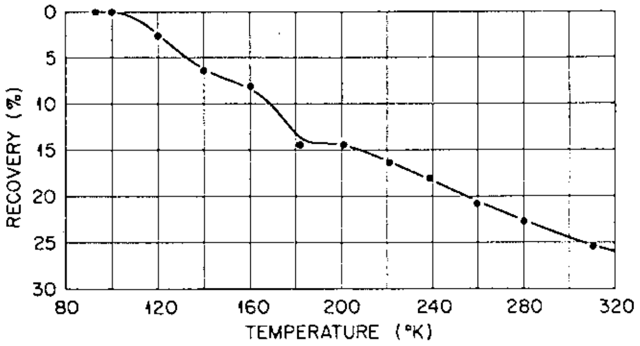
Reference 11	Thermal Conductivity at Low Temperature of Neutron-Irradiated BeO
	A. W. Pryor, R. J. Tanish and G. K. White
	J. Nucl. Mater. 14 (1964) 208-219

A-72

Material	BeO (sintered)	Property	Thermal resistivity	1/1
Irradiation Condition	1×10^{11} n/cm^2·sec (E > 0.6 MeV) Oak Ridge Graphite Reactor -182°C			



Increase in thermal resistivity, $\Delta\rho$ vs irradiation time.



Isochronal annealing of beryllium oxide irradiated at 91°K.

Reference 3	Low-temperature Irradiation of Beryllium Oxide
	D. L. McDonald
	Appl. Phys. Letters, 2 (1963) 175

A-73

Material	β-SiC	Property	Thermal conductivity, Swelling	1/1
Irradiation Condition	2.7 ∿ 7.7 x 10^{21} n/cm^2 (E > 0.18 MeV) ETR 550, 780, 950, 1100°C			

Irradiation conditions and thermal conductivity for irradiated silicon carbide

Capsule no.	Cell no.	Irradiation conditions			Volume expansion of sample (%) (± SD)	Thermal conductivity (cal/cm·°C·sec) at room temperature (average of 2 to 6 measurements)	
		Fast neutron fluence (n/cm^2, $E > 0.18$ MeV)	Mean temperature (°C)	Temperature variation during irradiation (°C)		1400 °C deposits	1750 °C deposits
–	–	0	–	–	–	0.15	0.12
P-13-J	3	3.8×10^{21}	1100	± 100	0.2 ± 0.1	0.045	a)
	5	2.7×10^{21}	550	± 30	1.1 ± 0.1	0.018	a)
P-22	1	6.0×10^{21}	780	± 30	0.4 ± 0.1	0.024	0.025
	3	7.7×10^{21}	1130 b)	± 100 b)	0.8 ± 0.2	0.022	0.020
	5	5.2×10^{21}	950	± 50	0.4 ± 0.2	0.026	0.028

a) Not tested.

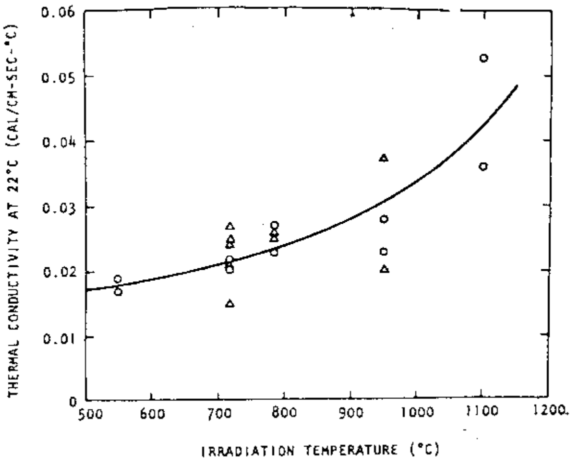
b) Sample temperature dropped to ~ 720 °C during last 100 h of irradiation.

Reference 19	Thermal Conductivity of Neutron-Irradiated Pyrolytic β-Silicon Carbide	
	R. J. Price	
	J. Nucl. Mater. 46 (1973) 268-272	

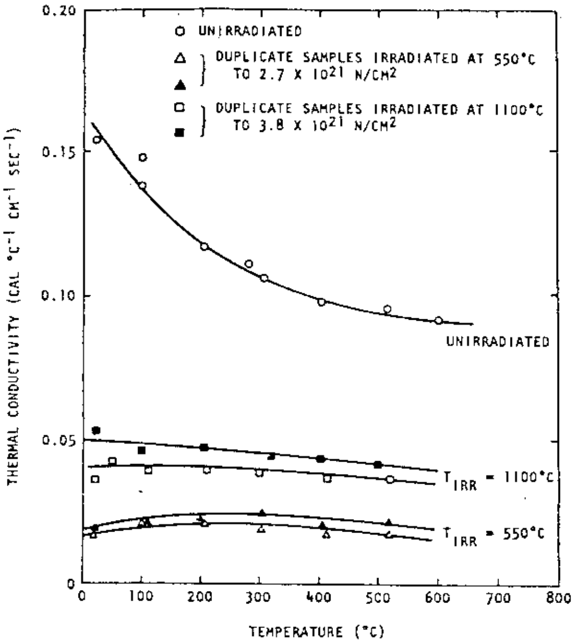
A-74

Material	β-SiC	Property	Thermal conductivity	1/1

Irradiation Condition	$2.7 \sim 7.7 \times 10^{21}$ n/cm^2 (E > 0.18 MeV) ETR 550, 780, 950, 1100°C



Room-temperature thermal conductivity of pyrolytic β-silicon carbide irradiated to $2.7\text{–}7.7 \times 10^{21}$ n/cm^2 ($E > 0.18$ MeV), as a function of irradiation temperature. ○: material deposited at 1400 °C, △: material deposited at 1750 °C.



Thermal conductivity of unirradiated and neutron-irradiated pyrolytic β-silicon carbide, deposited at 1400 °C, as a function of measurement temperature.

Reference 19	Thermal Conductivity of Neutron-Irradiated Pyrolytic β-Silicon Carbide
	R. J. Price
	J. Nucl. Mater. <u>46</u> (1973) 268-272

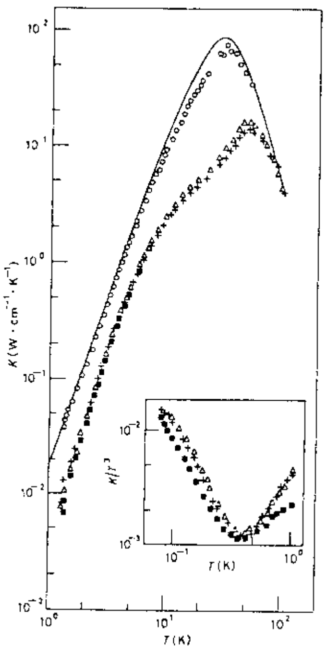
A-75

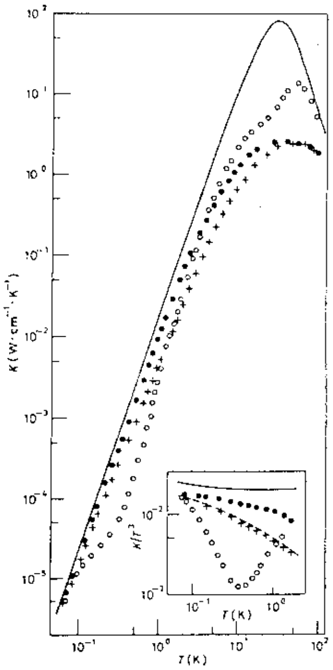
Material	Al_2O_3 (sc)	Property	Thermal conductivity	1/1

Irradiation Condition	2 MeV e $3 \times 10^{19}/cm^2$ + 3×10^{18} n/cm^2 (E > 0.1 MeV) RT

Irradiations.

	γ(^{60}Co)	Electrons ($E \simeq 2$ MeV)	Fast neutrons ($E > 0.1$ MeV)
Al_2O_3	—	$\simeq 3 \cdot 10^{19}/cm^2$	$3 \cdot 10^{18}/cm^2$
Al_2O_3 + Ni	$\simeq 5 \cdot 10^7$ R	$\simeq 2 \cdot 10^{20}/cm^2$	$3 \cdot 10^{18}/cm^2$





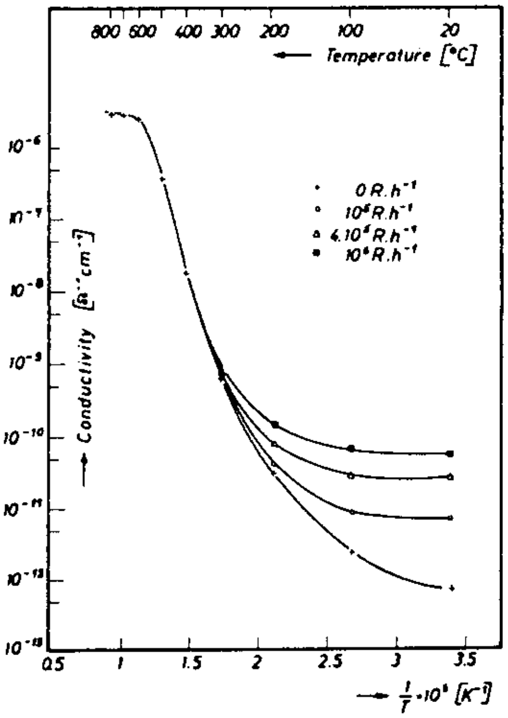
– Thermal conductivity as a function of temperature. The results below 1 K are plotted again as K/T^3 *vs.* T in the inset. Pure Al_2O_3: before irradiation (solid line), after *neutron irradiation* (●). Ni-doped Al_2O_3: before irradiation (○), after *neutron irradiation* (+). The dashed line in the inset is calculated (see text).

Thermal conductivity as a function of temperature. The results below 1 K are only shown in the inset as K/T^3 *vs.* T. Pure Al_2O_3: before irradiation (solid line); after *electron irradiation* (○). Ni-doped Al_2O_3: before irradiation (△); after *γ-irradiation* (+); after *electron irradiation* (■).

Reference 55	Glasslike Behavior of a Neutron-Irradiated Ni-doped Al_2O_3 Crystal
	A. M. De Goer and B. Salce
	Europhys. Lett. 1 (1986) 141

A-76

Material	Al_2O_3 insulated cable	Property	Electrical conductivity	1/1
Irradiation Condition	γ-ray, 10^6 R/h, 20∼800 °C			



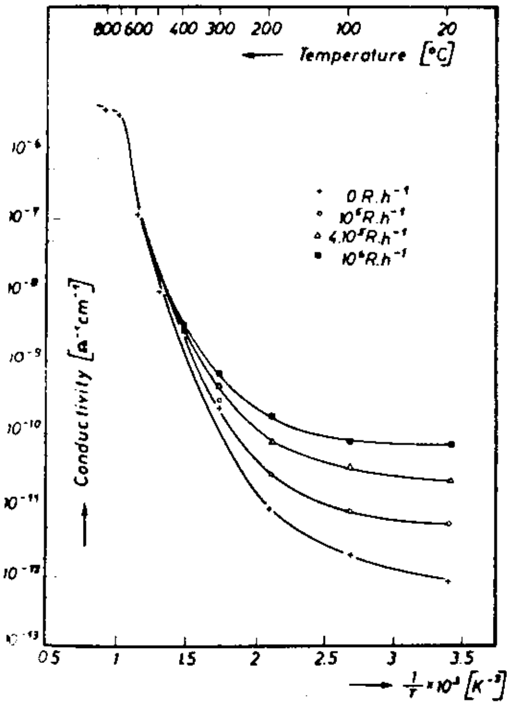
Conductivity as a function of temperature for a 1.5 mm Al_2O_3 insulated cable.

Reference 25	Investigation of Mineral Insulated Cables Exposed to High Temperature and Intense Gamma Radiation
	H. Böck and M. Suleiman
	Nucl. Inst. Methods 148 (1978) 43

A-77

Material	MgO insulated cable	Property	Electrical conductivity	1/1

Irradiation Condition	γ-ray, < 10^6 R/h, 20~800°C

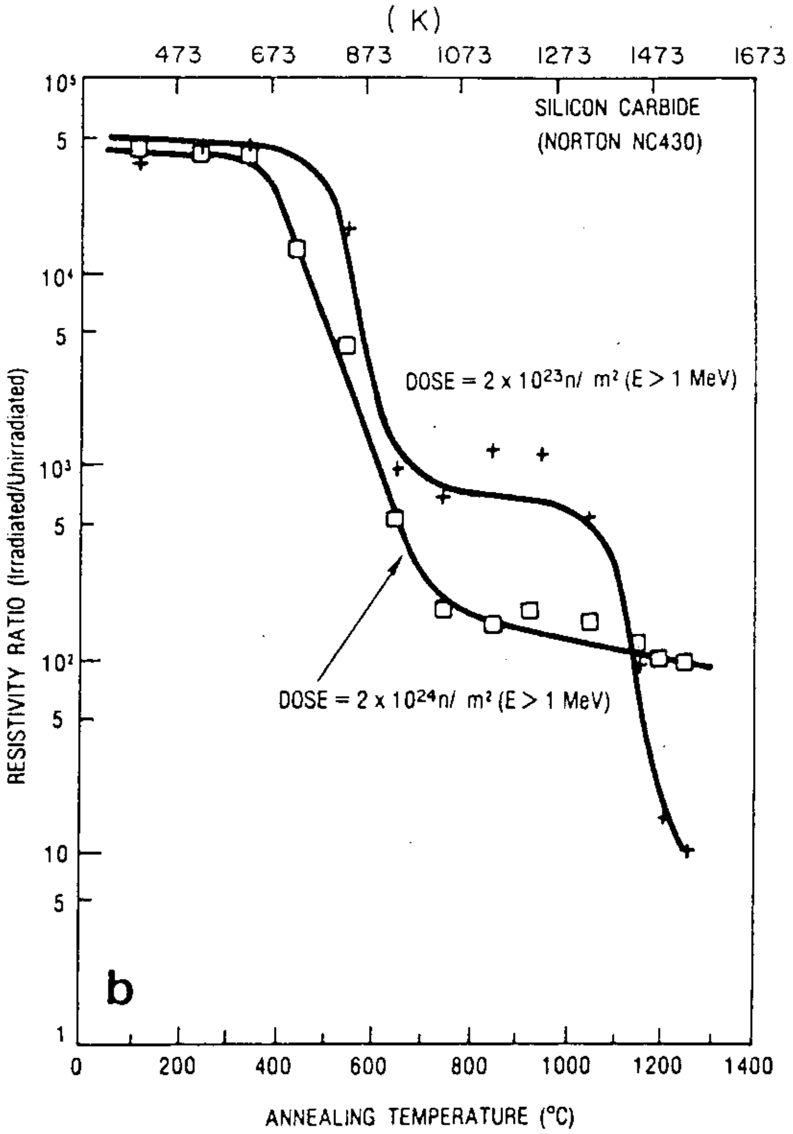


Conductivity as a function of temperature for a 1 mm MgO insulated cable.

Reference 25	Investigation of Mineral Insulated Cables Exposed to High Temperature and Intense Gamma Radiation
	H. Böck and M. Suleiman
	Nucl. Inst. Methods 148 (1978) 43

A-78

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



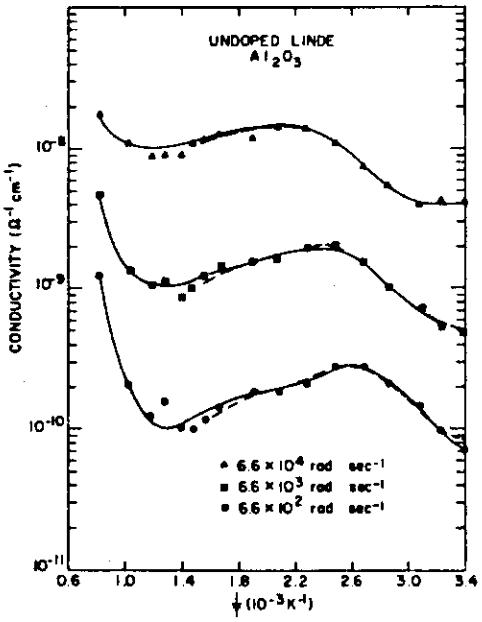
Isochronal annealing (600 s at each temperature), resistivity ratio vs. annealing temperature for silicon carbide

Reference 27	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

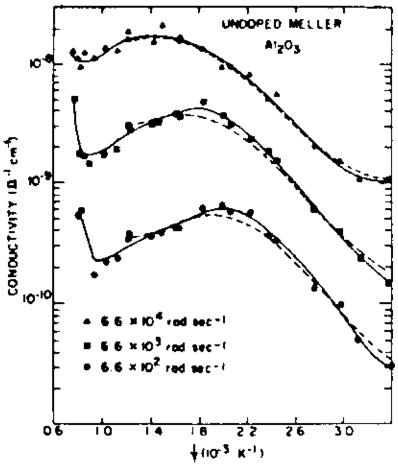
A-79

Material	Al_2O_3(sc)	Property	Conductivity	1/1

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 Al_2O_3 sample.



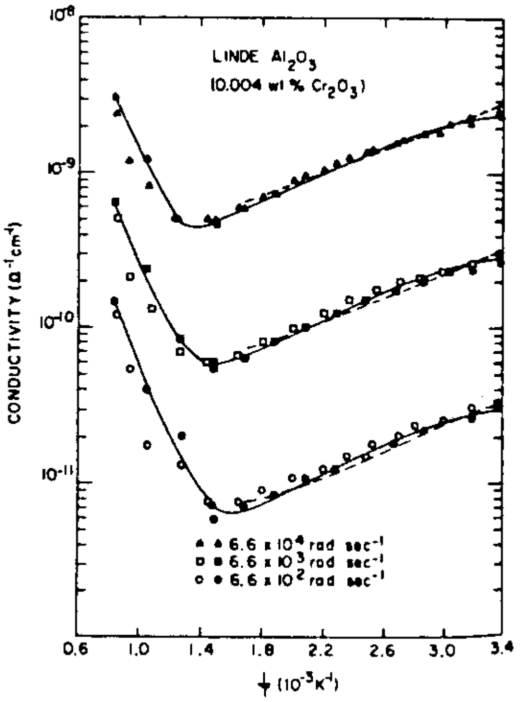
Temperature dependence of the RIC for the undoped Meller Al_2O_3 sample at the dose rates indicated.

Reference 31	Radiation-induced Conductivity of Al_2O_3: Experiment and theory
	R. W. Klaffky, B. H. Rose, A. N. Goland and G. J. Dienes
	Phys. Rev. B 21 (1980) 3610

A-80

Material	Al_2O_3 (sc)	Property	Conductivity	1/1

Irradiation Condition	1.5 MeV electron (BNL Dynamitron)

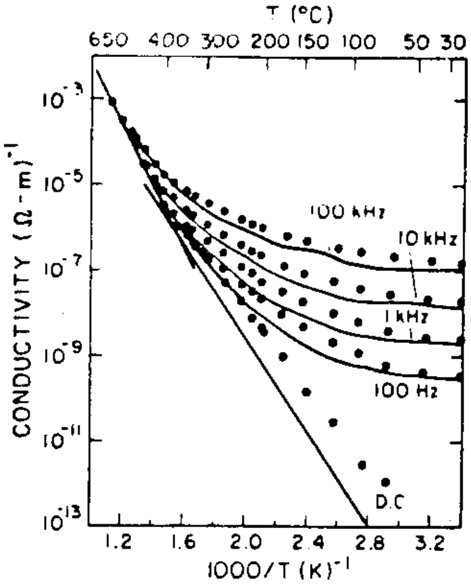


Temperature dependence of the RIC for the 0.004-wt.%-Cr_2O_3-doped Linde Al_2O_3 sample.

Reference 31	Radiation-induced Conductivity of Al_2O_3: Experiment and theory
	R. W. Klaffky, B. H. Rose, A. N. Goland and G. J. Dienes
	Phys. Rev. B 21 (1980) 3610

A-81

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

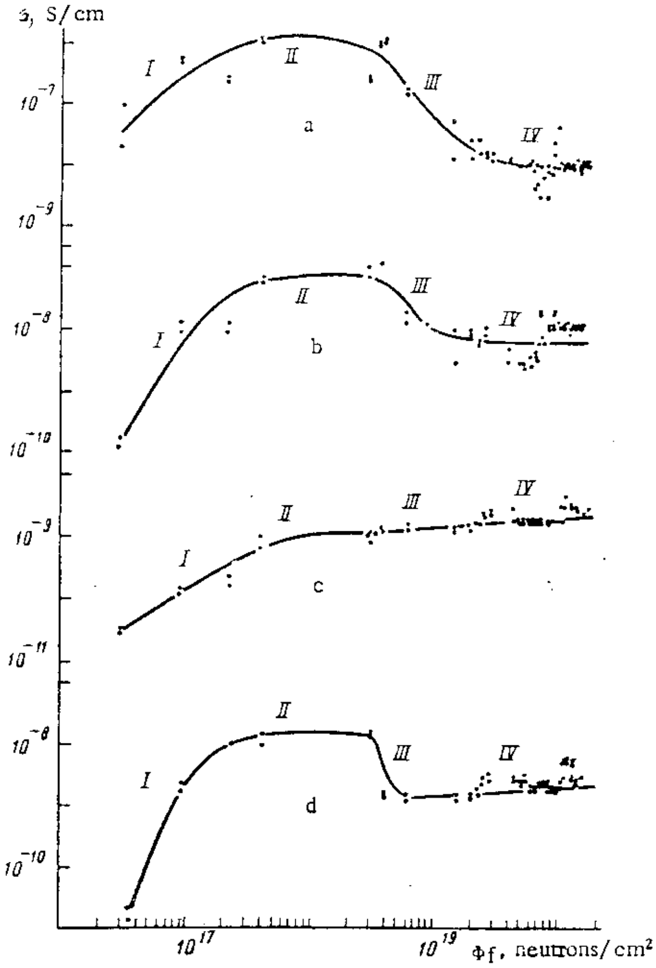


Electrical conductivity of MACOR. Lines are fits to controls; points are data for samples irradiated to 10^{22} 14 MeV n/m^2.

Reference 32	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. 103 & 104 (1981) 755

A-82

Material	Al_2O_3 , $MgAl_2O_4$	Property	Electrical conductivity	1/1
Irradiation Condition	$< 3 \times 10^{20}$ n/cm^2 (E > 0.1 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 μm fraction).

Reference 35	Electrophysical Properties of Plasma-Deposited Refractory Oxides under Reactor Irradiation
	V. M. Ivanov, G. M. Kalinin, V. F. Kuzovitkin, S. P. Sklizkov, N. V. Markina, V. V. Sarksyan and V. A. Skobeleva
	Inorg. Mater. 17 (1981) 1203

A-83

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

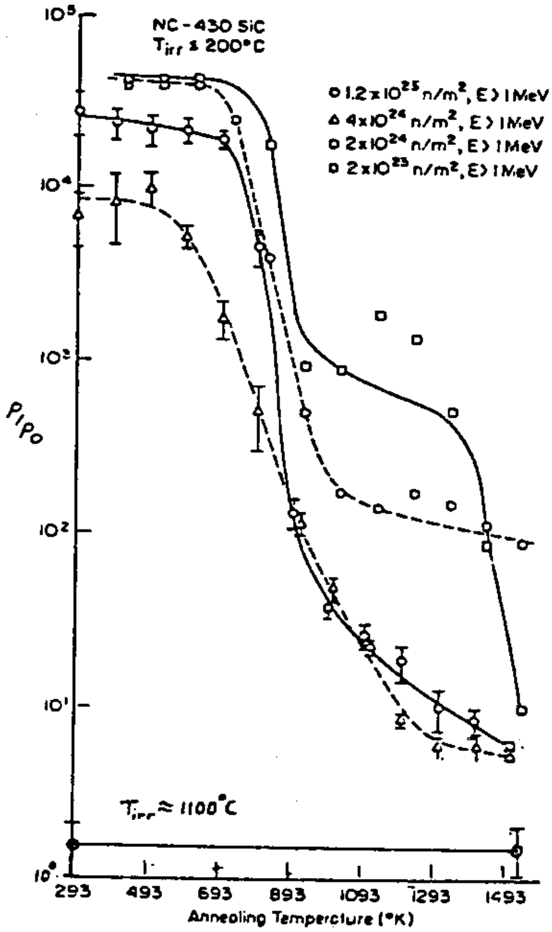


Figure 9

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

Reference 36	Ceramic Materials for Fusion Reactors
	G. Hopkins, G. C. Trantina and J. Corelli
	AP-1702, EPRI Research Project 992, Interim Report, February 1981

A-84

Material	Alumina Porcelain	Property	Electric resistivity	1/2
Irradiation Condition	9.25×10^{10} n/cm^2 (14.3, 2.3, 4.5 MeV)			

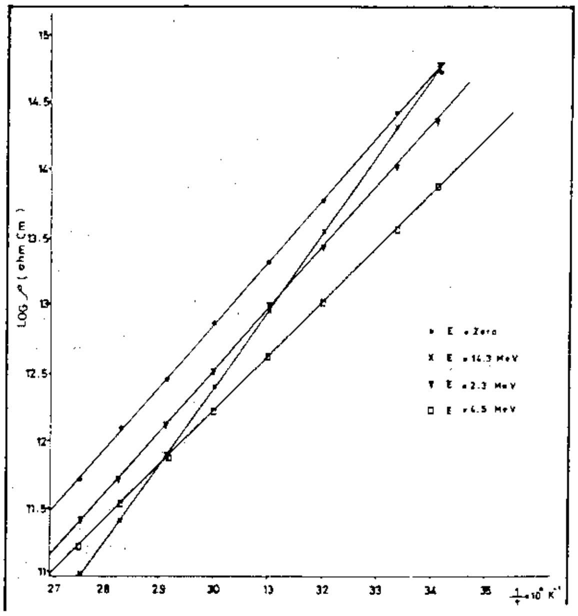


FIG. 6. Variations of log ρ vs $1/T$ for alumina porcelain samples after irradiation with a constant neutron fluence (9.25×10^{10} n/cm^2) and of different fast-neutron energies.

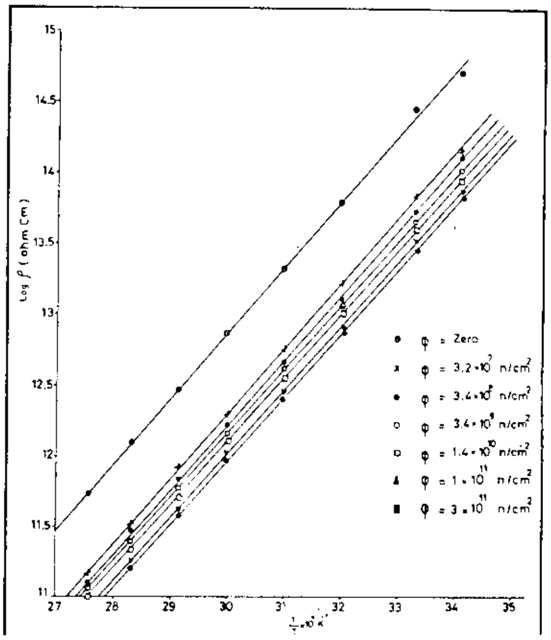
Reference 41	Effect of Fast Neutrons on the Electric Resistivity of Porcelain for Application in Fast Neutron Dosimetry
	M.A.Fadel, W.J.Abdel-Faatlah, A.A.Abdulla and A.A.Kadum
	Radiation Res. 92 (1982) 221

A-85

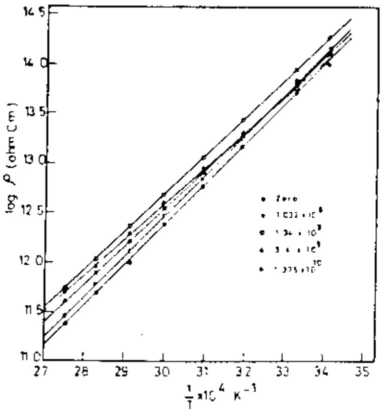
Material	Alumina Porcelain	Property	Electric resistivity	2/2
Irradiation Condition	$< 3 \times 10^{11}$ n/cm^2 (^{252}Cf, ^{241}AmBe)			

Calculated Oxide Compositions of the Fired Porcelain Samples

Sample No.	Oxides (weight %)							
	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	TiO_2	K_2O	Na_2O
1	72.26	23.01	0.63	0.34	0.82	1.25	1.03	0.66
2	53.52	41.17	0.67	0.40	1.03	1.48	1.03	0.70



Variation of log ρ vs $1/T$ for alumina porcelain samples before and after irradiation with different fission neutron fluences.

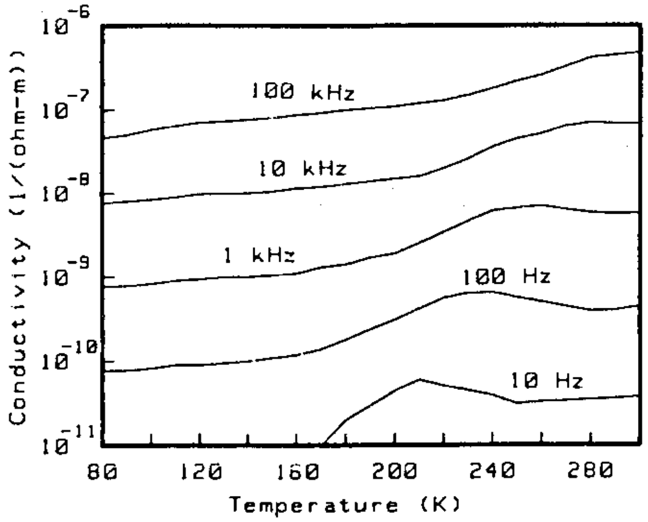


Variation of log ρ vs $1/T$ for quartz porcelain samples before and after irradiation with different fission neutron fluences.

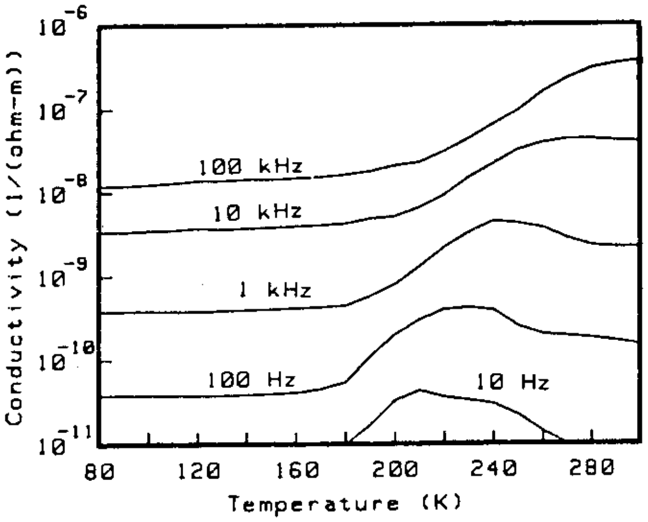
Reference 41	Effect of Fast Neutrons on the Electric Resistivity of Porcelain for Application in Fast Neutron Dosimetry
	M.A.Fadel, W.J.Abdel-Fatlah, A.A.Abdulla and A.A.Kadum
	Radiation Res. 92 (1982) 221

A-86

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



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



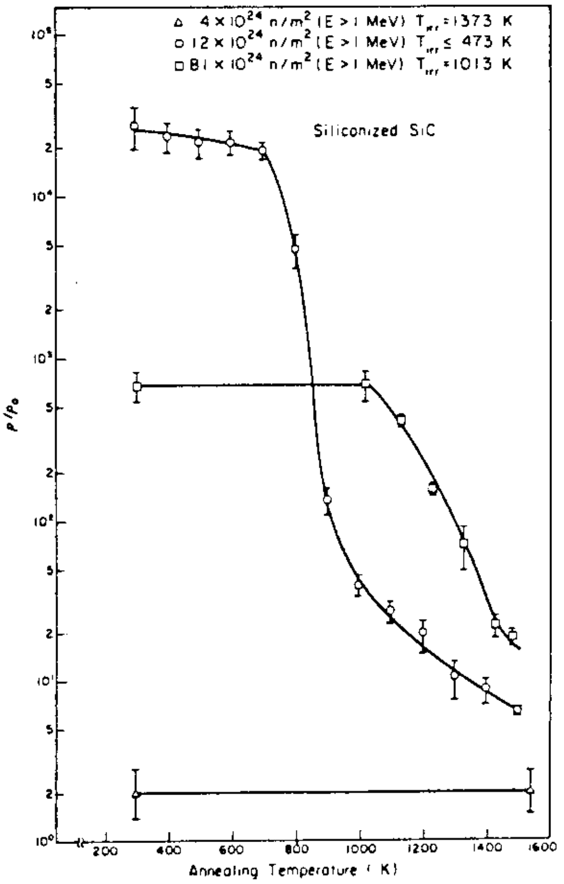
Electrical conductivity for glass-bonded mica sample irradiated to 10^{22} fast n/m^2. Frequencies are indicated.

Reference 44	Electrical Conductivity of Neutron-Irradiated Glass-bonded MICA Insulator from 80-800K
	J. D. Fowler, Jr.
	DOE/ER-0113/1, August 1982, P. 57

A-87

Material	SiC (NC-430)	Property	Resistivity	1/1

Irradiation Condition	1.2×10^{21} n/cm^2 (E > 1 MeV) HRBR (BNL) $\lesssim$ 147°C 8.1×10^{21} n/cm^2 (E > 1 MeV) HFIR (ORNL) $\sim$ 730°C



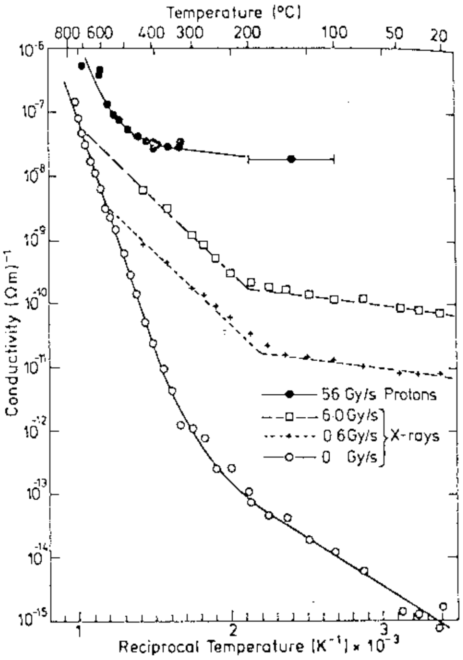
Relative resistivity vs annealing temperature for siliconized SiC; sample was held at each temperature for 10 min, and resistivity was measured at 296 K.

Reference 45	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

A-88

Material	Al_2O_3 (pc)	Property	dc conductivity	1/1

Irradiation Condition	X-ray (60kV peak) 7 Gy/s -500°C 200MeV proton, ∿ 2×10^6 W/m^2 (4.6×10^{-3} Gys^{-1}/nAm^{-2})



Log dc conductivity of Vitox alumina as a function of reciprocal temperature with and without irradiation.

Reference 52	Radiation Effects on the Electrical Properties of Alumina from dc to 65 MHz
	G. P. Pells and G. J. Hill
	J. Nucl. Mater. 141-143 (1986) 375

A-89

Material	SiO_2 α-Al_2O_3(coor AD-995)	Property	Loss tangent, Density dielectric constant	1/1

Irradiation Condition	6×10^{17} n/cm^2 (fast) Brookhaven Reactor 95°C 2.5×10^{19} 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.

Fused Silica

Irradiation (neutrons per cm^2)	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

α Alumina

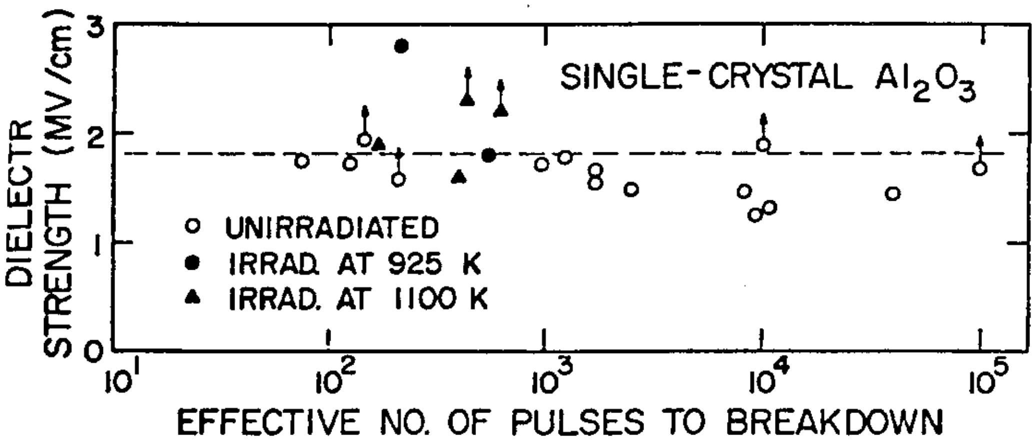
Irradiation (neutrons per cm^2)	ϵ'	$\tan\delta$ (10^{-4})	Cell constants a (Å)	Cell constants c (Å)	Density change (%)
Unirradiated	9.2 ±0.1	0.3 ±0.1	4.757 ±0.002	12.978 ±0.002	0
6×10^{16}	9.2 ±0.1	0.3 ±0.1	...	...	...
2×10^{17}	9.0 ±0.1	0.5 ±0.1	...	...	...
6×10^{17}	8.9 ±0.1	4.0 ±0.5	4.759 ±0.002	12.984 ±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 δ was measured at 1 MHz

Reference 14	Room-Temperature Dielectric Properties of Fast-Neutron-Irradiated Fused Silica and α Alumina
	J. B. MacChesney and G. E. Johnson
	J. Appl. Phys. 35 (1964) 2784

A-90

Material	Al_2O_3 (sc)	Property	Dielectric strength	1/1
Irradiation Condition	∿ 2×10^{22} n/cm^2 (E > 0.1 MeV) EBR-II 650°C, 827°C			



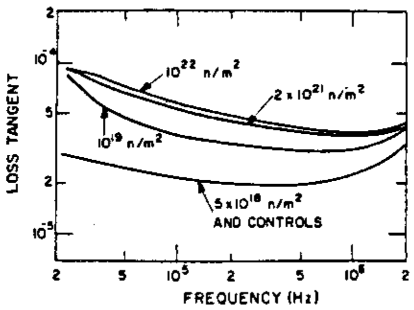
RT, short-pulse dielectric breakdown strength of Al_2O_3 before and after elevated-temperature irradiation to ~2×10^{26} n/m^2 (E > 0.1 MeV).

Reference 37	The Inorganic Insulator Program at LASL
	F. W. Clinard, Jr. and D. M. Parkin
	USDOE Report No. CONF-801237, 1981, P17-1

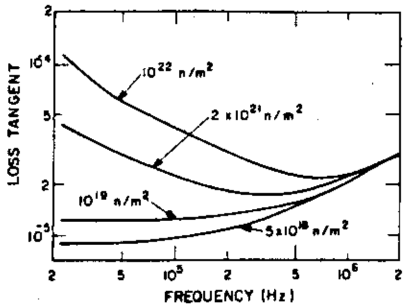
A-91

Material	Al_2O_3 (sc,pc)	Property	Loss tangent	1/1

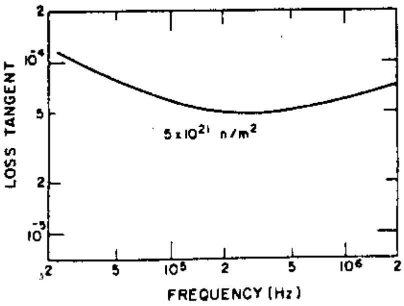
Irradiation Condition	5×10^{17} n/cm^2 (RTNS-II) 1×10^{18} n/cm^2 (LAMPF)



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

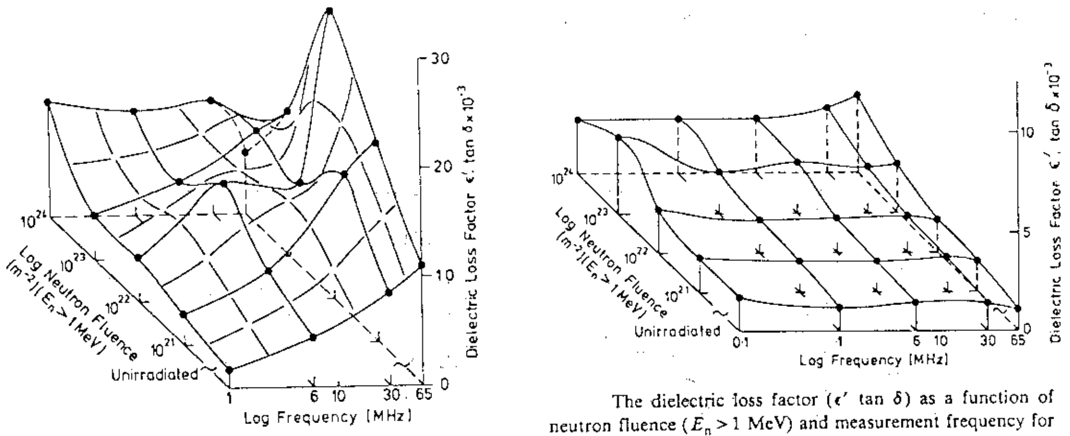
A-92

Material	Al_2O_3 (pc)	Property	Dielectronic loss	1/1

Irradiation Condition	$1 \times 10^{17} \sim 10^{20}$ n/cm^2 (E > 1 MeV) Herald reactor 67°C

Permittivity and dielectric loss factor (ϵ' tan δ) for two grades of neutron irradiated alumina

Material	Neutron fluence (n/m^2) ($E_n > 1$ MeV)	Permittivity at 1 MHz	Dielectric loss factor (ϵ' tan δ)$\times 10^{-3}$ at the stated frequency (MHz)				
			0.1	1	6	30	65
Vitox (99.9% Al_2O_3)	As received	10.130	–	1.68	4.59	8.49	11.0
	10^{21}	10.228	–	2.80	6.71	15.5	18.2
	10^{22}	10.298	–	4.14	10.81	10.7	26.4
	10^{23}	10.234	–	4.12	7.03	11.5	13.3
	10^{24}	–	–	10.54	9.53	10.40	5.57
Deranox (97.5% Al_2O_3)	As received	9.516	1.75	1.20	1.45	1.41	1.07
	10^{21}	9.567	1.77	1.60	1.59	1.78	1.55
	10^{22}	9.547	2.19	1.68	1.74	1.84	1.66
	10^{23}	9.588	3.86	2.03	2.55	2.31	2.43
	10^{24}	–	2.71	2.73	2.73	3.29	3.90

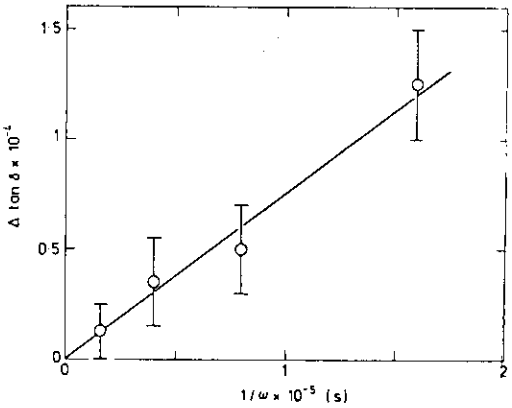


The dielectric loss factor (ϵ' tan δ) as a function of neutron fluence ($E_n > 1$ MeV) and measurement frequency for (a) Vitox (99.9% pure alumina) and (b) Deranox (97.5% pure alumina). Note the change in ordinate scales.

Reference 52	Radiation Effects on the Electrical Properties of Alumina from dc to 65 MHz
	G. P. Pells and G. J. Hill
	J. Nucl. Mater. 141-143 (1986) 375

A-93

Material	Al_2O_3 (pc)	Property	Loss tangent	1/1
Irradiation Condition	1×10^{18} n/cm^2 (E > 1 MeV) Herald reactor 670°C +X-ray, ∿8 Gy/s			



The increment in dielectric loss of 97.5% pure alumina fast neutron irradiated to 10^{22} n/m^2 ($E_n > 1$ MeV) at 340 K as a function of reciprocal frequency, while exposed to 60 kV peak X-rays at a dose rate of ~ 8 Gy/s.

Reference 52	Radiation Effects on the Electrical Properties of Alumina from dc to 65 MHz
	G. P. Pells and G. J. Hill
	J. Nucl. Mater. 141-143 (1986) 375

A-94

Material	BeO	Property	Lattice parameter	1/1

Irradiation Condition	1×10^{20} ∿ 1×10^{21} n/cm^2 HIFAR 75 ∿ 100°C

Details of materials

Material reference	Powder source	Fabrication method	Density (% theoretical)	Grain size (μm)
A	Pechiney	Hot pressed at 1750° C for ½ h at 1 tsi	96–98	10–20
B	Brush UOX pre-ground	Cold pressed at 20 tsi Sintered at 1600–1620° C	97–98	7.5–15
C	,,	Cold pressed at 20 tsi Sintered at 1500–1550° C	95–96	2–3
D	,,	Cold pressed at 20 tsi Sintered at 1450–1500° C	90–94	1–2

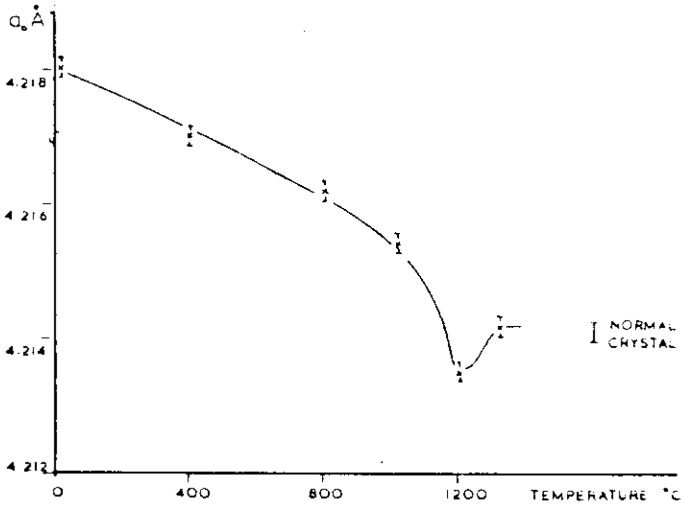
Lattice parameter changes in materials A and C irradiated to 5×10^{20} nvt.

Material	Condition	c Parameter change (%)	a Parameter change (%)
A	Powdered	1.6 ± 0.2	0.105 ± 0.005
C	Solid	0.5 ± 0.1	0. 14 ± 0. 01
C	Crushed	1.4 ± 0.1	0. 10 ± 0. 01

Reference 2	Effect of Microstructure on the Irradiation Behavior of Beryllium Oxide
	B. S. Hickman and D. G. Wlaker
	J. Nucl. Mater. 10 (1963) 243

A-95

Material	MgO (sc)	Property	Lattice parameter	1/1
Irradiation Condition	4×10^{19} n/cm^2 < 200°C			

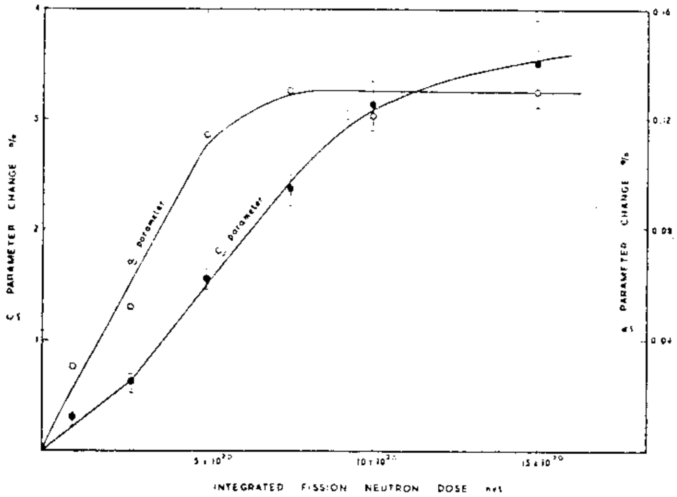


The recovery of the x-ray lattice parameter measured with CuK radiation. The values have been corrected to 25 c.

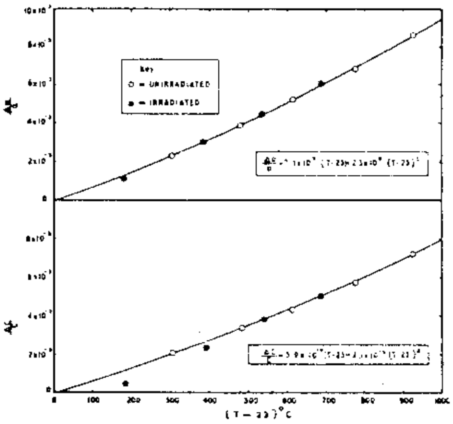
Reference 4	Neutron Damage in MgO G. W. Groves and A. Kelly Phil. Mag. 8 (1963) 1437

A-96

Material	BeO (hot pressed, sintered)	Property	Lattice parameter	1/1
Irradiation Condition	$< 1 \times 10^{21}$ nvt 75 ∿ 100°C, 510 ∿ 700°C			



Variation of *c* and *a* parameters with neutron dose for material irradiated at 75–100 C.



Thermal expansion of the *c* and *a* parameters.

Details of materials used in the investigation.

Material No.	Starting Material	Fabrication Method	Density % Theoretical	Grain Size μ
1	Pechiney	Hot pressed at 1750°C at 1 tsi	96–98	15–20
2	Brush UOX	Cold pressed at 20 tsi and sintered for 1 hour at 1550°C	95–96	10–15
3	Brush UOX	Cold pressed at 20 tsi and sintered for 1 hour at 1500°C	95–96	2–3
4	Brush UOX	Cold pressed at 20 tsi and sintered for 1 hour at 1450°C	90–93	1–2

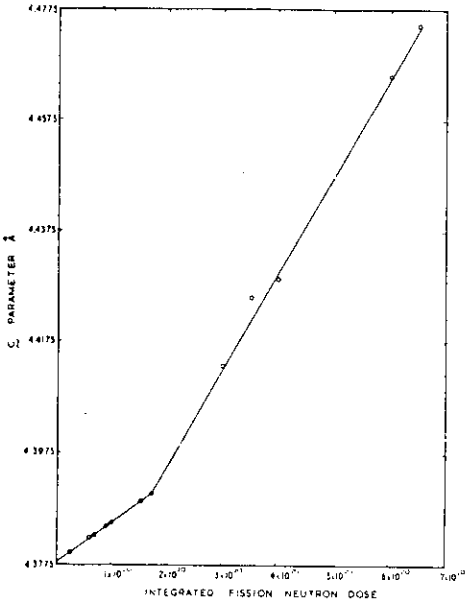
c parameter changes during elevated temperature irradiation

Temperature C	Dose nvt	$\Delta c/c$ %	$\Delta c/c$ for same dose at 100°C
510–540	5.5×10^{20}	0.60 ± 0.03	1.75
520–550	9×10^{20}	1.42 ± 0.03	3.0
580–600	4.5×10^{20}	0.51 ± 0.04	1.4
570–600	1.1×10^{21}	1.2 ± 0.1	3.3
650–690	6.5×10^{20}	0.5 ± 0.1	2.1
670–700	1.2×10^{21}	1.0 ± 0.2	3.4

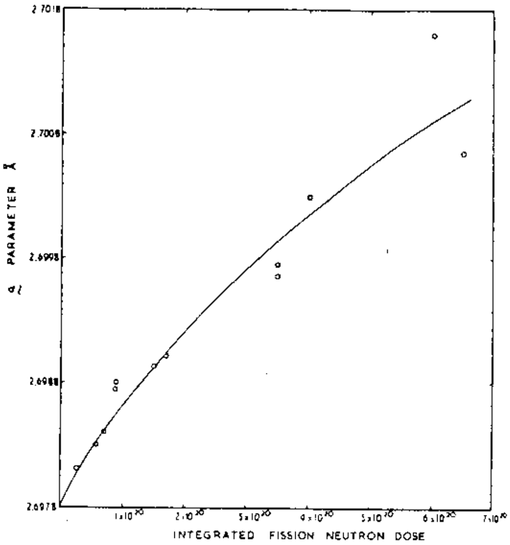
Reference 9	X-ray Diffraction Studies of Irradiated Beryllium Oxide
	D. G. Walker, R. M. Mayer, and B. S. Hickman
	J. Nucl. Mater. 14 (1964) 147-158

A-97

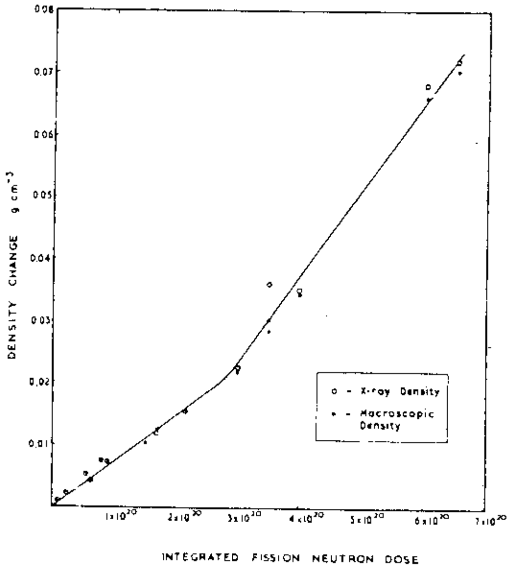
Material	BeO (sc)	Property	Lattice parameter	1/1
Irradiation Condition	$8.1 \times 10^{18} \sim 6.5 \times 10^{20}$ nvt $7.5 \sim 100$°C			



The variation of the *c* parameter with neutron dose.



The variation of the ***a*** parameter with neutron dose.



Comparison of the variation of macroscopic density and X-ray density with neutron dose.

Reference 10	Comparison of Macroscopic and X-ray Growth in Irradiated BeO Single Crystals
	B. S. Hickman, D. G. Walker and R. Hemphill
	J. Nucl Mater. <u>14</u> (1964) 167-174

A-98

Material	BeO (hot-pressed, sintered)	Property	Lattice parameter	1/1

Irradiation Condition	1.2 ∿ 3.65 x 10^{21} n/cm^2 ETR 583 ∿ 1100°C

Results of X-ray diffraction examinations of irradiated BeO †

Capsule no. and BeO type ††	Neutron dose (nvt)	Temperature (°C)	$\Delta c/c_0$	$\Delta a/a_0$	$(\Delta c/c_0)/(\Delta a/a_0)$
	($\times 10^{21}$)		($\times 10^{-3}$)	($\times 10^{-2}$)	
1 CP	1.2	583 †	0.62	0.32	1.9
2 CP	1.95	906	0.43	0.10	4.3
HP			0.57	0.07	7.7
3 CP	2.65	915	1.12	0.11	10.2
HP			0.75	0.08	9.6
4 CP	3.28	969	0.68	0.14	4.9
HP			0.71	0.06	11.3
5 CP	3.65	926	1.39	0.14	9.9
HP			1.07	0.12	8.9
6 CP	3.63	825	1.44	0.07	20.6
HP			1.46	0.04	36.5
7 CP	3.05	935	0.07	0.01	7.0
HP			0.48	0.06	8.0
8 CP	2.25	1100	0.32	0.14	2.7
HP			0.23	0.09	2.7

† The values of the lattice parameters of the control samples are as follows: cold-pressed, $a_0 = 2.69782 \pm 0.00005$ Å, $c_0 = 4.37770 \pm 0.00020$ Å; hot pressed, $a_0 = 2.69781 \pm 0.00005$ Å, $c_0 = 4.37792 \pm 0.00023$ Å.

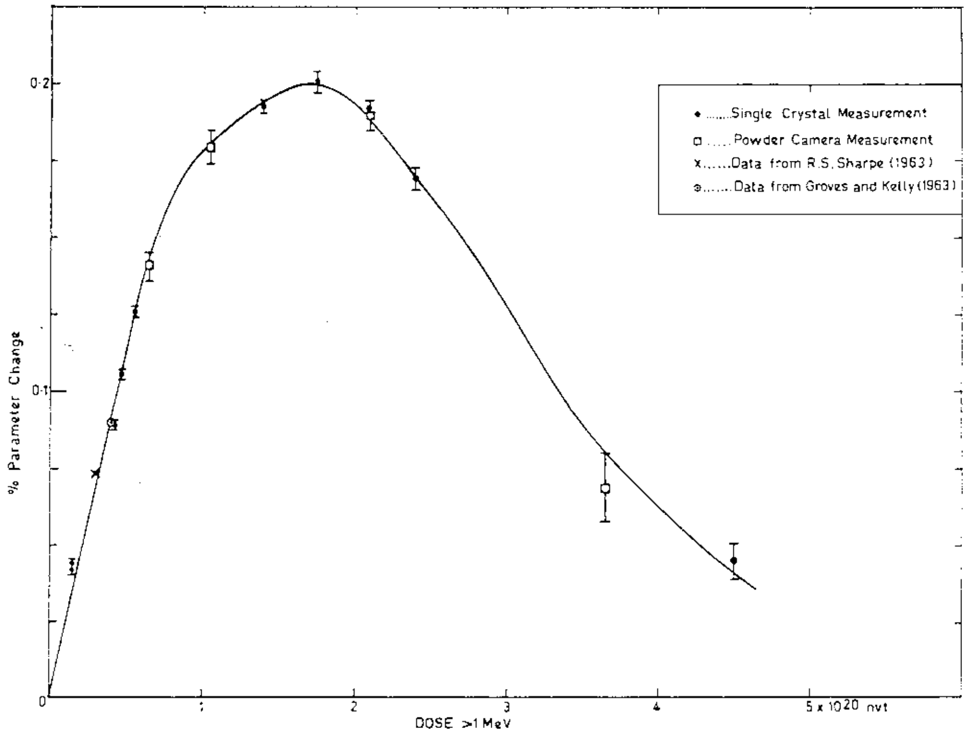
The ranges of probable errors in the parameter measurements of the irradiated samples are as follows: a, 0.00004 – 0.00010 Å; c, 0.0004 – 0.0010 Å.

†† The symbols CP and HP refer to cold-pressed and sintered and hot pressed BeO, respectively.

Reference 12	The Effect of Fast-neutron Irradiation on Beryllium Oxide Compacts at High Temperatures
	G. W. Keilholtz, J. E. Lee, Jr. and R. E. Moore
	J. Nucl. Mater. 11 (1964) 253

A-99

Material	MgO (sc, pc)	Property	Lattice parameter	1/1
Irradiation Condition	$1.4 \times 10^{19} \sim 6.5 \times 10^{20}$ n/cm^2 (E > 1 MeV) HIFAR 75 ∿ 100°C			

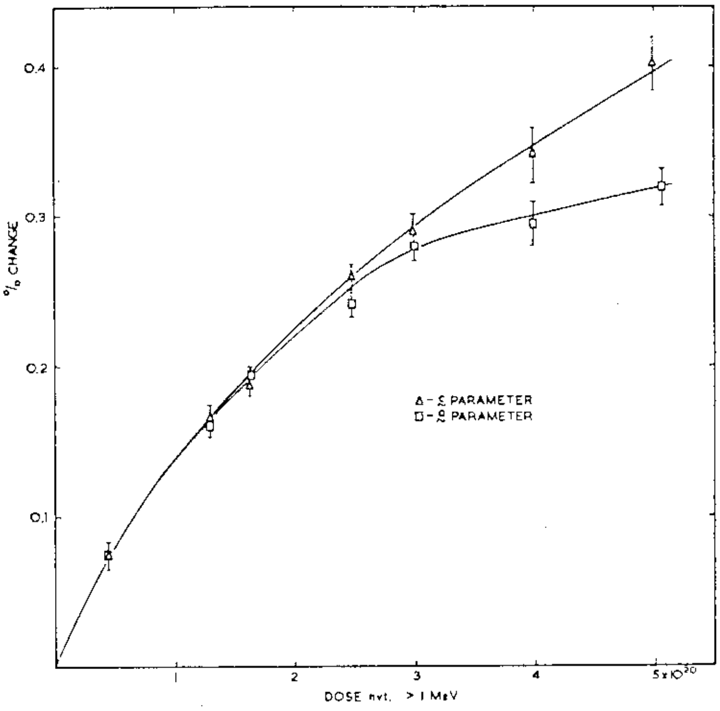


Variation of lattice parameter with neutron dose. The results of Sharpe (1963) and Groves and Kelly (1963) are also shown for comparison.

Reference 13	Growth of Magnesium Oxide during Neutron Irradiation
	B. S. Hickman and D. G. Walker
	Phil. Mag. 11 (1965) 1101

A-100

Material	Al_2O_3 (sc, pc)	Property	Lattice parameter	1/1
Irradiation Condition	< 5 x 10^{20} n/cm^2 (E > 1 MeV) HIFAR 75 ∿ 100°C, 500 ∿ 700°C			



Lattice parameter changes as a function of neutron dose at 75–100° C.

Results of lattice parameter measurements on aluminium oxide irradiated at elevated temperatures

Dose (nvt)	Temperature (°C)	$\Delta c/c$ (%)	$\Delta a/a$ (%)	$\Delta V/V$ (theor.)
2.8×10^{20}	550	0.12	0.11	0.34
3.2×10^{20}	600	0.12	0.13	0.38
2.5×10^{20}	700	0.06	0.07	0.20

Reference 15	The Effect of Neutron Irradiation on Aluminium Oxide
	B. S. Hickman and D. G. Walker
	J. Nucl. Mater. 18 (1966) 197

A-101

Material	BeO (sintered)	Property	Lattice parameter	1/1
Irradiation Condition	$< 2 \times 10^{21}$ 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[a]	BeO Type	Fast-Neutron Dose (>1 MeV) (n/cm^2)	Fast-Neutron Flux (>1 MeV) [(n/(cm^2 sec)]	Temp. (°C)	$\Delta a/a_0$	$\Delta c/c_0$	$\Delta V/V_0$[b]
		$\times 10^{21}$	$\times 10^{14}$		(± 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 Kα x radiation from BeO compacts irradiated in Experiments 41-8 and 41-9, which were ground to a fine powder.

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

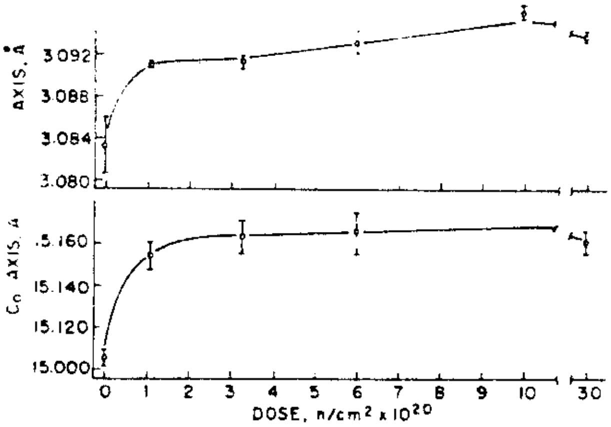
[b] The fractional volume increase $\Delta V/V_0$ was calculated from the equation $\Delta V/V_0 = 2\,\Delta a/a_0 + \Delta c/c_0$.

Reference 16	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. Soc. and Eng. 26 (1966) 329

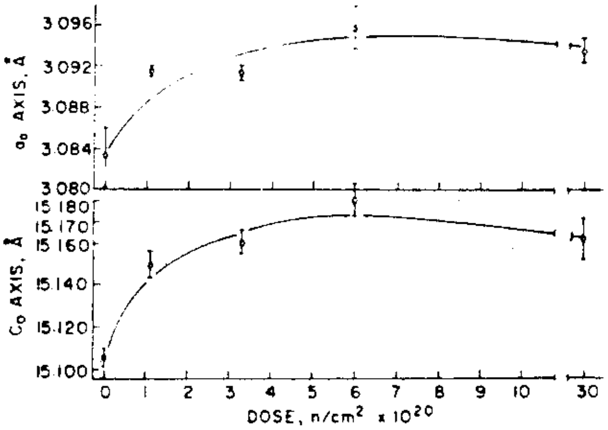
A-102

Material	SiC (α-SiC)	Property	Lattice parameter	1/1

Irradiation Condition	3×10^{21} n/cm^2 (E > 1 MeV) 450, 650°C



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

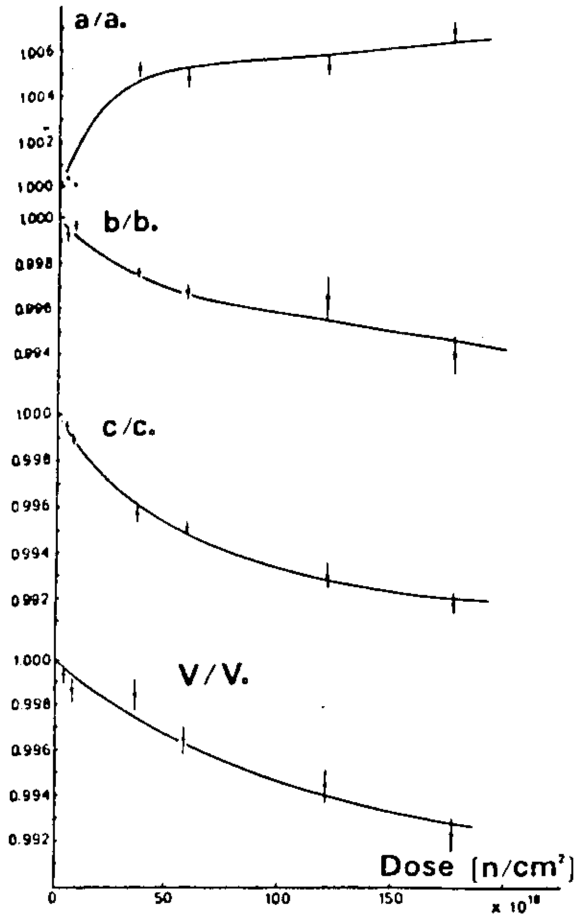


α-SiC lattice parameters as a function of irradiation at 650°C.

Reference 22	Irradiation Damage in Reaction-bonded Silicon Carbide
	R. B. Mattews
	J. Nucl. Mater. 51 (1974) 203

A-103

Material	Si_2N_2O	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 Si_2N_2O with fast neutron irradiation.

Reference 29	Variation of the Lattice Parameters of Si_2N_2O with Fast Neutron Irradiation
	M. Billy, J. C. Labbe, A. Selvaraj, G. Roult and L. Cartz
	J. Am. Ceram. Soc. 62 (1979) 540

A-104

Material	Si_3N_4, Sialon, Si_2ON_2	Property	Lattice parameter	1/1

Irradiation Condition	3×10^{21} n/cm^2 (E > 0.1 MeV) EBR-II 742°C

Material	**Major Phase**	**Impurity Phases**
Norton Si_3N_4	β-Si_3N_4	σ-Si_3N_4 Si_2ON_2 MgO
Ceradyne Si_3N_4	β-Si_3N_4	MgO
Si_2ON_2	Si_2ON_2	β-Si_3N_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%

[a] Norton NC-132

[b] Ceradyne

Reference 38	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, P.2-3

A-105

Material	Al_2O_3 (sc)	Property	Optical absorption Coefficient	1/2
Irradiation Condition	5 ∿ 15 MeV proton (LASL Tandem Vaan 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	5.6×10^{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

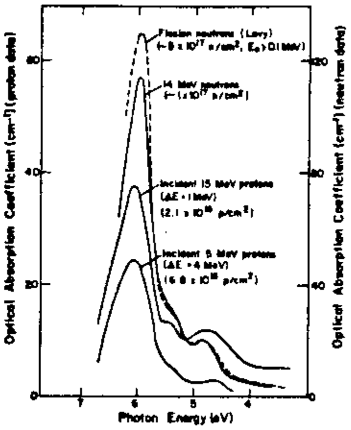
**This may have underestimated by ~30% because of spectrophotometer stray light.

Reference 24	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

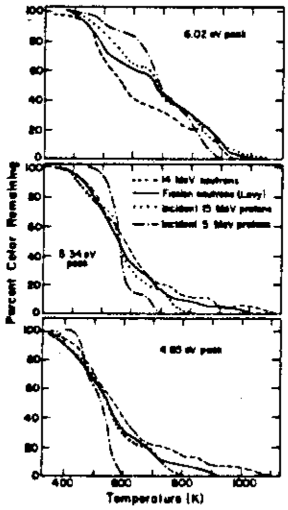
A-106

Material	Al_2O_3 (sc)	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 24	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

A-107

Material	$BeO, Al_2O_3, Al_2O_3-SiO_2$	Property	Helium liberation Helium migration	1/1
Irradiation Condition	$0.73 \sim 1 \times 10^{21}$ n/cm^2 ($E \geq 0.8$ MeV)			

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

Material	Chemical composition, mass %							Nuclear reaction	Neutron fluence ($E \geq$ 0.8 MeV), neutr./cm^2	Irradiation temp., °C	Concn. of helium, atom/cm^3 (calculation)	Concn. of stored vacancies per 1 cm^3 [12-14]
	Al_2O_3	SiO_2	Fe_2O_3	CaO	B_2O_3	MgO	LiO					
BeO								$^9Be(n, \alpha)^6Li$ $^9Be(n, 2n)2^4He$	$6 \cdot 10^{20}$	~ 75	$1,44 \cdot 10^{19}$	$2,88 \cdot 10^{21}$
GB-7	97,07	0,92	0,08	0,9	0,02	—	—	$^{10}B(n, \alpha)^7Li$	$1,26 \cdot 10^{20}$ $1,0 \cdot 10^{21}$	~ 100	$6,4 \cdot 10^{19}$ $1,22 \cdot 10^{20}$	$1,15 \cdot 10^{20}$ $9,2 \cdot 10^{20}$
MG-2	60,14	21,12	0,4	2,32	1,67	2,54	—	$^{10}B(n, \alpha)^7Li$	$1,26 \cdot 10^{20}$ $1,0 \cdot 10^{21}$	~ 100	$9,38 \cdot 10^{19}$ $1,66 \cdot 10^{20}$	$1,15 \cdot 10^{20}$ $9,2 \cdot 10^{20}$
L-24	47,5	41,67	2,01	0,61	—	7,2	0,5	$^6Li(n, \alpha)^3H$	$1,26 \cdot 10^{20}$ $1,0 \cdot 10^{21}$	~ 100	$2,52 \cdot 10^{19}$ $3,88 \cdot 10^{19}$	$1,15 \cdot 10^{20}$ $9,2 \cdot 10^{20}$

Activation Energy for Migration of Helium in Different Irradiated Ceramic Specimens

Specimen	Activation energy, 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	
	0,5—1,4	350—500	10,0
GB-7	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
AlN	0,1—0,2	100—300	1,26
	0,5—0,6	200—400	
	0,25—1,0	600—800	12,0

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

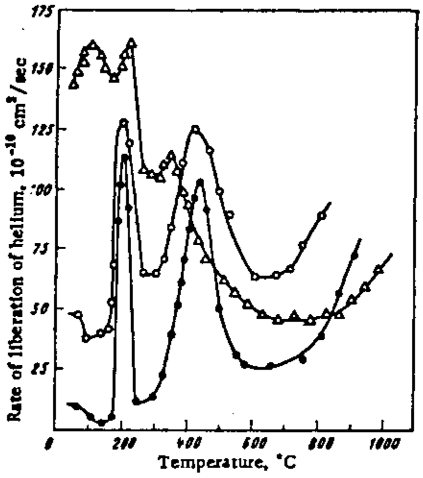


Fig. 3

Temperature dependence of the rate of liberation of helium out of beryllium oxide, irradiated to a fluence of $6 \cdot 10^{20}$ (●); $7 \cdot 10^{20}$ (○); and $1.2 \cdot 10^{21}$ (△) neutrons/cm^2. The annealing rate was 5°C/min.

Reference 42	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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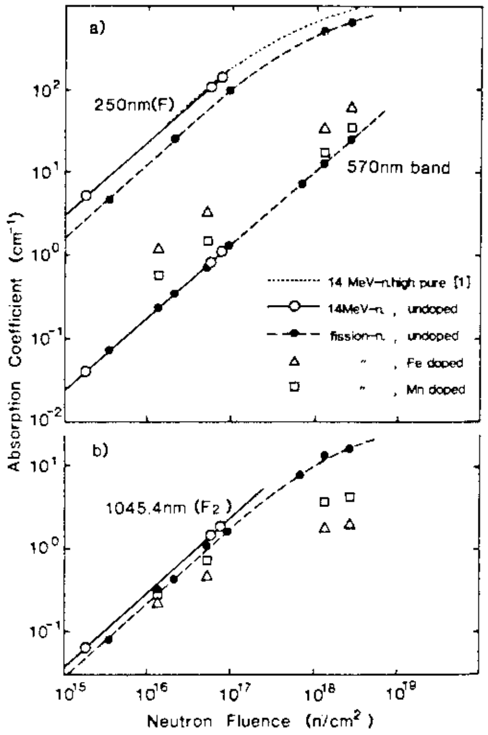
Material	MgO (sc)	Property	Optical absorption	1/1

Irradiation Condition	1.4 x 10^{10} n/cm^2 KUR < 100°C 8 x 10^{16} n/cm^2 (E = 14 MeV) RTNS-II RT



Absorption coefficient of the (a) 250 (F-type centers) and 570 nm bands, (b) 1045.4 nm line (F_2 center) resulting from neutron irradiations in the RTNS-II and KUR as a function of neutron fluence. The dotted line of the upper part in (a) is a curve of the absorption coefficient of F-type centers for the high-purity MgO crystals irradiated by 14 MeV neutrons from the RTNS facility obtained by Chen et al. [1]. Solid lines: the observations of the nominally pure samples irradiated by 14 MeV neutrons. Broken lines: the observations of the nominally pure samples irradiated by fission neutrons.

Reference 51	Optical Properties of MgO Irradiated by Fast Neutrons
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7. Summary

A data base of radiation effects on ceramic insulators was made by collecting the published literatures during 1960 to 1986. The data were classified according to the properties of ceramics. As to swelling, the data were compiled as a function of neutron fluence and irradiation temperature. As the study of radiation damage on ceramics is now in progress, the data base is thought to be insufficient for getting sound understanding of radiation effects and optimizing materials to radiation environment. However, in the present work, general response of ceramics to radiation, especially swelling behavior, would be clarified to some extent.

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