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INSULATOR APPLICATIONS IN A TOKAMAK REACTOR

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ABSTRACT

Insulators, among which insulators ceramics, have great potential applications in fusion reactors. They will be used for all plasma-facing components as protection and, magnetic fusion devices being subject to large electrical currents f.owing in any parts of the device, for their electrical insulating properties.

Graphite, silicon carbide and titanium carbide are potential candidates for the first wall protection against disruptions. Alumina, spinel, magnesium oxyde should be used as insulating materials for windows to equip radio frequency heating antennae. To minimise eddy current losses and to limit electromagnetic forces in the nuclear island ceramic electrical current breakers have to be foreseen. Diagnostics must in general, be separated from the plasma by ceramic windows. Future magnetic fusion devices will make a large use of superconducting coils ; organic insulators such as epoxy resins and polyimides are largely present in such coils but are very sensitive to radiation effects, so ceramic insulators are candidates for this purpose. Other possible utilisations of ceramic insulators exist, for electrical insulation of the vacuum pump motors for example.

Considering these uses of insulators in fusion devices, their behaviour in a strong neutron and gamma-ray field is of utmost importance. Many measurements have been performed in fission reactors on most of the candidate materials but the effects of 14 MeV neutrons and high gammaray fields ($> 10^7$Gy) are unknown. A worldwide research and development programme is under way in the world, mainly in the European countries, to get this information in due time for the construction of the next-generation fusion devices such as **INTOR/NET**.

INSULATOR APPLICATIONS IN A TOKAMAK REACTOR

1. INTRODUCTION

In the next generation of fusion reactors (INTOR, NET, FED) and even more in the future devices such as DEMO and the first commercial reactors, a large use of electrical insulators will be needed. Radiation levels and/or high temperature are sufficiently high to require ceramic insulators. In addition to these dielectrical property requirements some parts of the device will impose the use of ceramics transparent to a well-defined wavelength range for optical diagnostics. Moreover the first wall of the next generation devices will be subject to strong sputtering due to energetic particles and severe damages by runaway electrons and disruptions. Even for the present generation of large tokamaks like JET a first wall protection against such damage had to be set up.

The most severe conditions in magnetically confined fusion reactors for insulating or protective material occur for components directly facing the plasma, but other parts of the device require the use of ceramic insulators like superconducting coil insulators, vacuum pump motors, insulated parts of different sensors, etc... Each of these different utilisations will require different ceramics with well defined properties and a large effort of development has to be undertaken if we wish to reach the goal in due time.

2. WORKING CONDITIONS FOR INSULATORS.

For fusion reactors consider for electricity production it is foreseen, accounting for the damage in structural materials, to exchange the first wall and blanket module every two years. This results in the 14 MeV neutron fluence given in TABLE I.

The fluence level indicated in this table implies that all components directly facing the plasma have to support a number of impinging 14 MeV neutrons ranging between 5.10^{25} to 10^{26} $n.m^{-2}$. This will lead to a very high structural damage level in these component materials.

In addition to this high neutron bombardment level materials have to work in a broad temperature range, leading to thermal fatigue effects and to mechanical stresses which also affect the integrity of these insulators or protective materials. Surface effects like sputtering, blistering, etc... would increase the difficulty of selecting possible materials and solutions to be retained for a fusion reactor. TABLE II give a possible selection of these materials and their working conditions (from [4]).

3. FIRST WALL PROTECTION MATERIALS.

In the present large fusion tokamak a first wall protection against deleterious effects of disruptions and runaway electrons, generally present at the start of major disruptions, has to be provided, at least in the inboard part of the machine. Effects of such phenomena have been reported in ref. [5] . Moreover in ref. [6] a new disruption scenario is described, raising the problem of an energy deposition duration of 2 ms instead of 20 ms as referred to previously.

For the first wall protection the primary candidate is graphite, followed by silicon carbide, titanium carbide and boron carbide in that order.
Some other candidates such as tungsten and molybdenum have been contemplated in some studies (ref. [2]) but from the plasma contamination aspects low Z materials as the above mentioned are preferable by far.

A concern with a first wall ceramic protection is the tile attachment to the structural material (stainless steel). Ceramic brazing on steel or attachments using compliant material (composite fibres) are, at present, not reliable. Proposed solutions use mechanical attachments to fix tiles to the structural first wall, which implies that the heat flux is evacuated only by radiation and of the heat flux fraction flowing through the thin mechanical connection is then negligable compared to the radiation flux. The immediate effect is that tiles work in the high temperature range 1300-1800 K.

3.1 - Graphite is the most commonly proposed material for first wall protection and is widely used in today's machines. Among different property requirements for the first wall protective material a good resistance to thermal fatigue, thermal stresses and a low sputtering yield are the most important. Resistance to thermal shock and cyclic fatigue depend on high thermal conductivity, a large strength to Young's modulus ratio and a low thermal expansion coefficient. The irradiation behaviour of graphite is strongly anisotropic, reflecting the layer structure of its lattice. Irradiation strains and thermal and mechanical changes are dependent on the microstructure of polycrystalline graphite. Isotropic carbone can be obtained in which the anisotropy is averaged out by randomisation of the grains.

The fabrication process may therefore be expected to have an important influence on irradiation behaviour. Diametral changes have been measured on carbon fibres after irradiation to 1.4 x $10^{25}n.m^{-2}$. Strains depend on fibre type. Low density, amorphous carbons have been irradiated and contractions observed [7].

The thermal expansion coefficient changes depend on structure, temperature and fluence. The thermal conductivity is degraded rapidly at low fluences and falls to a plateau above $10^{26}n.m^{-2}$ ($E > 0.1$ MeV). Effects on mechanical properties are similar, with a 25-150 % increase in Young's modulus for fluences of $10^{26}n.m^{-2}$. The fracture stress shows a slight decrease up to a high neutron fluence, where dimensions begin to expand beyond their original size due to the formation of large cracks with an approximate limit to useful life of 2 x $10^{26}n.m^{-2}$.

Chemical sputtering is a concern with graphite at low temperature ; a maximum erosion rate is measured around 800 K, then sputtering decreases at temperatures considered for fusion reactors (1300-1800 K) and increases again above 2000 K.

3.2 - Silicon carbide can exist in different structural forms. Cubic βSiC is the stable structure formed in the temperature range 1900-2300 K whilst above 2800 K hexagonal 6H SiC is formed. Below 1900 K both types may be regarded as stable. Silicon carbide is relatively stable under neutron irradiation, both types undergoing nearly isotropic expansion which saturates with increasing doses. The thermal conductivity of SiC is reduced by neutron induced damages. Degradation occurs rapidly at low fluences and then continues much more slowly. The fractional change is considerably smaller following high temperature irradiation.

The modulus of rupture and elastic modulus of SiC are not significantly changed by neutron fluences of $1.2 \times 10^{26} n.m^{-2}$ at temperatures of 1300 K and below. The fracture strength falls rapidly with initial exposure, then levels out and even recovers slightly with increasing neutron doses up to $6 \times 10^{25} n.m^{-2}$. Young's modulus shows a similar pattern with an initial drop of 15 % followed by recovery with increasing dose [8].

As in the case of graphite, the chemical sputtering of SiC should be a concern. The highest level is less than for graphite, but this may lead to a silane production which will raise problems in the tritium system.

3.3 - **Titanium carbide and boron carbide** are also both considered to protect the first wall against disruption. Very little work has been done on these two materials. One concern is the high reactivity of titanium with hydrogen (tritium) which may lead to a large tritium inventory.
Measurements have been carried out [9] on implanted deuterium profiles inside a thin titanium carbide coating on molybdenum ; results are shown on fig. 2. Deuterium atoms in the film are considered to be very stably trapped near the surface and do not diffuse to the bulk. The saturation concentration is found to be 0.75 D/host, leading to very high inventories. The total retention to a depth of 2000 Å is measured as 2.6×10^{17} D/cm^2 for a dose of 2.3×10^{18}D/cm^2. The depth profile of titanium exhibits no change after irradiation but the carbon profile shows a concentration peak close to the surface, followed by a strong depletion zone.

Helium production by the $^{10}B(n, \ )^7Li$ reaction in boron carbide raises the swelling problem. Single crystals of B_4C have been irradiated at 250°C up to a fluence of $11.10^{19} n/cm^2$ (E > 0.183 MeV) with a ^{10}B burnup of about $3 \times 10^{21} (n,\alpha)/cm^3$, and sintered pellets at 500°C with a burnup ranging from 2.65 to $10.4 \times 10^{20} (n,\alpha)/cm^3$ [10]. Helium bubbles were formed in both cases with a highly anisotropic distribution in single crystals. Fig. 3 shows the volume change of neutron irradiated B_4C single crystals calculated from density changes. The volume decreases after annealing at 1000°C, indicating that strain fields around helium bubbles are reduced.

4. INSULATORS FOR R.F. HEATING WINDOWS.

In the present fusion reactor designs, plasma heating is provided by radio frequency heating devices. Three distinct heating modes are foreseen :

Ion Cyclotron Resonance Heating (ICRH) : frequency range 50 to 300 MHZ.

Lower Hybrid Resonance Heating (LH) : frequency range 1 to 10 GHz.

Electron Cyclotron Resonance Heating (ECRM) : frequency range 50 to 300 GHz.

To contain the fuel and for impurity control, it is desirable to have a window separating the plasma region from the radio frequency transmission system. Also some antennae require the use of SF_6 in the transmission system to prevent voltage breakdown in the waveguide. Ceramics are prime candidate materials for such RF windows owing to their low loss characteristics and mechanical strength, while in addition some ceramics offer a high thermal conductivity compared to other insulators.

Relevant properties of possible ceramics for RF window are given in TABLE III [11].

The working conditions of such RF windows are severe calculations made for the INTOR ICRH launcher [12] are given in TABLE IV.

4.1 - Electrical Properties.

Power losses in any material depend mainly on the frequency of the wave, the loss tangent and the dielectric constant of the material. Low loss tangents are required for the RF systems to minimise power losses. Insulators tend without irradiation effects to have low loss tangent (10^{-3}-10^{-4}) in the ICRH frequency range and obviously low AC electrical conductivity.

Loss tangent measurements after neutron irradiation with a neutron spallation source have been carried out on Al_2O_3 single crystals and polycrystalline Al_2O_3 [13] . As illustrated in fig. 4 and 5 an increase in loss tangent is apparent at small doses, but higher doses lead to smaller increases. However irradiations with a 14 MeV neutron source show significantly more damage than do fission-spectrum neutrons. The frequency ranges of interest are in any case higher by several orders of magnitude than the measurement area, and possible degradation of the loss tangent in the domain considered for RF heating is totally unknown. Changes in loss tangent could create serious thermal gradient effects in ceramics if the increased loss tangent exceed those of the unirradiated values by about an order of magnitude, raising the operating temperature and consequently accelerating the structural failure due to thermal stresses.

Irradiation degrades the electrical resistivity of the material by altering the electronic properties and inducing chemical and structural defects. A radiation flux of 10^4Gy/s results in a conductivity change of 10^{-4}-$10^{-9}(\Omega m)^{-1}$, comparable to that induced by thermal effects at 1000°C. No data are available in this area.

4.2 - Thermal and mechanical properties.

High thermal conductivity values for ceramics result in lower operating temperatures and thermal stresses. Thermal conductivity is significantly reduced by irradiation. The magnitude of the reduction varies greatly with the ceramic and depends on temperature and irradiation dose. The general features are the following : a decrease in thermal conductivity with temperature and fluence ; a more prononced reduction at lower irradiation temperatures and a tendancy to saturate at higher irradiation fluences. Reductions as high as 95 % have been measured after irradiations at 925 K and fluence of 2.3 x 10^{22}m.cm^{-2}. However it should be pointed out that radiation-induced effects anneal out in the high temperature range (900-1100°C).

Ceramic swelling, with accompanying stresses and dimensional changes, is the major structural problem in RF windows. In general the degree of swelling increases with neutron fluence. In some cases, the non-cubic structure of certain ceramics reduces the tolerance for radiation damage because of anisotropic swelling. Swelling of some candidate ceramics is illustrated in fig. 6 and 7 (from ref. [11]). In general Al_2O_3, MgO and mainly spinel show a good radiation resistance to swelling, in the single crystal form of spinel in particular exhibiting essentially no volume change after high temperature irradiation to 2 x 10^{26}n.m^{-2} (E > 0.1 MeV).

5. SUPERCONDUCTING COIL INSULATORS.

Superconducting material of the A15 type will be of general use in the magnetic system, even for the next generation of tokamak like INTOR. Such composites suffer neutron irradiation effects which shift the transition temperature to a value at which the superconductivity disappears. This is illustrated in fig. 8 (ref. [14]) for different A15 composites.

This phenomenon appears at neutron fluences of $\sim 10^{22} n.m^{-2}$. Superconducting magnets present a complex structure formed roughly by successive layers of superconducting material, copper as stabiliser and insulator. It is important that dose limitations be given by the most interesting component and not, as now, by the insulator. Actually the major part of the insulation system comprises a high strength glass reinforced polymer composite material. Properties of organic materials and glasses are degraded by the neutrons and gamma rays present in fusion magnets. As a result the radiation response of organic insulation depends upon the mix of neutron and gamma ray intensities, which depend on the design. The serious damage is to the electrical properties, while structural degradation of organics occurs moreover at lower neutron doses than for other magnet materials. Calculations show that 55 to 80 % of the deposited energy in the insulator results from neutrons, the balance from gamma rays [15].

The consequences are that for a specified neutron dose the deposited energy in organics increases with hydrogen content and that defect production mechanisms differ between neutrons and gamma rays, raising the possibility that details of the radiation mixture may affect the nature of damage.

Compressive stresses, estimated to be 275 to 400 MPa, arise in insulation from magnetic forces as the winding layers are thrust out one against another. Shear stresses are generated by interaction between coils. Additionally, mechanical stresses arise from a variety of other effects such as bending stresses in unsupported regions. Although not yet fully defined, the mechanical requirements seem likely to define the major lifetime-limiting property of the insulation. The electrical requirements are nonetheless important. Maximum voltages of a few hundred volts between burns and a thousand or more on the terminal exist and the breakdown of the insulation is a potential problem.

Organic materials used in superconducting magnets are expoy resins with aliphatic or aromatic amines, polyimides, polyester and diglycidyl ether of bisphenol A as glue. Radiation dose limits of about 10^6 Gy have to be considered for most of these compounds, though polyimide may support doses of 10^7 Gy. Beyond these doses mechanical properties degrade very rapidly as shown in fig. 9.

Ceramics are also candidate materials for superconducting magnet insulation. SiO_2 and mica are both considered in this area. Their main advantage is that they are more resistant to radiation damage and gamma rays are without effect on their properties. Neutron fluences to the level of $10^{25} n.m^{-2}$ are possible with these materials and they are no longer a limitation for the magnet design. Unfortunatly, very little work is carried out in this area and ceramic insulators should be considered only for commercial fusion reactor applications.

6. OTHER INSULATOR APPLICATIONS.

Insulators in general and more specifically ceramics have other potential applications in a fusion reactor. One of the most important is their use for diagnostic windows. In today's machines considerable use is made of single crystal quartz windows for diagnostic purposes. These diagnostics cannot be applied directly to the next generation of devices and developments are required in this area. It seems very difficult to develop windows without having the input data coming from diagnostic requirements. Work in this area is therefore held up until specifications that have to come from the new diagnostic developments become available.

This is less true for the torus current breakers, for which Al_2O_3 is the main candidate. There again, the specifications for breakers are design dependant and a separate study cannot be pursued independently from the designers.

Other applications, mentioned in TABLE II, are in the same situation and a close collaboration is required between ceramic experts and design teams to ensure good development of insulator research.

7. CONCLUSIONS

Insulators and more specifically ceramics have great potential applications in a tokamak, mainly for the plasma facing components and for superconducting magnets. Of prime importance for these applications, is a good knowledge of the behaviour of their electrical and mechanical properties under the very high neutron and gamma-ray flux level which will be present in such reactors. This knowledge is relatively good with regard to thermal neutron effects and up to gamma dose rates of 10^7 Gy, but needs to be developed under 14 MeV neutron flux and gamma-ray doses of 10^8 to 10^{10} Gy. The vigorous research and development programme under way, at least in the E.C., to develop this knowledge will give the required results within the coming ten years, in due time for the next generation of tokamak such as INTOR/NET.

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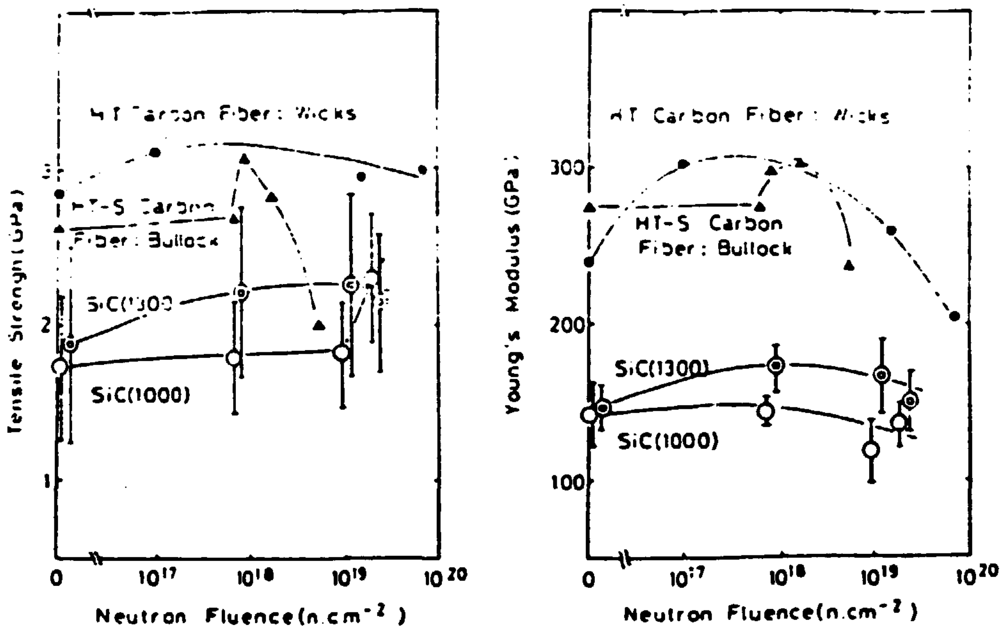

Fig.1. Effects of neutron irradiation on tensile strength and Young's modulus of the SiC fibers. [8]
O.SiC (1000) fiber ; ⊙. SiC (1300) fiber ; ▲. HT-S carbon fiber by Bullock ; ●. HT carbon fiber by Wicks.

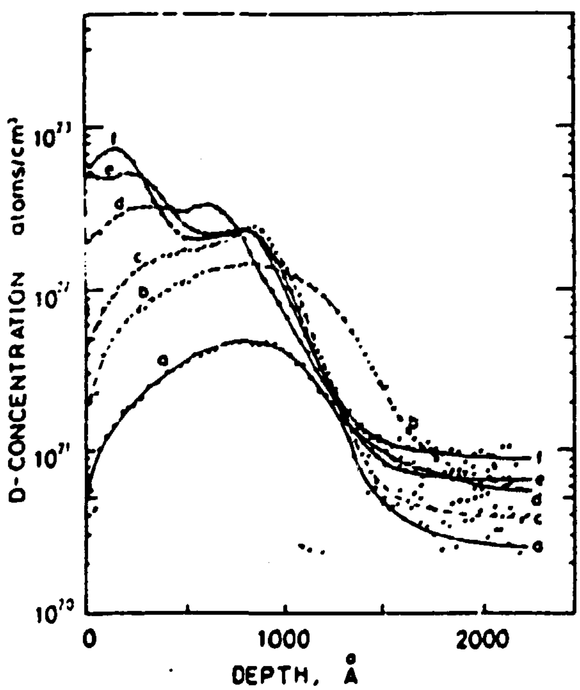

Fig.2. Depth profiles of deuterium for titanium carbide coatings on molybdenum irradiated with 7 keV D^+ at ambient temperature at a dose of (a) 9.0×10^{16} D/cm^2, (b) 3.6×10^{17} D/cm^2, (c) 5.4×10^{17} D/cm^2, (d) 2.6×10^{18} D/cm^2, (e) 3.1×10^{19} D/cm^2 and (f) 6.7×10^{19} D/cm^2. Ref. [9]

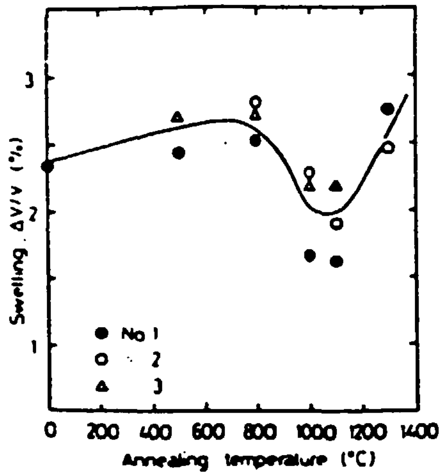

Fig.3. Dimensional change vs. annealing temperature of neutron irradiated B_4C pellet. [10]

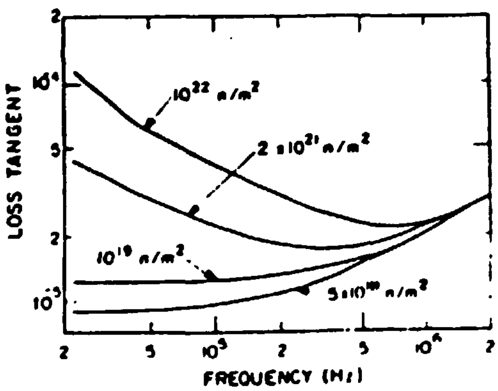

Fig.4. Loss tangents for single crystal Al_2O_3 irradiated with high-energy [from 13] neutrons.

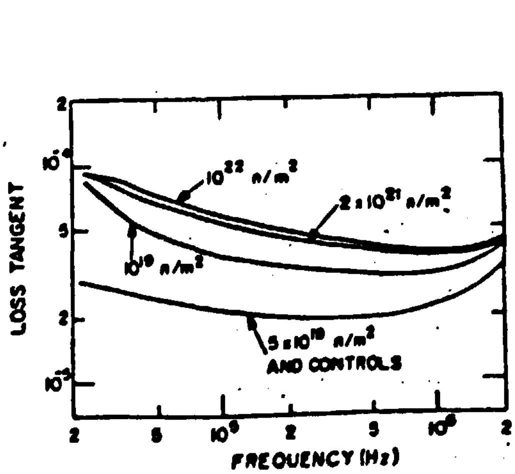

Fig.5. Loss tangents for polycrystalline Al_2O_3 irradiated with fast [from 13] neutrons.

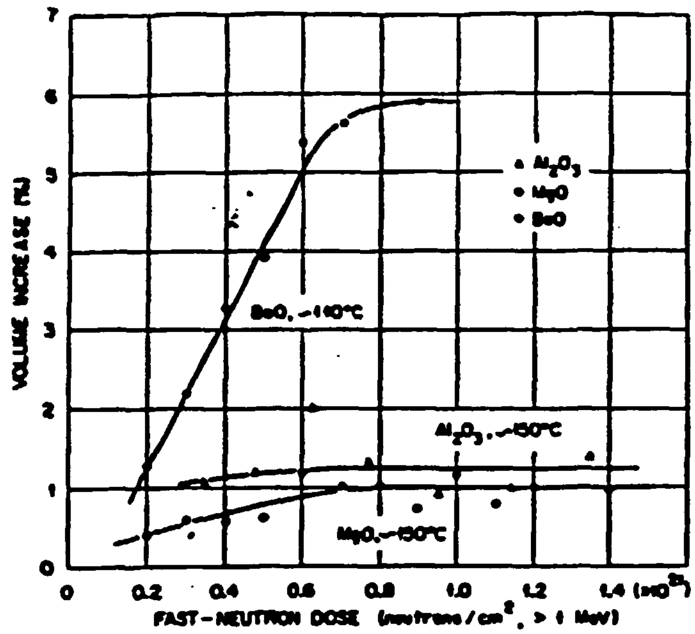

Fig.6. Volume increase of sintered BeO, MgO, and Al_2O_3 irradiated with fast fission neutrons. [11]

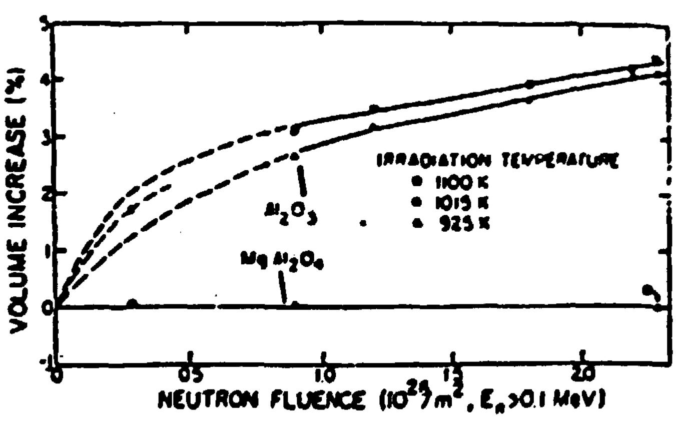

Fig.7. Swelling in single crystals Al_2O_3 and spinel as a function of fission neutron fluence for three irradiation temperatures. [11]

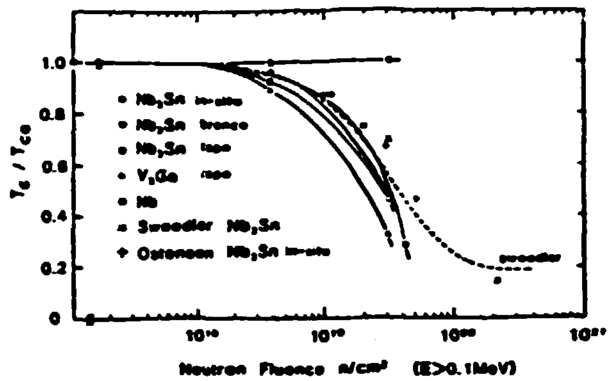

Fig.8. Reduced transition temperature (T_c/T_{c0}) as a function of neutron fluence (E>0.1 MeV) for various A15-type superconducting materials. [14]

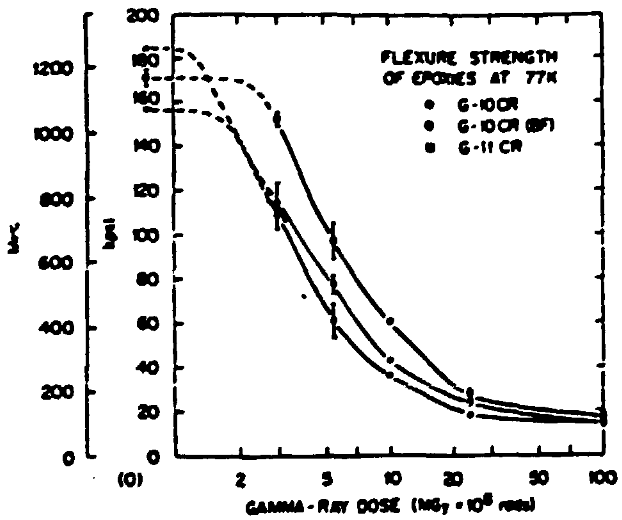

Fig.9. The results of flexure strength tests at 77 K on glass-fabric filled epoxies after gamma-ray irradiation at 4.9 K and warmup to 307 K. [15]

	INTOR [1]	DEMO [2]	STARFIRE [3]
Average neutron wall load	1.3 $MW.m^{-2}$	2.6 $MW.m^{-2}$	3.6 $MW.m^{-2}$
Neutron fluence	3 $Mw.a.m^{-2}$	3.1 $Mw.a.m^{-2}/2$	5.4 $Mw.a.m^{-2}/2$

Table I. Neutron wall load in future tokamak reactors.

	Annual fluence $n.m^{-2}$	Temperature K	Candidate materials
Insulators for R.F heating systems	10^{26}	500-800	Al_2O_3, MgO, ALN, ALON $MgAl_2O_4$
Low Z first wall protection	10^{26}	1200-1800	graphite, SiC, TiC, B4C
Neutral beam insulators	10^{23}- 10^{24}	500	glass, Al_2O_3, SiO_2
Toroidal current breakers	10^{26}	1200	Al_2O_3, $MgAl_2O_4$
Diagnostic windows	10^{25}- 10^{26}	>500	
Superconducting coil insulators			$MgAl_2O_4$, Al_2O_3, epoxy fiberglass, polyimides
Electrical motor insulator (pumps)	10^{22}	300	epoxy, polyimides

Table. II. Working conditions for insulating materials.

Material	Type of Conductor	DC Electrical Resistivity (Ω-cm)	Dielectric Constant	Dielectric Strength (kV/mm)	Loss Tangent (at 100 MHz)	Thermal Conductivity (cal/cm-s°C) at 100°C	Thermal Stress Resistance
Al_2O_3	Non-cond.	5×10^{13}	8.8	40-160	0.0003	0.069	Very good
BeO	Non-cond.	10^{16}	6.6	10		0.5	Excellent
MgO	Non-cond.	10^{15}	9.65		< 0.0003	0.082	Fair-Poor
$MgO\text{-}Al_2O_3$	Non-cond.	$> 10^{14}$				0.033	Fair
Si_3N_4	Non-cond.	10^{13}	9.4			0.045*	Excellent
SiO_2	Non-cond.	10^{15}	3.8	0.35	0.0002	0.0033	Excellent

* At room temperature

Table III. Characteristics of Ceramics.

Neutron flux	2.8×10^{14} n/cm^2.s
Gamma flux	1.53×10^{14} γ/cm^2.s
Fast neutron fluence (E > 0.1 MeV) after one full power year (FPY)	5.77×10^{21} n/cm^2
Power density	8.53 W/cm^3
Absorbed dose rate	8.9×10^{12} rad/FPY

Table IV. Nuclear Radiation Parameters in the BeO window for 1 MW/m^2 Wall loading