The effects of radiation on electrical insulators in fusion reactors

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IN FUSION REACTORS

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ABSTRACT

The effects of radiation on organic polymers and ceramics are reviewed with particular reference to the possible uses of these materials as electrical insulators in fusion reactors.

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INTRODUCTION

The successful development of fusion reactors will require the solution of materials problems which are even more severe than those which have been encountered in the development of fission reactors. At present there are no practical detailed designs of fusion reactors and it is only possible to discuss the materials problems rather generally, as the specific problems which will arise will depend on the type of reactor developed and the operating conditions selected. All reactors which will employ magnetic confinement of the plasma will require electrical insulators which may be subjected to higher combined levels of radiation and temperature than ever before experienced. The purpose of this report is to help anticipate some of the problems which may arise in practice by reviewing the present state of knowledge of some of the effects of these conditions on potentially useful materials, and by indicating the research which will be required to minimise eventual engineering problems.

Several different generic types of fusion reactor have been suggested and conceptual reactor designs based on these have been developed\(^{(1)}\)(\(^{(2)}\)(\(^{(3)}\)). Although some of the designs are at an advanced stage they are hypothetical and will undoubtedly require considerable modification before prototype reactors are constructed. They do, however, provide useful data on the likely radiation levels, temperatures and stresses which will occur and the operating modes which will be possible. All the conceptual designs employ the deuterium-tritium reaction

\[
\text{D} + \text{T} \rightarrow \text{^4He (3.5 MeV)} + \text{n (14.1 MeV)}
\]

the tritium being provided by a breeding reaction inside the reactor between neutrons and lithium. The plasma reaction will therefore produce a considerable flux of very energetic neutrons and in addition \(\alpha\) particles, \(\gamma\)-rays, X-rays, energetic ions and electrons.

Differences in design philosophy and their effects on operating conditions are well illustrated by the Culham Tokamak and the Los Alamos Reference Theta-Pinch Reactor (RTPR). There are very significant differences between these designs. For example, the RTPR was designed to work in a pulsed mode with a burn time \(\sim 0.08\) seconds and a period between burns of \(\sim 10\) seconds, while the Tokamak was designed to operate in a quasi-steady-state mode. Continuous operation of a Tokamak will not be possible if reactor products and impurities do not diffuse out of the plasma sufficiently quickly, and it will probably be necessary to run the Tokamak cyclically with a reacting time \(\sim 100-1000\) seconds and a rest period \(\sim\) few seconds. During plasma reaction the first wall will experience temperatures which will reach a maximum in the probable range \(600^\circ\text{C}\) to \(1000^\circ\text{C}\) in both reactors but which will cycle during operation with a frequency which will depend on the reactor design. Another major difference, directly affecting electrical insulation, is that the Tokamak design employed superconducting magnetic coils which were shielded against radiation, while the coils of the RTPR were non-superconducting copper and were less well shielded.

Table I lists possible applications of electrical insulating materials in fusion reactors in the expected order of decreasing severity of radiation damage\(^{(4)}\)(\(^{(5)}\)(\(^{(6)}\)). The most obvious application is in the insulation of the large magnets which will be employed
in magnetically confined systems. In addition they may be required to provide first wall insulation in theta pinch reactors; provide an insulating gap in the torus of the Tokamak to facilitate ohmic heating of the plasma; to insulate direct convertors in mirror machines; as insulating materials in the neutron blanket to reduce eddy current losses; to provide insulation in devices which will couple radio frequency power into Tokamak plasmas and inject neutron beams into mirror machines and Tokamaks; and finally to provide insulation in power supplying cables and electronic control devices. A further application for ceramic insulators is as a liner for the first wall where their electrical properties are not important but their low atomic mass will reduce the problems of contamination of the plasma from first wall sputtering.\(^7\)

The levels of radiation, temperature and fluctuating thermally induced stresses, which the materials will be required to withstand in these applications, will depend very critically on the reactor design, their distance from the plasma, and the ability to provide shielding. The conceptual reactor designs have provided information about the likely conditions to which the materials will be subjected and Figure 1a\(^8\)\(^9\)\(^1\) shows for example some typical radiation levels estimated for a Tokamak, illustrating how neutron dose will decrease with increasing distance from the first wall. Clinard\(^5\) has listed some of the most severe conditions to which insulators could be subjected in the vicinity of the first wall and his figures, compiled from a number of different reactor types, are presented in Table 2. In practice it is unlikely that the first wall of any reactor will be subjected to a combination of conditions quite as severe as these.

Insulators at the first wall will experience the whole range of plasma radiation products but the shielding provided by the first wall and breeding blanket will filter out all but the \(\gamma\) and neutron radiation at the magnets. In a 20 year lifetime insulators at the first wall might well be required to withstand a total neutron dose of \(\sim 10^{23}\ \text{ncm}^{-2}\) (corresponding to a power rating in the range 10-40 MW years m\(^{-2}\)), of which about 20% would have an initial energy as high as 14.1 MeV, at likely operating temperatures of 600\(^\circ\)C to 1000\(^\circ\)C. Away from the first wall the doses and temperatures are more speculative, depending on the detailed design. There are several ways of quantifying the interaction of radiation with matter. One way is to calculate the energy deposited by the radiation in the solid. Another is to calculate the number of events, such as atomic displacements, which occur in the solid. The former method is normally employed for organic polymers and the basic unit in this system is the rad, which is an energy absorption of 100 erg gm\(^{-1}\). The other method is commonly employed to describe the processes occurring in metals and ceramics when subjected to neutron or ion irradiation, and the basic unit is the dpa (displacement per atom). The dpa will be described in more detail later. As well as knowing the neutron flux and energy spectrum, it is also important to know the rad dose in order to assess the effect of radiation on any organic materials present. Figure 1b shows the results of some recent calculations of radiation dose in rads at the magnets of the Culham MkII Tokamak\(^4\)\(^8\). These have been calculated on the basis of a first wall neutron loading of 1 MW m\(^{-2}\) for a reactor working for 30 years at an 80% load factor. In these calculations the shielding had not been fully optimised. The maximum rad dose at the magnet insulation is \(\lesssim 2 \times 10^{10}\) rad and by optimising the shielding it is estimated that this could be reduced to \(\sim 4 \times 10^9\) rad.
For a larger, first wall, neutron power loading this figure would be scaled up less than linearly with power rating because proportionately greater shielding could be employed. Hence for this type of reactor we are concerned with a typical 30 year dose of $4 \times 10^9$ to $2 \times 10^{10}$ rad of which about 90% would be contributed by neutrons and 10% by $\gamma$ \textsuperscript{(48)}.

Radiation can result in sputtering and blistering of the insulators at the first wall, swelling, loss of mechanical strength, transient and permanent changes in electrical properties, and changes in thermal conductivity, while thermal cycling may lead to fatigue cracking. Clinard\textsuperscript{(5)(6)} has produced a good review of these effects in ceramic insulators in fusion reactor environments and has discussed potential problem areas. This report will therefore be restricted to a more detailed account of what is known about the effects of neutron and $\gamma$ radiation on electrical insulators with particular reference to structural changes.

**GENERAL COMPARISON OF MATERIALS**

The three classes of materials which might be selected for electrical insulation in fusion reactors are:

- crystalline inorganic ceramics
- inorganic glasses
- organic polymers.

Differences in atomic bonding and packing between these materials result in very different susceptibilities to the effects of ionising ($\beta/\gamma$) radiation and temperature.

Solids can be divided into two broad classes by reference to their susceptibility to permanent damage by ionising radiation. Some materials, in particular organic polymers and low melting point ionic solids such as the alkali halides, are very susceptible to structural damage by $\gamma$ and low energy radiation ($< 0.3-0.4 \text{ MeV}$), while other materials, in particular metals, ceramics and inorganic glasses, suffer no damage. Gamma and low energy electron radiation lose energy on passing through a solid by exciting the electrons of the solid rather than by colliding with the atomic nuclei to cause atomic displacements. In organic polymers and alkali halides the excitation of electrons can result in atomic displacements and thus cause irreversible changes in physical properties. In metals and ceramics electronic excitation cannot cause atomic displacements, and these materials are only permanently affected by high energy electrons and heavier particles which are able to cause atomic displacements by nuclear collisions. The basic criterion for an atomic displacement to result from an excited electronic state is that the excited state should have both sufficient energy and sufficiently long lifetime ($\sim 10^{-13}$ to $10^{-12}$ seconds, the time of an atomic/molecular vibration)\textsuperscript{(9)}. In a metal the electronic excitation is dissipated among conduction electrons in times $\sim 10^{-15}$ seconds and therefore the excited state does not last long enough for displacement to occur. In inorganic insulators the reason is less obvious and is best understood by considering the reason for the susceptibility of the alkali halides to damage by $\gamma$ radiation. An early explanation for their radiation sensitivity was that multiple ionisation of an atom could lead to atomic displacement by virtue of the electrostatic forces acting upon it (Varley mechanism). However
this is now discounted as degradation of the electronic excitation to electron-hole pairs occurs too rapidly. The electron-hole pairs themselves, however, have lifetimes $> 10^{-9}$ seconds and therefore exist long enough to be able to produce displacements if they are sufficiently energetic. It is now generally accepted that the energies of electron-hole pairs in the alkali halides are greater than the atomic displacement energies, while in oxides they are less, so that atomic displacements occur in the former but not in the latter (Pooley-Hersh mechanism). The explanation of radiation sensitivity of organic polymers is rather different. Electronic excitation leads to the disruption of a bond between the atoms in the polymer molecule and thus to the production of two radicals which are free to react with other radicals resulting in changes in molecular weight and local chemical structure. Bond rupture occurs selectively either by selective absorption of energy by certain bonds or by energy migration within or between molecules prior to bond rupture. In addition, radical mobility by hydrogen radical addition and abstraction reactions can cause reaction to occur at some distance from the original site of the radiation absorption event $^{(10)}$.

The susceptibility of organic polymers to radiolysis by $\gamma$ and low energy electron radiation causes their mechanical properties to begin to degrade at $\gamma$ and $\beta$ doses as low as $10^6 - 10^7$ rad and very few polymers are useful at doses greater than $10^9$ rad. This sensitivity to purely ionising radiation coupled with the relatively low temperatures at which they degrade (usually less than 300°C) renders them unsuitable for the more severe conditions of a fusion reactor; while their ease of processability, low cost and advantageous mechanical properties, such as flexibility and toughness, make them superior to the inorganic insulators for applications within their temperature and radiation capabilities.

In contrast to the organic polymers the structures of inorganic glasses and ceramics such as $\text{Al}_2\text{O}_3$, $\text{MgO}$, $\text{Y}_2\text{O}_3$, $\text{Si}_3\text{N}_4$, etc., are unaffected by gamma radiation and by electron radiation at energies lower than that which can cause direct atomic displacement from lattice sites. This insensitivity to purely ionising radiation and their higher temperature capabilities make these materials the most suitable candidates for fusion reactor insulators where conditions are most severe. When choosing between the crystalline ceramics and the glasses, the higher strength, toughness, softening temperature, and structural stability at temperature of the crystalline materials tend to outweigh the easier processability of the glasses and make the crystalline ceramics the prime candidates for the most severe applications.

In the following report, the mechanisms of structural degradation and their effect on mechanical and electrical properties will be considered separately for organic polymers and crystalline ceramics. The mechanisms of structural degradation of glasses are somewhat similar to ceramics in that they involve direct atomic displacements but differ because of the amorphous structure of the glasses. The most obvious effect of radiation on glasses is a colouration induced by ionising radiation, which tends to saturate at about $10^{10}$ rad and has little effect on mechanical and permanent (as opposed to transient) electrical properties. It has been reported that changes in physical properties of glasses due to atomic displacing radiation tend to be less than for crystalline ceramics because of the relatively high degree of disorder in the structure of the glass before
irradiation. Since the properties of glasses are poorer than those of ceramics prior to radiation, this probably merely implies that after considerable irradiation the properties of the ceramics tend to diminish towards those of the glasses. Although it is possible that for some polycrystalline ceramics anisotropy of grain swelling at high neutron doses, and the resulting internal stressing, could render them inferior to glasses. Information about the effects of neutron irradiation on glasses has been given by Wullaert et al(11) and glasses will not be discussed further here.

ORGANIC POLYMERS

The susceptibility of polymers to damage by purely ionising radiation, and their degradation at moderate temperatures, renders them unsuitable for use under the most severe conditions which will be experienced by insulators in fusion reactors. Their uses will be restricted to regions of relatively low radiation levels and temperatures where they can be employed more conveniently and cheaply than inorganic insulators. A good deal of information already exists about their uses as electrical insulators in radiation environments from the development of fission reactors and high energy particle accelerators, and fairly clear limits of total dose and temperature can already be defined for their application, subject to the qualifications discussed below.

Organic polymers which might be employed as insulators can be divided into three classes: thermosets, thermoplastics and elastomers. Examples of thermosets are the epoxide and polyester resins. They are utilised by mixing the resin with a curing agent which then react together so that the molecules of the curing agent tie the molecules of the resin together in a process known as cross-linking. The final solid is hard, insoluble and infusible. When heated they do not soften or melt, but at high enough temperature (typically ~200°C) they begin to degrade. Thermoplastics differ from thermosets in that they generally consist of linear molecules of very much greater molecular weight and length with relatively little cross-linking. On heating they soften and melt. Plastics such as polyethylene, polypropylene, polymethylmethacrylate (PMMA) and nylons belong to this category. They again can be broadly divided into two classes, those capable of considerable crystallinity (such as polyethylene) and those which are largely or completely amorphous or glassy (such as PMMA). Elastomers, which include synthetic and natural rubbers, are similar in molecular structure to thermoplastics but are capable of much greater elastic strains at ambient temperature because their molecules are capable of greater mobility.

The two main effects of radiation on polymeric solids are scission of the molecular chains and cross-linking between molecules. In the high molecular weight, long molecular length, thermoplastics and elastomers, relatively low radiation doses can produce either a significant decrease in molecular chain length by scission or a significant increase in cross-linking density, either of which can markedly alter the mechanical properties of the polymer. These effects are less pronounced in the highly cross-linked, relatively low molecular weight thermosets, and as a general rule the mechanical properties of the latter are rather less affected by radiation than are the former. Commercially available plastics, resins and rubbers invariably contain a variety of additives such as antioxidants, u-v inhibitors, pigments and fillers, which are included to improve properties, price and
appearance. These additives, together with differences in molecular weight distribution and other structural variations, result in plastics of similar types, such as for example commercially available polyethylenes, having widely varying properties. They also lead to differences in the detailed radiation chemistry of the materials so that data obtained from one polyethylene may not accurately reflect the behaviour of another polyethylene.

A further factor which must be taken into account in assessing radiation damage data is the nature of the radiation employed. Organic polymers will be subjected to two main types of radiation, gamma and fast neutron. Gamma radiation is largely absorbed by interaction with electrons in a series of events which are relatively widely spaced in the polymer so that reactive species are widely separated. Neutrons however tend to lose their energy by collision with the atomic nuclei. The knocked-on atoms then lose their energy over a short distance by interaction with electrons so that corresponding to each neutron collision there is a local volume containing a relatively high density of reactive species. For the same average energy absorption, the changes resulting from fast neutron irradiation may therefore be different from those due to $\gamma$ radiation, ionisation and excitation being confined to a number of discrete regions in the former case. Most of the data which is available about the effects of radiation on polymers has been obtained from $\gamma$ and electron irradiation, and there is very little comparative information on the effects of fast neutron and $\gamma$ radiation$^{(12)}$. When polymers are subjected to neutron irradiation it is usual to calculate the energy deposited in the polymer through nuclear collisions, express it as a rad dose, and then assume that the effect of this is similar to that of an equivalent rad dose from $\gamma$ radiation. Calculations of radiation dose (in rads) at the magnet insulation of a conceptual reactor (in this case the Culham MkII Tokamak) have shown (Figure 1b) that the contribution from $\gamma$ and X-radiation amounts to only about one tenth of the total dose, the remainder coming from the neutron flux. It is easier and cheaper to irradiate polymers with $\gamma$ radiation than neutrons and clearly there is a need to establish more exactly the relative effects of similar rad doses of neutrons and $\gamma$, in order to determine the validity of $\gamma$ radiation data for fusion reactor design.

The mechanisms of radiation induced changes in polymers

The interaction of radiation with polymer molecules leads to the formation of positive ions and excited molecules as illustrated in Figure 2. Thus for a molecule AB

\[
\begin{align*}
\text{AB} & \rightarrow \text{AB}^+ + e^- \quad \text{ionisation.} \\
\text{AB} & \rightarrow \text{AB}^* \quad \text{excitation.}
\end{align*}
\]

The electron produced by ionisation can cause further excitation and ionisation until it loses its energy and is trapped by a neutral or ionised molecule to produce an excited molecule. Excited molecules may dissociate to form radicals

\[
\text{AB} \rightarrow \text{A}^* + \text{B}^*
\]

A major feature in the radiation induced changes of organic compounds is that a considerable degree of selectivity occurs. This may be attributed either to energy not being deposited at random or to migration of the absorbed energy within or between
molecules before giving rise to ionisation or excitation\(^{(10)}\). Thus considerable differences exist in the yield of different radicals in a polymer and the yields may be modified by the addition of certain groups, notably aromatic groups. The radicals and ions produced by the primary events, the so-called reactive intermediates, may remain trapped for a considerable time after irradiation but eventually react to produce further chemical transformations.

The main processes which occur after dissociation of bonds in polymers are illustrated schematically in Figure 2b. The most important are: cross-linking, which is the formation of chemical bonds between two chains; and degradation or chain scission, which is the fracture of the polymer molecule. Additional processes are: unsaturation, which is the formation of double bonds; gas evolution, due to the dissociation of small side molecules from the polymer; and reaction with the environment.

A major problem in radiation chemistry lies in understanding the way in which the isolated reactive species produced by the primary event can migrate until they are in suitable conjunction for reaction. The role played by ions in the transformations occurring in irradiated polymers is very poorly understood. The production of ionic species results in the enhanced conductivity of plastics on irradiation due to creation of free electrons and positive holes, and their persistence and slow decay result in the slow decay of radiation enhanced conductivity. A much better understanding exists of the role of radicals. Physical migration of radicals by a radical molecular diffusion process is unlikely to be important as it has a low diffusion rate. More probable explanations are provided by hydrogen atom transfer or by diffusion of hydrogen radicals as shown in Figure 3, in both of which the radical nature is transferred through the solid with only limited mass transfer. Difficulties still remain with explanations of this type\(^{(10),(14)}\), but even accepting these explanations, although there is a general understanding of the effects in the simpler organic materials, the detailed events occurring in the structural modification of commercially available materials have not been quantified. An improved understanding of the role of the various reactions occurring after irradiation is important in the development of commercial plastics with improved resistance to radiation.

There is a better understanding of the effects of radiation on mechanical properties than on electrical properties. In any polymer all the events outlined in Figure 2b may occur on irradiation and the mechanical properties at any stage will be determined by competition between the processes. The most important processes are cross-linking and chain scission. Cross-linking leads to increasing hardness, tensile strength, softening temperatures, and elastic moduli and to decreasing elongation to failure and solubility, the properties eventually degrading as the material becomes embrittled and evolves gases. Chain scission produces the opposite effects on the properties and leads eventually to a soft, gummy or tar-like material.

Some very rough, general rules have been formulated to assist in assessing the probable behaviour of a polymer on irradiation\(^{(13)}\). Long chain polymers with a single side group \(R_1\) or no side group (i.e. \(-CH_2-\) \(-CH_2-\) or \(-CH_2-CHR-\)) tend to cross-link, while polymers containing two side groups \((R_1, R_2)\) attached to the same carbon atom
(i.e. \(-\text{CH}_2 - \text{CR}_1\text{R}_2\)) tend to undergo chain scission. This is due at least partly to the larger molecular strains which occur in polymers of the latter type acting to part the polymer radicals formed by rupture of the main chain bonds. There is a wide range of rate of radical production among organic compounds as illustrated in Table 3(13) which gives the number of free radicals produced per 100 eV of absorbed radiation energy (the \(G\) value) for a range of organic compounds. Aromatic compounds are relatively very stable to radiation and the presence of aromatic groups in a polymer can confer stability. For example, the rate of cross-linking of polyethylene

\[
\begin{array}{ccc}
\text{H} & \text{H} \\
\text{C} & \text{C} \\
\text{H} & \text{H} \\
\end{array}
\]

is 50 times higher than that of polystyrene

\[
\begin{array}{ccc}
\text{H} & \text{H} \\
\text{C} & \text{C} \\
\text{H} & \text{O} \\
\end{array}
\]

Compounds containing halogen are very much less stable and halogen containing polymers are rather susceptible to radiation. Saturated aliphatic compounds are more radiation resistant than unsaturated ones. For example, polyethylene

\[
\begin{array}{ccc}
\text{H} & \text{H} \\
\text{C} & \text{C} \\
\text{H} & \text{H} \\
\end{array}
\]

is more stable than polybutadiene

\[
\begin{array}{ccc}
\text{H} & \text{H} & \text{H} \\
\text{C} & = & \text{C} \\
\text{H} & \text{H} \\
\end{array}
\]

The environment in which the polymer is irradiated can also have a considerable effect on its behaviour. Gases such as \(\text{O}_2, \text{NO}\) and \(\text{NO}_2\) can react with the polymer radicals to alter the course of the chemical reactions. In such environments the behaviour is affected by dose-rate, which determines the rate of radical formation, and specimen dimensions and temperature, which affect the rate at which diffusion of the environmental gas can reach the created radicals. The main effect of oxygen is to increase the rate at which chain scission occurs so that degradation is promoted over cross-linking(13). A typical series of reactions leading to chain scission is shown in Figure 4. A consequence is that polyethylene cross-links more slowly when irradiated in air than in a vacuum, and that some polymers, such as polyvinylchloride, polystyrene and polypropylene, which normally cross-link when irradiated in vacuum, degrade when irradiated in oxygen. This simple model does not always apply and the rate of degradation of some polymers (e.g. \(\text{PMMA}\) and \(\text{PTFE}\)) is lower in air than in vacuum.
The effects of radiation on electrical properties

Radiation produces both transient and permanent changes of the electrical properties of polymers. The transient effects are very sensitively affected by dose rate and are due to the ionisation of polymer molecules and the excitation of the freed electrons into conduction states. When irradiation is stopped, the number of conduction electrons decay as they are trapped and recombine with the ionised molecules. The permanent effects are associated with permanent structural changes and begin to occur at similar total doses to those which produce permanent changes in mechanical properties. The transient changes of electrical conductivity are relatively small and do not have a significant effect on the insulating properties of polymers except at very high dose rates. The permanent effects too are rather small until the polymer has absorbed a sufficiently high dose to degrade its mechanical properties, and in general the breakdown of electrical insulation at high doses is due primarily to the loss of mechanical properties, cracking, and gas evolution, rather than to intrinsic increases in conductivity of the irradiated material\(^{(13)}\).

Figure 5 illustrates the typical response of electrical conductivity to a pulse of radiation. The response can be divided into three regions. In Stage I, conductivity initially increases exponentially with time as the number of charge carriers increases. In Stage II, the conductivity has reached a constant value and the rate of creation of charge carriers equals the rate of trapping and recombination. In Stage III, when the radiation is removed, the conductivity decays as the charge carriers are trapped and the freed electrons eventually recombine with ionised molecules. The recovery in Stage III may take hours or even days, and the conductivity may not return to its original value if significant structural damage has occurred.

It has been shown\(^{(15)}\) that for many polymers, irradiated in the dose rate range \(10^{-3}\) to \(10^4\) rad/sec, the three stages may be described by

\[
\begin{align*}
\sigma - \sigma_0 &= A_1(1 - e^{-t/\tau_0}) & \text{Stage I} \\
\sigma - \sigma_0 &= A_2 \gamma^\delta & \text{Stage II} \\
\sigma(t - b) &= \sigma_{eq} \sum_{i=1}^{n} k_i \exp\left(-(t - b)/\tau_i\right) & \text{Stage III}
\end{align*}
\]

where \(\sigma\) = conductivity at time \(t\)
\(\sigma_0\) = initial conductivity
\(\sigma_{eq}\) = \(\sigma_0 + A_2 \gamma^\delta\) = equilibrium conductivity
\(A_1, A_2\) and \(\delta\) = are empirical constants
\(\tau_0\) = \(f(\gamma)\) = a time constant
\(\tau_i\) = one of \(n\) decay time constants describing recovery
\(k_i\) = one of \(n\) weighting factors.

Under conditions of steady radiation the loss of resistance described by the Stage II equations is the most important feature, but Stages I and III need to be borne in mind when
considering pulsed irradiation conditions especially if electrical insulation is not important during the pulse but is required after the pulse has stopped (as in the first wall of the RPRT).

Explanations of radiation induced conductivity in polymers have developed around two alternative theories(10): an extension of semiconductor band model theory in which the electron is delocalised in an energy band extending over many atoms(16); and a hopping model in which the polymer is considered to contain a number of discrete traps with the electron hopping from one to another under the influence of the electric field. Charleby(10)(17) has briefly discussed some of the problems associated with theoretically understanding the process of radiation induced conductivity in polymers, and at present the details of the processes involved are far from understood. For example, under steady state conditions conductivity is described empirically by the Stage II equation, i.e. the increase in conductivity is proportional to the dose rate to some power ($\gamma_n^\delta$). Charleby has pointed out that if each electron released by radiation or after untrapping drifts in the direction of the field and is permanently trapped by an impurity or reaches the electrode, the current should vary as $\gamma_1^\delta$; if however it drifts until it combines with a positive charge produced by radiation, conductivity should vary as $\gamma_0^\delta$. For most polymers $\delta$ lies in the range 0.5 to 1.0 usually approximately 0.8. This can be explained by a combination of the two processes, but only over a limited range of intensities, and further it is not unknown for polymers to exhibit values outside this range(15).

Empirical information exists which enable an estimate to be made of the effects of radiation on the transient conductivity of polymers. Table 4, which is taken from Reference 15, gives values of $A_2$ and $\delta$ for a number of polymers at different temperatures. If it is assumed that the fusion reactor will operate under essentially continuous conditions so that dose rate can be considered constant; that the insulation must have a life of at least ten years; and that the maximum dose that it can tolerate is $10^{10}$ rad, the maximum continuous dose rate must be $\sim 30$ rad/sec. The most likely candidates for magnet insulations are epoxide resins or polyimides. For an epoxide resin for which Table 4 gives values of $A_2$ and $\delta$ of $3.3 \times 10^{-17}$ and 1.0 respectively a dose rate of 30 rad/sec implies an increase of conductivity of $\Delta \sigma = \sigma - \sigma_0 \approx 10^{-15}$ $(\Omega \cdot cm)^{-1}$. If the reactor is run in a pulsed mode with the maximum dose rate existing for $\sim 0.1$ secs with 10 secs rest between pulses, and if it is assumed that an equilibrium current can be achieved in the 0.1 sec, then on the same assumption the maximum dose rate of 3000 rad/sec implies the rather more severe effect of an increase in conductivity of $10^{-13}$ $(\Omega \cdot cm)^{-1}$. The volume conductivity of epoxide resins is typically $10^{-12}$ to $10^{-14}$ $(\Omega \cdot cm)^{-1}$ (18) and the radiation induced contribution to conductivity is clearly therefore not too important. Rather more significant increases in conductivity are calculated when considering some other polymers, and the implication of these increases in conductivity must clearly be borne in mind, but they do not represent situations which cannot readily be taken into account in design.

The mechanisms which produce permanent effects in polymers have been described in the preceding section. As well as affecting mechanical properties they can also affect electrical properties. However it is usually the case that failure of the electrical integrity occurs through degradation of the mechanical properties rather than the intrinsic electrical properties(13)(15) and that data about the former can be used to judge the
probable suitability of a material. Permanent changes in dielectric loss, dissipation factor and insulation from exposure to radiation have been recorded, but these are usually quite small and Hanks and Hamman(15) considered that they would only present problems in uncommon applications.

Empirical data on the effects of radiation on the mechanical and electrical properties of polymers

The preceding section has discussed some general effects which occur on irradiating polymers, and outlined some of the fundamental mechanisms responsible for these effects. Although there is a good appreciation of the way in which radiation can affect the physical properties of polymers and an understanding of some of the mechanisms involved, the complicated nature of commercially available polymers introduces a good deal of variation into the behaviour of superficially similar materials, and the environments, dose rates and temperatures of irradiation can have significant effects upon behaviour. A good deal of information has been obtained empirically on the effects of radiation on commercial organic polymers and summarised in useful, fairly recent publications by Van de Voorde and Restat(19) of CERN, Parkinson and Sisman(20) of Oak Ridge and Hanks and Hamman(15) of Battelle, Columbus. More extensive, earlier information is provided in References 12, 21 and 22. These documents provide a useful approximate guide to levels of radiation at which significant permanent changes begin to occur in the mechanical and electrical properties. Some of this information will be presented here in order to indicate the maximum levels of radiation which might be tolerable in practice. However, it must be borne in mind that commercial polymeric materials are constantly being modified by manufacturers, and that differences in their composition and in the dose rates and environments to be employed in a fusion reactor might significantly alter their behaviour. Existing information on permanent effects should therefore be used as a guide to selecting promising commercial materials whose performance must then be evaluated in a simulation of the proposed conditions. Such simulation is considerably easier than for the first wall ceramic insulators, and a good deal of information may be achieved in short times by the use of $\gamma$ sources or electron accelerators. Although it may also be necessary to carry out some neutron irradiation to determine the significance of the difference in effects obtained by equivalent doses of neutrons and $\gamma$, and longer term measurements will be required to determine the effects of dose rate and environment.

Figures 6 and 7 illustrate very generally the relative resistance to radiation of some thermoplastic and thermosetting materials at room temperature(13). For the reasons mentioned earlier, guides of this type are very approximate and must be treated with caution. It can be seen however that very few materials are affected by doses of less than $10^6$ rad and that most thermoplastics are seriously damaged at $10^8$ rad while some thermosetting resins are not seriously damaged at doses as high as $10^9$ to $10^{10}$ rad. Figure 8 shows the behaviour of a typical thermoplastic, a polyethylene employed as cable insulation(19), illustrating the characteristic way in which embrittlement occurs at doses in the range $10^7$ to $10^8$ rad.

Polymides, such as "Kapton", are reported to have very good radiation resistance(13), the tensile strengths (initially $\approx 180$ MNm$^{-2}$) decreasing only $\approx 10\%$ on irradiation in
vacuum to $4 \times 10^{10}$ rad. A greater decrease in strength was obtained on irradiating in air although, even so, it appears that the material could be used at $175^\circ$C in air to doses of $5 \times 10^9$ rad without trouble.

The behaviour of thermosetting resins depends not only on the type of resin, but also the curing agent. For example the flexural strength of Ciba-Geigy MY720, a viscous liquid glycidyl amine resin, was unaffected by doses of $10^{10}$ rad in air when cured with HY932, an aromatic diamine, but began to decrease at $10^9$ rad when cured with aniline.$^{23}$

Changes in mechanical properties are accompanied by the evolution of gases which could produce problems. Accumulation of gas as bubbles might encourage electrical breakdown, while if the gas is generated and trapped at cryogenic temperatures its subsequent release on return to ambient could disrupt the polymer.$^{24}$ Table 5 shows values of the rate of gas evolution from a variety of polymers irradiated in air at about $20^\circ$C.$^{25}$

The transient effects of radiation on electrical properties have been discussed earlier. In addition to transient effects, permanent changes can occur as a result of changes in, and damage to, the polymer structure. Van de Voorde and Resta$^{19}$ tabulate much useful information on the effects of radiation on volume and surface resistivity, dielectric strength, arc resistance, dielectric constant and dissipation factor of polymers. As a general rule the dose at which the onset of changes in mechanical properties occurs may be taken as the level at which electrical properties begin to alter and Reference 19 may be consulted for more detailed information.

Sufficient information therefore exists about polymers to define broadly the levels of radiation to which they might be employed. A few, including polyimides and some epoxides, can be used to doses slightly in excess of $10^{10}$ rad. Polyimides possess the best resistance to heat of commercially available plastics and may be used continuously at temperatures $\sim 250^\circ$C, while the long term operating temperatures of epoxide resins is lower than $200^\circ$C. Thus a temperature of $\sim 250^\circ$C and a dose of $\sim 10^{10}$ rad define the limits of applications of plastics as insulators in fusion reactors.

A value of $\sim 10^{10}$ rad is currently estimated as the maximum dose likely to be experienced by the magnet insulation of the Culham MKII Tokamak over thirty years, and this dose could be reduced by improved shielding. Organic polymers, therefore, could be suitable for insulation of the superconducting magnets and for applications further from the plasma. However, before embarking on the use of these materials it would be necessary to establish for the chosen material the effects of radiation at cryogenic temperatures, a regime in which very little information is currently available.

**CERAMIC INSULATORS**

The problems posed when considering the possible uses of ceramic insulators in fusion reactors are very different from those of organic polymers. The temperature and dose limits of polymers are known and their use will not be possible at the maximum temperatures and doses in the vicinity of the first wall. Ceramics are the only insulating materials which might be employable under those conditions. The main question then is whether even ceramics can withstand those conditions and retain useful properties. At present no data
exists on the behaviour of real ceramic systems at the high neutron doses of $\sim 10^{23}$ n.cm$^{-2}$ expected near the first wall.

Fast neutrons will collide with some of the target nuclei to displace atoms in the solid from their lattice sites to produce interstitials and lattice vacancies (an interstitial and a lattice vacancy is called a Frenkel defect). In the study of radiation damage effects in metals and ceramics, it is often helpful to discuss atom displacing radiation doses in terms of the number of atoms initially displaced by the damaging radiation. This enables a comparison to be made between different sorts of radiation, such as neutrons and charged particles. This is useful because damage can be introduced much more rapidly by charged particle accelerators than by existing neutron sources, and a good deal of information may be obtained in relatively short periods of time. Standard procedures exist for calculating the number of displaced atoms and it is usual to express this number as a ratio of the number of target atoms, i.e. the number of displaced atoms per atom or dpa. Two important parameters which control the number of atoms displaced for a given flux of particles of a given energy are the displacement cross-section, or probability of an atomic displacement event, and the displacement energy, the minimum energy required to displace the atom. The displacement cross-section depends upon the nature of the interaction between the incident particle and the target nucleus. The interaction between neutrons and atomic nuclei can be approximated by hard sphere collision for neutrons of energy up to several MeV. Under these conditions the probability of a collision is rather small but the average energy imparted when a collision occurs is high. The interaction between charged particles and nuclei is quite different because of the Coulomb forces involved. Under these conditions the probability of a collision is much greater but the average energy imparted is rather small. In addition the probability of a displacement event decreases as the particle energy increases and as the atomic displacement energy increases. The physics of these processes will not be described further here as they have been covered extensively in a range of standard texts (49).

Fast (14 MeV) neutron doses of $\sim 10^{23}$ cm$^{-2}$ are expected to produce displacement doses in oxide insulators of at least 10 dpa and possibly one or even two orders of magnitude more. A good deal of work has been carried out on metals and the alkali and alkaline earth halides to study the effect of doses of this magnitude. In metals these doses have been achieved largely by simulating the effects of neutrons through the use of heavy ions with energies of several MeV or through the large 1 MeV electron fluxes possible with the high voltage electron microscope. The susceptibility of alkali and alkaline earth halides to radiolysis and subsequent atomic displacement by low energy radiation has enabled the creation of damage in these diatomic solids by conventional 100 keV electron microscopy. In the following we shall review the mechanisms of structural damage in crystalline materials which these studies have revealed and consider their probable effect on the behaviour of ceramics; we shall briefly review the sort of information on ceramics which is already available and define the areas where additional information is required; and we shall consider how such information may be obtained.

Mechanisms of structural damage in crystalline inorganic insulators

The mechanical properties of the wide band gap, crystalline, inorganic insulators such as MgO, Al$_2$O$_3$ and Y$_2$O$_3$ are unaffected by $\gamma$ radiation and by electron radiation with
energy lower than approximately 0.3 to 0.4 MeV. Higher energy electrons; neutrons and protons with energies greater than a few hundred eV; and heavier particles with lower energies, can displace atoms from their lattice sites to create lattice vacancies and interstitials (Frenkel defects). As the energy of the incident particle increases, greater energy can be imparted to the displaced atom which can in turn collide with other atoms to produce a cascade of displacement damage of lattice vacancies and interstitial atoms.

The effect of atom-displacing radiation is best understood in metals where the material consists predominantly of one atomic type, the behaviour of diatomic materials being rather more complex. Similar numbers of atoms are initially displaced in a crystalline solid whatever the temperature of irradiation, but the final form that the damage takes depends critically on the ease of diffusion of vacancies and interstitials, and thus on temperature. At sufficiently low temperatures, where both vacancies and interstitials are relatively immobile, the displacement damage saturates at high dose when a sufficiently high number of vacancies and interstitials are generated to make recombination of further displaced atoms and vacancies very probable. Vacancies and interstitials are not generally equally mobile and at higher temperatures the situation can arise where one species is mobile and the other relatively immobile. The mobile species can then aggregate at some nucleating site. For example the aggregation of interstitial atoms onto a plane results in a localised extra plane of atoms in the crystals, the boundary of this plane being a dislocation loop. Again saturation of damage occurs. At a sufficiently high temperature, approximately one third of the melting point, both vacancies and interstitials become mobile and at high displacement doses clustering can occur. Vacancy aggregates nucleate at inert gas atoms and grow into three-dimensional voids, and simultaneously interstitials cluster and collapse into dislocation loops. The separation of vacancies and interstitials into separate, relatively large sinks prevents their recombination so that the saturation in damage which occurs at lower temperatures is prevented. Instead voids and dislocation networks are created, resulting in swelling of the metal(26). Usually the voids are distributed randomly, but under some circumstances they can form a three-dimensional array, a superlattice, with the same structure and crystallographic axes as the host lattice(27). There have been suggestions that the creation of a superlattice leads to less void swelling than a random array of voids, but the arguments are indirect and there is no direct evidence that this is correct. At higher temperatures, voids decrease in size as a result of diffusion of vacancies away from the voids, and void swelling decreases. From an engineering standpoint, the important fact is that there is a temperature range starting at approximately 0.3 $T_M$ and extending upwards, within which high doses of atom-displacing radiation lead to considerable swelling due to void growth. Increases in volume of up to 100% have been observed in model experiments in the high voltage electron microscope (HVEM) but in practice under fast reactor conditions or in variable energy cyclotron simulations the maximum increases of volume have been $\sim 10\%$.

Diatomic crystalline solids appear to exhibit the same general pattern of behaviour but the details of the processes involved are rather more complicated because of the two different atomic species present. The atoms in a diatomic solid may be regarded as being situated on two separate interpenetrating sublattices. For example in MgO the Mg$^{++}$ and O$^{++}$

where $T_M$ is the melting point
ions occupy two separate interpenetrating fcc lattices. The cross-sections and displacement energies of the two atomic species may differ, and thus the rate of creation of defects in the two sublattices will differ. At a fundamental level the events which occur in the two different lattices have to be considered both separately and also in the way that they can affect each other to produce the final damage structure.

Significant fundamental work has been carried out on the alkali and alkaline earth halides which are susceptible to radiolysis by $\gamma$ and electron irradiation. In these materials the anion species (the halogen) is readily displaced from its lattice site by $\gamma$ and low energy electron irradiation by an electron-hole recombination process (Pooley-Hersh mechanism) which is not effective in the oxides. Thus it has been possible to study the effect of high displacement doses which occur on one sublattice alone. This represents an extreme case of the behaviour which will occur in oxides under neutron irradiation, and it is instructive to examine this behaviour, especially as the Pooley-Hersh mechanism has permitted the achievement of much higher numbers of atomic displacements than can be obtained readily in oxides.

In ionic crystalline materials, such as the alkali and alkaline earth halides and the ceramic oxides of practical interest as insulators, one sublattice bears the negatively charged anions and the other the positively charged cations. The primary effect of $\gamma$ and low energy electron radiation on the alkali and alkaline earth halides is to displace atoms from the anion (halogen) sublattice alone, resulting in vacancies and interstitials in the anion sublattice. An aggregation of vacancies in the anion sublattice may be regarded as analogous to a void in metals but, considering both anion and cation sublattices together, this 'void' is not a region devoid of atoms but is a region where only cations exist - a colloidal metallic particle. The aggregation of radiation damage in materials of this type has been studied by optical absorption techniques and transmission electron microscopy and has recently been reviewed\(^{27}(28)\). At low temperatures both anion vacancies and interstitials are immobile. As the temperature is increased, the anion interstitials first become mobile. Finally at higher temperatures the anion vacancies also become mobile. In alkali halides the interstitial is mobile down to $\sim 300^\circ K$ but the vacancy only attains mobility above $\sim 300^\circ K$. In the temperature range where anion vacancies are immobile but interstitials are mobile, the rate of production of vacancies and interstitials decreases with increasing dose due to increasing recombination, saturation of damage occurring at $\sim 0.1\ dpa$, as shown in Figure 5\(^{(28)}\). During this stage mobile interstitial halogen atoms pair up to form interstitial molecules. The elastic strain energy of these molecules is high and a sufficiently large aggregate of them can shear the crystal lattice to displace anion-cation pairs which then form an interstitial dislocation loop, the halide molecules occupying the resulting anion-cation vacancy pairs. This gives rise to a planar dislocation loop structure, which can be observed by electron microscopy to grow and coarsen with increasing dose until saturation of damage occurs, and a uniform distribution of substitutional halogen molecular point defects, which give rise to characteristic optical absorption bands. At these temperatures the damage structure of coarse dislocation loops does not alter even with doses 100 times saturation. At temperatures where the vacancies are mobile, an entirely different pattern emerges as the vacancies aggregate to produce regions containing cations alone - the colloidal metal particles - and considerably
greater amounts of displacement damage can be sustained (as shown in Figure 9). The temperature range over which this behaviour occurs in the alkali halides begins at around a third of the melting point and extends for ~ 50^\circ \text{K}. Coincidentally this temperature of $T_M/3$ is the region of great interest for oxide insulators in fusion technology.

In the alkali halides and barium fluoride the metal colloids are distributed randomly but in calcium fluoride, and to a lesser extent in strontium fluoride, they form a regular array analogous to a void lattice in metals. These differences in behaviour have been attributed to differences in lattice spacings between the alkali earth metals and alkali earth halides, and because alkali metal crystallites cannot be coherently accommodated in the alkali halide crystal structures.

These studies have indicated an extreme of behaviour which occurs when the primary result of radiation is to cause displacement in one sublattice alone. Where a diatomic material is subjected to neutron or heavy particle irradiation which produces displacement on both lattices, the resulting processes will be even more complex, with the possibility of formation of "voids" which are anion rich, cation rich or devoid of atoms.

The development of damage and its effect on the properties of a typical insulator $\alpha\text{Al}_2\text{O}_3$:

Radiation damage studies of metals and of alkali and alkaline earth halides have shown that in a temperature range around approximately $T_M/3$ massive amounts of displacement damage can occur, saturation of damage is inhibited by the migration of vacancies into voids and interstitials into dislocation loops, and the material swells. Similar effects are to be expected in diatomic ceramic insulators, but to what extent is information about this available?

A good deal of work has been carried out on the effects of fast neutron damage in some of the oxide ceramics but none of this has reached the dose levels of interest to fusion reactors. In this section we shall review the information available about just one of the possible materials, $\alpha\text{Al}_2\text{O}_3$, as this is typical of the class, consider what further information is required, and discuss how this might be achieved.

The neutron flux at the first wall of a fusion reactor has been estimated to be $10^{15} \text{ n cm}^{-2} \text{ sec}^{-1}$, and therefore for a 20 year life we must consider the effect of a total flux of up to $7 \times 10^{23} \text{ n cm}^{-2}$ of neutrons with an energy spectrum up to 14 MeV. In $\text{Al}_2\text{O}_3$, the maximum doses which have been studied are $6 \times 10^{21} \text{ n cm}^{-2}$ (1 MeV) of average energy less than 14 MeV, so that available information takes us to a regime two orders of magnitude lower than that of interest. The main reason why total doses have so far been limited to $6 \times 10^{21} \text{ n cm}^{-2}$ is that this is the maximum which can be obtained in realistic times ~ 1 year in fission reactors. In order to study damage which will be equivalent to that obtained by $7 \times 10^{23} \text{ n cm}^{-2}$ of high energy neutrons it will be necessary to introduce the damage by means of charged particle beams. This raises a number of problems.

It is first necessary to calculate the displacement dose corresponding to a flux of $7 \times 10^{23} \text{ n cm}^{-2}$ of 14 MeV neutrons on a material, and to calculate the flux of charged particles of a given energy which will produce an equivalent displacement dose. These calculations are not straightforward and require the use of assumptions which introduce uncertainties into their accuracy. For relatively low energy neutrons incident on
relatively heavy atomic weight crystalline materials there is a generally accepted standard technique - the TRN standard (29) - for calculating the number of Frenkel pairs generated. It is well recognised that the TRN standard is only of very limited reliability in the calculation of neutron damage in light elements in a fusion reactor neutron spectrum. Simple calculations of displacement damage assume an equal probability of transfer of any energy, up to the maximum transferable, in a neutron collision. In reality, a beam of 14 MeV neutrons has wave-like properties and is diffracted so that strong maxima and minima appear in the primary knock on atom (PKA) spectrum; inelastic scattering occurs; the neutron flux is not monoenergetic and the cross-section for scattering and absorption vary with energy. Calculations have been made of the PKA spectrum of 14.1 MeV neutrons incident on niobium, which have enabled more accurate calculations of damage in that material (30), but such calculations do not exist for the low atomic mass diatomic solids of interest as insulators. Approximate calculations of displacement damage that have been made for oxides suggest that $10^{15}$ n cm$^{-2}$ give rise to $6 \times 10^5$ dpa, and thus that the total dose of $7 \times 10^{23}$ n cm$^{-2}$ can produce $4 \times 10^5$ dpa. More accurate calculations, however, are required.

Displacement doses of this magnitude are best introduced by energetic particles. Two techniques have been much used with metals and are feasible with ceramics - 1 MeV electrons from the high voltage electron microscope and ions with several MeV energies obtained from charged particle accelerators. Currently work is in progress to apply these techniques to the study of structural damage in ceramics. Simulation of the conditions at the first wall is not straightforward even with monatomic metals. It is believed that the nature of the damage structure can vary depending on the presence or absence of helium gas atoms which act as nucleating sites for voids. These are produced by nuclear transmutations under neutron irradiation but not under charged particle irradiation, and there is debate about the injection of such gases during ion irradiation. In diatomic materials the problem is further complicated by the choice of the bombarding ion - in metals ions of the same metal are commonly used but in diatomic materials there is a choice of two ions.

Charged particle simulation of neutron damage in ceramics is still in its infancy. In particular there is a need for the accurate calculation of displacement doses resulting from fusion reactor and particle accelerator irradiation. In order to carry these out it will be necessary first to measure experimentally the displacement energy of each of the atomic species in the ceramic. This can be done in a number of ways. One way is to employ a low energy electron beam and to vary the energy of the electrons until damage occurs. Measurements of this type on Al$_2$O$_3$ have produced data which suggest that the displacement energy of the aluminium ion is a good deal lower than that of the oxygen ion (30). If this is correct it could add another complication to the simulation of neutron damage by charged particles since the ratio of the displacement cross-section of the two atomic species will be very different for charged particles and neutrons, and hence differences in stoichiometry will rapidly occur during irradiation by the different techniques.

Direct observation of neutron damage (31-40) have been carried out on both single crystal and polycrystalline alumina at irradiation temperatures from 600°C to 1230°C and fast neutron doses up to $6 \times 10^{21}$ n cm$^{-2}$. In addition, post-irradiation annealing studies have been carried out at annealing temperatures up to 1800°C. A good review of the
information available prior to 1968 has been given by Wilks (37) and References 38-40 describe more recent work. Comparison of data obtained by different workers must be treated with caution because of differences in the materials studied and in the neutron spectra employed. The differences in the neutron spectra in particular make comparison of doses achieved in different studies difficult. For example, in Wilks' work rather different expansions were obtained on irradiating identical material to nominally identical doses in different parts of a reactor. Further, some workers refer to fast neutron doses > 1 MeV while others refer to doses > 0.1 MeV. The effect of this can be seen later in Figure 11 and Table 6 where at 650°C a dose of $4.3 \times 10^{21}$ (E > 0.1 MeV) produced the same swelling as a dose of approximately $1 \times 10^{21}$ (E > 1 MeV).

Swelling

Figures 10 and 11(36)(37) show the macroscopic growth, or swelling, of single crystal Al$_2$O$_3$ when bombarded with neutrons at 150°C and 650°C. At the lower temperature swelling is slightly anisotropic with c axis swelling becoming larger than a axis swelling, but at the higher temperature it is highly anisotropic, the growth in the c axis direction being considerably greater than in the a axis direction. At 150°C after a dose of $10^{21}$ n cm$^{-2}$ (E > 1 MeV) the linear expansion in both a and c directions is approximately 0.47% while at 650°C it is approximately 0.40% in the a direction and 0.95% in the c direction. Figure 12(31) shows the effect of neutron dose to $5 \times 10^{20}$ n cm$^{-2}$ at 75°C - 100°C on the lattice parameters of Al$_2$O$_3$, and Table 6(39) presents isolated lattice parameter and macroscopic dimensional changes obtained at 377°C, 602°C and 752°C at doses $\sim 5 \times 10^{21}$ n cm$^{-2}$ (E > 0.1 MeV). Comparison of Figure 10 with Figure 12 shows that there is good agreement between the lattice parameter expansion and macroscopic swelling at low temperatures (75°C - 150°C) and doses to $5 \times 10^{20}$ (E > 1 MeV). Figure 11 and Table 6, however, show that at higher temperatures (380°C - 750°C) there is no agreement; for a dose $\sim 5 \times 10^{21}$ n cm$^{-2}$, in the a axis direction the lattice parameter increases slightly at 377°C but decreases at 620°C and 752°C, the macroscopic dimension is increased on irradiation but the amount of swelling reduces as the temperature increases; for the same dose at the same temperatures, in the c-axis direction the lattice parameter is increased at all temperatures but the size of the increase reduces as the temperature increases while the macroscopic growth increases with increasing temperature.

Macroscopic growth and lattice dilation are equal under conditions where the number of vacancies and interstitials distributed through the lattice are equal. Discrepancies between macroscopic growth and lattice dilation can be attributed to clustering of defects, and it has been suggested that the effect in Al$_2$O$_3$ is due to the formation of a preferentially oriented void distribution in the lattice(39). Such measurements combined with electron microscope observation can therefore assist in an understanding of the mechanisms of defect aggregation.

The swelling produced by irradiation at low temperatures can be removed by annealing at higher temperatures - a typical recovery curve is shown in Figure 13(32) - as interstitials and vacancies recombine. No information however appears to be available concerning the annealing of material which has been irradiated at high temperatures and in which void growth has occurred.
The occurrence of anisotropic swelling in single crystals can lead to strains between grains in polycrystalline material and to the generation of intergranular cracking. Wilks has considered the strain energy requirements for cracking of polycrystalline alumina and has argued that the dose at which microcracking will first occur decreases as the irradiation temperature increases from 150°C to 650°C. For irradiation at 150°C he inferred that microcracking would not be expected at doses below $1.1 \times 10^{21}$ (E > 1 MeV) in material of grain sizes ≤ 100 µm but could be expected at a dose of $5 \times 10^{20}$ at 650°C.

Kellholtz et al. (58) have studied the effect on several commercial polycrystalline aluminas of fast neutron fluences of up to $5.8 \times 10^{21}$ n cm$^{-2}$ (> 1 MeV) at irradiation temperatures from 60°C to 1250°C. Their data is the most useful presently available for assessing the probable performance of alumina in a fusion reactor. The materials they studied are shown in Table 7. They observed three types of macroscopic damage: gross fracturing; grain swelling leading to a volume increase; and grain boundary separation, or microcracking, which increases the effect of swelling. They correlated this damage with irradiation dose, irradiation temperature, and as far as possible with purity of the alumina and grain size. Their data are extremely useful, but the number of parameters involved is large and they did not carry out an exhaustive study of the effects of varying parameters, so that their conclusions are indicative rather than definitive.

The most serious effect, gross fracture, was virtually absent in specimens irradiated at temperatures below 100°C to doses of $5 \times 10^{21}$ n cm$^{-2}$. Specimens were also irradiated at temperatures in the range 580°C to 1070°C to doses of $1.6 \times 10^{21}$ n cm$^{-2}$. Some of these specimens fractured but there was no obvious correlation of propensity to fracture with dose (in this range), temperature (in this range) and grain size. There did appear to be a correlation with purity, the specimens of higher purity exhibiting fewer failures than the less pure specimens.

Irradiation temperature had a very pronounced effect on the swelling which was due either to grain swelling alone or magnified by grain boundary separation caused by grain swelling. They defined five temperature regimes:

1. $< 100°C$
   - Damage is least in this range with little or no grain boundary separation.
   - There is a gradual increase in volume with increasing fluence (v. Figure 14).

2. 100°C - 600°C
   - Damage increases with increasing temperature. Large grained alumina exhibits grain boundary separation at high fluences (v. Figure 14).

3. 600°C - 1070°C
   - Irradiation temperature has little effect, damage increases with fluence.

4. $< 1100°C - 1200°C$
   - Damage is less than in Stage 3.

5. $> 1200°C$
   - Damage is much worse than in Stage 3. Severe grain boundary separation, especially in large-grain alumina, causes large volume expansion and some fracturing.
The transition from Stage 1 through Stage 2 to Stage 3 was tentatively explained in terms of the anisotropy in single crystal swelling that occurs in the range corresponding to Stage 2. Stage 4 appears to be due to annealing, but there is no satisfactory explanation of Stage 5 although it has been suggested that the experimental conditions in this range involved thermal cycling which might have aggravated grain boundary separation.

As a result of their work Keilholtz et al.\textsuperscript{(38)} drew the following practical conclusions:

1. Alumina should be of high purity and small grain size to minimise gross fracturing and grain boundary separation.

2. Thermal cycling should be avoided as there is evidence that this promotes grain boundary separation in irradiated alumina.

3. Electrical insulators made from alumina of high purity and small grain size should be able to withstand fast neutron fluences of $3 \times 10^{21}$ n cm$^{-2}$, the exact fluence depending on the neutron energy spectrum.

4. Practical designs should permit volume increases of up to 3%.

These calculations appear to define the present state of practical knowledge of swelling and fracture of alumina under irradiation.

At the microstructural level, Wilks has summarised electron microscope observations of damage in Al$_2$O$_3$ prior to 1966.\textsuperscript{(37)} These are presented in Table 8. More recent work\textsuperscript{(40)} has reported the occurrence of features resembling pores in Al$_2$O$_3$ irradiated to $6 \times 10^{21}$ n cm$^{-2}$ (E > 0.1 MeV) at 600$^\circ$C and 750$^\circ$C, the features resembling those seen in the alkali and alkaline earth halides at high displacement doses. At the time of writing the significance of these features has not yet been unambiguously defined. Studies of such features, especially at the high displacement doses attainable with charged particle accelerators, could provide useful information about the extent of swelling that might be expected at neutron doses higher than those readily achieved in a fission reactor.

**Mechanical properties**

There is little information available on the effects of neutron irradiation on the mechanical properties of alumina. Compression tests on polycrystalline material irradiated in the range $10^{20} - 5 \times 10^{20}$ n cm$^{-2}$ at $\sim 100^\circ$C indicated a possible increase in strength in this range, but only a small number of tests were carried out.\textsuperscript{(33)} Young’s modulus of polycrystalline material is reduced by 3% by irradiation to $1.5 \times 10^{20}$ n cm$^{-2}$ at $\sim 70^\circ$C \textsuperscript{(33)} and by 5 - 10% by irradiation to doses in the range $10^{20} - 10^{21}$ n cm$^{-2}$ in the range 250$^\circ$C to 700$^\circ$C.\textsuperscript{(34)}

Clearly when anisotropic swelling produces significant intergranular stresses or cracks the strength will decrease, and intergranular cracking will also reduce the effective stiffness of the material, but this is not an area which has been investigated in depth. In recent years there have been considerable advances in the development of engineering design techniques for use with ceramics. In particular there has been a recognition of the time dependence of ceramic strength due to slow crack growth, and the probabilistic nature of ceramic strength due to the statistical distribution of flaw sizes, and these ideas have been incorporated into unified theories which relate strength, probability and
This approach to ceramic design has already been used in a conceptual reactor design and ought undoubtedly to be of considerable use in the future. It will require, however, knowledge of the nature and geometry of the strength controlling flaws in highly irradiated materials, and the relationship between the velocities (v) with which they grow in the reactor environment under the range of stress intensity factors (K) to which they will be subjected. The size of specimens required for Kv determinations are such that it will not be possible to obtain this information through charged particle simulations, and long term fission reactor irradiations will be required.

**Thermal properties**

Irradiation of polycrystalline alumina in the range $10^{20}$ to $10^{21}$ n cm$^{-2}$ at temperatures between 250°C and 700°C had negligible effect on the thermal expansion coefficient but reduced thermal conductivity, the reduction increasing with increasing dose and decreasing irradiation temperature as shown in Figure 15. Klemens et al. have attempted to estimate theoretically the reduction in thermal conductivity of ceramics which would result from radiation damage, with particular reference to fusion reactor applications.

**Gas production**

Neutron irradiation of a solid can cause transmutation of some of the atoms of the solid through nuclear reactions. This can result in the formation of inert gases. At low temperatures the gas atoms are dispersed individually in the lattice, but at higher temperatures they are able to diffuse and coalesce to produce bubbles which might in principle aid swelling and reduce strength. Wilks has considered this effect in Al$_2$O$_3$ where the important gas-producing reactions are

$$\text{Al}^{27} + n \rightarrow \text{Na}^{24} + \text{He}^4$$
$$0^{16} + n \rightarrow \text{He}^4 + \text{C}^{13}$$

and has calculated for a fission reactor flux of $10^{20}$ n cm$^{-2}$ (≥ 1 MeV) the number of gas atoms produced per cc as $1.73 \times 10^{16}$ and the number of displaced atoms as $2.78 \times 10^{22}$. The number of displaced atoms is an upper limit which would be reduced by one or two orders of magnitude by recombination processes at temperatures of practical interest, while the numbers of gas atoms would be unaffected. Even with recombination, the number of gas atoms produced by transmutation is negligible compared with the number of displaced atoms so that the volume of gas produced is unlikely to significantly affect the swelling of Al$_2$O$_3$ directly. It is believed, however, that inert gas atoms can act as nucleating sites for voids and gas production might therefore indirectly promote swelling.

**Electrical properties**

In view of the technological importance of alumina as an electrical and electronic engineering material, it is perhaps surprising that its electrical properties are poorly characterised and not well understood. Kofstad has reviewed information available prior to 1971 and there have been no significant advances since then. Much of the early work overestimated the electrical conductivity because of the experimental problems inherent in measurement of small electrical currents through a material. Figure 16 shows
some of the more accurate data for single crystal and polycrystalline material. At about 800°C the electrical resistivity of polycrystalline Al₂O₃ is about 10⁷ Ω cm, a value which is a good deal lower than that of single crystal sapphire, probably because of the contribution from grain boundary conduction. Below 1300°C Al₂O₃ appears to be a mixed ionic and electronic conductor.

The absorption of radiation can produce both transient and permanent changes in the electrical properties. The transient effects occur as a result of electronic excitation and ionisation which produce a strong photoconductive effect, and according to Hanks and Hamman the change in conductivity on irradiation can be described by similar equations to plastics (equations 1-3 earlier) with a value of A₂ between 10⁻¹⁶ and 10⁻¹⁸, and a value of δ of 1. Assuming this to be correct for alumina, the transient increase in conductivity can easily be calculated for various radiation fluxes. For example, a fast neutron flux of 10¹⁵ n cm⁻² sec⁻¹ on Al₂O₃ is approximately equivalent to a dose rate in rads of \( \approx 5 \times 10⁵ \) rad sec⁻¹ and this will produce an increase in conductivity of \( \approx 10⁻¹¹ \) Ω⁻¹ cm⁻¹ compared with a conductivity at 800°C of \( 10⁻⁶ \) Ω⁻¹ cm⁻¹. The effect is therefore small and radiation enhanced conductivity does not appear to be important. This is supported by the work of Ahrens and Wooten who have considered theoretically the enhanced conductivity produced by radiation and developed a model which predicts a dependence of conductivity on radiation of similar form to Equation 2. They have collated transient conductivity data for a number of materials, Figure 17, and the experimental data for Al₂O₃ agree with the value calculated above. Van Lint et al have theoretically estimated the effects of the Reference Theta Pinch Reactor operating conditions on refractory insulators and have concluded that ionisation induced conductivity will not be a problem with the RTPR first wall insulator.

The permanent changes which occur on irradiation are a result of the structural changes resulting from atomic displacements. Hanks and Hamman quote some limited information for some specific inorganic insulators. They say that the predominant effect on electrical properties is a change in resistivity and that little or no change occurs in dielectric characteristics. Lucalox, a high purity alumina, did not experience a change in resistivity when subjected to a neutron fluence of \( 1.6 \times 10²⁰ \) n cm⁻² at temperatures of 800°C to 1000°C. At high displacement doses however the production of voids and the possible precipitation of metallic inclusions may have a deleterious effect on the dielectric properties and the electrical breakdown strength. This is an area in which there is little hard information and work is required to investigate the electrical properties of heavily damaged ceramics. It may be possible to carry out these measurements on the heavily damaged thin layers obtained in charged particle irradiated materials, in which case rapid simulation of damage conditions could be obtained. The experimental difficulties however are formidable and it may be necessary to resort to very long fission reactor irradiations.

**SUMMING UP**

In this report we have confined ourselves to considering the problems which will arise from the damaging effects of radiation on electrical insulators. The radiation damage problem, although important, is only one of several considerations which will need to be
taken into account in the selection of the best materials for the construction of a fusion reactor. Economic and technical factors such as cost, availability, ease of fabrication and, for some applications, chemical reactions with hydrogen or lithium, will also be important and have not been considered here.

Both organic polymers and ceramics are potentially useful electrical insulators for magnetically confined fusion reactors. The use of polymers will be limited to regions of relatively low radiation dose and temperature, but their easier processability, greater toughness and versatility, will make them more attractive than ceramics for applications in which they can withstand the environment. The decisions about where they may be used will depend very critically on the design of the reactor and the shielding which can be provided.

Some organic polymers which could be used as insulators are known to be able to withstand radiation doses somewhat in excess of $10^{10}$ rad. In principle these could be employed for magnet insulation in a reactor such as the conceptual Culham MkII Tokamak. However there are several fundamental points that need to be established before they could be employed with certainty. Most of the information which is available about the effects of radiation on polymers has been obtained from $\gamma$ or electron irradiation studies at room temperature. In the reactor, in the vicinity of the magnet, insulators would be subjected to a rad dose which was primarily due to neutrons rather than $\gamma$, and it is necessary to establish the relationship between neutron and $\gamma$ damage effects. In addition the insulation would normally be at $\sim 4.2^0 K$ and current ideas on superconducting magnets in reactors tend to the view that the temperature of the magnet should never rise above $\sim 80^0 K$, even under accident conditions. However, these ideas are still at the development stage and it may be that larger temperature fluctuations could occur. The effect of irradiation at $4.2^0 K$ on mechanical and electrical properties is an area in which there is very little information and the behaviour needs to be established. In addition any effect of temperature cycling on the irradiated material, such as possible swelling due to gas generation as radicals become mobile, needs to be determined.

No information yet exists about the effects on ceramics, at reactor operating temperatures, of the very large fluxes of energetic neutrons which will occur near the first wall during the reactor lifetime. The main danger in making an arbitrary selection of a ceramic is the possibility that under the combination of high displacement dose and temperature it may be prone to excessive swelling. The large displacement doses of interest cannot be achieved readily by reactor irradiation but, as with metals, a good deal of information may be obtained from charged particle simulation techniques. These techniques subject very small volumes of material to very high displacement doses, and the swelling behaviour of macroscopic specimens may be inferred from electron microscopy studies of the irradiated material. The use of these techniques with ceramics is still in its infancy. Calculations need to be made of the displacement doses to which ceramics will be subjected in a reactor environment, and of the conditions necessary to produce equivalent doses by a simulation technique. Calculations of this sort have been made for metals but no accurate calculations appear to exist for ceramics. Since any ceramic is made up of two or more atomic species, the behaviour of displaced atoms in such systems, where the atoms will have different displacement cross-sections, displacement energies,
diffusion characteristics, etc., needs to be determined. One advantage of ceramics in this respect is the range of solid state physics techniques which can be employed in the study of their defect state, and which are not available for metals, such as optical absorption and luminescence. Other experimental techniques which might be used to study the defect state include positron annihilation, x-ray low angle scattering and neutron scattering.

Charged particle techniques may be used to compare, relatively quickly, a range of candidate ceramics in order to select those which appear to swell least. Samples of these could then be subjected to very long term fission reactor irradiation in order to provide sufficient amounts of material for macroscopic measurements of electrical and mechanical properties. Alternatively it may be possible to develop charged particle simulation techniques to accelerate the acquisition of even this data, although the experimental difficulties will be formidable.

Although it is unlikely that a demonstration fusion reactor will be operational for another twenty-five years, data of the sort described here is already important for developing improved conceptual designs, and will be essential later for prototype reactor designs. For the last few decades much effort has been expended in understanding the physics of plasmas. Over the next few decades the problems associated with the engineering technology and materials science of reactors will become of increasing importance.

ACKNOWLEDGEMENTS

I am grateful to Dr. L.J. Baker for calculating radiation doses for the Culham MkII Tokamak, to Mr. G.P. Pells for many useful discussions on the effects of radiation on ceramics, and to Drs. D.H. Bowen, R. Hancox, A.E. Hughes and D. Pooley for their useful comments during the writing of the report.

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TABLE 1

Applications of fusion insulators in an approximate order of decreasing severity of radiation damage

<table>
<thead>
<tr>
<th>Application</th>
<th>Reactor Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF insulator</td>
<td>Tokamak</td>
</tr>
<tr>
<td>First wall insulator</td>
<td>Theta pinch</td>
</tr>
<tr>
<td>Low atomic number first wall liner</td>
<td>All reactors but especially Tokamak</td>
</tr>
<tr>
<td>Neutral beam injector insulation</td>
<td>Tokamak and mirror machine</td>
</tr>
<tr>
<td>Direct converter insulator</td>
<td>Mirror machine</td>
</tr>
<tr>
<td>Torus current breaker</td>
<td>Tokamak</td>
</tr>
<tr>
<td>Magnet insulation</td>
<td>All reactors</td>
</tr>
<tr>
<td>Cables and electronic control device insulations</td>
<td>All reactors</td>
</tr>
</tbody>
</table>

TABLE 2

Representative severe conditions for insulators near the first wall

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>1200°C</td>
</tr>
<tr>
<td>Stress</td>
<td>380 MPa</td>
</tr>
<tr>
<td>Voltage</td>
<td>100 kV cm⁻¹ at 700°C</td>
</tr>
<tr>
<td>Fusion neutrons</td>
<td>~ 10¹⁹ m⁻² sec⁻¹</td>
</tr>
<tr>
<td>Photons</td>
<td>~ 0.7 MJ m⁻² per pulse</td>
</tr>
<tr>
<td>D-T ions</td>
<td>~ 10¹⁸ m⁻² sec⁻¹</td>
</tr>
<tr>
<td>He ions</td>
<td>~ 5 x 10¹⁶ m⁻² sec⁻¹</td>
</tr>
<tr>
<td>Impurity ions</td>
<td>~ 3 x 10¹⁶ m⁻² sec⁻¹</td>
</tr>
<tr>
<td>Compound</td>
<td>G-value</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>Benzene:</td>
<td>1.8</td>
</tr>
<tr>
<td>Styrene: CH = CH₂</td>
<td>1.6</td>
</tr>
<tr>
<td>Chlorobenzene: Cl</td>
<td>17.3</td>
</tr>
<tr>
<td>O-Dichlorobenzene: Cl Cl</td>
<td>30.0</td>
</tr>
<tr>
<td>Acetone: CH₃ - CO - CH₃</td>
<td>50.0</td>
</tr>
<tr>
<td>Ethyl bromide: CH₃ - CH₂Cl</td>
<td>28.0</td>
</tr>
<tr>
<td>1,2-Dichloroethane: CH₂Cl - CH₂Cl</td>
<td>41.0</td>
</tr>
<tr>
<td>Chloroform: CHCl₃</td>
<td>59.5</td>
</tr>
<tr>
<td>Bromoform: CHBr₃</td>
<td>57.0</td>
</tr>
<tr>
<td>Carbon tetrachloride: CCl₄</td>
<td>70.0</td>
</tr>
</tbody>
</table>
**TABLE 4**

Measured values of $A_2$ and $\delta$ for eight materials as defined by $(C-C_0) = A_2 \gamma \delta$ (a)

(Conductivity in (ohm-cm)$^{-1}$ and dose rate in rads sec$^{-1}$)

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature $T_C$</th>
<th>$\delta$</th>
<th>$A_2$</th>
<th>Range of $\gamma$, rads (H$_2$O)/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polystyrene</td>
<td>38</td>
<td>0.97</td>
<td>$4.0 \times 10^{-17}$</td>
<td>1.7 $\times 10^{-2}$ to 5.0 $\times 10^3$</td>
</tr>
<tr>
<td></td>
<td>49</td>
<td>0.97</td>
<td>$4.0 \times 10^{-17}$</td>
<td>1.7 $\times 10^{-2}$ to 5.0 $\times 10^3$</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>0.97</td>
<td>$4.0 \times 10^{-17}$</td>
<td>1.7 $\times 10^{-2}$ to 5.0 $\times 10^3$</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>38</td>
<td>0.74</td>
<td>$5.2 \times 10^{-16}$</td>
<td>8.3 $\times 10^{-2}$ to 1.7 $\times 10^3$</td>
</tr>
<tr>
<td></td>
<td>49</td>
<td>0.74</td>
<td>$6.3 \times 10^{-16}$</td>
<td>8.3 $\times 10^{-2}$ to 1.7 $\times 10^3$</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>0.74</td>
<td>$1.6 \times 10^{-15}$</td>
<td>8.3 $\times 10^{-2}$ to 1.7 $\times 10^3$</td>
</tr>
<tr>
<td>Epoxy 1478-1</td>
<td>38</td>
<td>No measurable photoconductivity below $\gamma = 1.7$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.0</td>
<td>$3.3 \times 10^{-17}$</td>
<td>1.7 to 4.2 $\times 10^3$</td>
</tr>
<tr>
<td></td>
<td>49</td>
<td>No measurable photoconductivity below $\gamma = 9.0$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.0</td>
<td>$3.3 \times 10^{-17}$</td>
<td>9.0 to 4.2 $\times 10^3$</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>No measurable photoconductivity below $\gamma = 7.5 \times 10^1$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.0</td>
<td>$3.8 \times 10^{-17}$</td>
<td>7.5 $\times 10^1$ to 4.2 $\times 10^3$</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>38</td>
<td>0.88</td>
<td>$3.8 \times 10^{-17}$</td>
<td>1.8 $\times 10^{-3}$ to 6.0 $\times 10^3$</td>
</tr>
<tr>
<td>H-film</td>
<td>38</td>
<td>1.1</td>
<td>$5.8 \times 10^{-18}$</td>
<td>1.8 $\times 10^{-3}$ to 6.0 $\times 10^3$</td>
</tr>
<tr>
<td>Teflon</td>
<td>38</td>
<td>1.0</td>
<td>$1.2 \times 10^{-16}$</td>
<td>1.8 $\times 10^{-3}$ to 6.0 $\times 10^3$</td>
</tr>
<tr>
<td>Nylon</td>
<td>38</td>
<td>No measurable photoconductivity below $\gamma = 8.0$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.3</td>
<td>$2.8 \times 10^{-18}$</td>
<td>8.0 to 6.0 $\times 10^3$</td>
</tr>
<tr>
<td>Diallylphthalate</td>
<td>38</td>
<td>0.30</td>
<td>$2.1 \times 10^{-16}$</td>
<td>1.8 $\times 10^{-3}$ to 3.0 $\times 10^2$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.7</td>
<td>$8.0 \times 10^{-20}$</td>
<td>3.0 $\times 10^2$ to 6.0 $\times 10^3$</td>
</tr>
</tbody>
</table>

(a) Data taken under steady state conditions after $1.8 \times 10^3$ seconds of electrification.

(b) Temperature is ± 1°C.

(c) Fifteen samples of polyethylene, polystyrene, and Epoxy 1478-1 and three samples of the other materials were measured.
TABLE 5

Gas yields from plastics irradiated at 20°C in air
The G value is defined as the number of molecules of gas per 100 eV of deposited energy. (A selection of data taken from Reference 25)

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Gas evolution rate</th>
<th>G-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( cm^3 \text{ (NTP) gm}^{-1} \text{ Mrad}^{-1} )</td>
<td></td>
</tr>
<tr>
<td>Low density polyethylene</td>
<td>0.09</td>
<td>3.86</td>
</tr>
<tr>
<td>High density polyethylene</td>
<td>0.07</td>
<td>3.06</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>0.0006</td>
<td>0.026</td>
</tr>
<tr>
<td>Plasticised PVC</td>
<td>0.027</td>
<td>1.16</td>
</tr>
<tr>
<td>Unplasticised PVC</td>
<td>0.018</td>
<td>0.77</td>
</tr>
<tr>
<td>Polymethylmethacrylate</td>
<td>0.027</td>
<td>1.18</td>
</tr>
<tr>
<td>PTFE</td>
<td>0.0022</td>
<td>0.098</td>
</tr>
<tr>
<td>Nylon 6</td>
<td>0.024</td>
<td>1.02</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>0.020</td>
<td>0.86</td>
</tr>
<tr>
<td>Polyethylene terephthalate</td>
<td>0.004</td>
<td>0.17</td>
</tr>
<tr>
<td>Polyimide</td>
<td>0.00006</td>
<td>0.0026</td>
</tr>
<tr>
<td>Epoxide resins (a range)</td>
<td>0.0029 to 0.13</td>
<td>0.12 to 0.57</td>
</tr>
</tbody>
</table>

TABLE 6

Comparison of changes in lattice and macroscopic dimensions

<table>
<thead>
<tr>
<th>Material</th>
<th>Neutron fluence(^{(a)}) ((10^{21} \text{ n/cm}^2))</th>
<th>Temp. (K)</th>
<th>(\Delta a/a_0) (%)</th>
<th>(\Delta d/d_0)(^{(b)}) (%)</th>
<th>(\Delta c/c_0)</th>
<th>(\Delta l/l_0)(^{(c)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>134</td>
<td>5.6</td>
<td>650</td>
<td>0.01</td>
<td>0.61</td>
<td>0.21</td>
<td>1.00</td>
</tr>
<tr>
<td>133</td>
<td>4.3</td>
<td>875</td>
<td>-0.06</td>
<td>0.30</td>
<td>0.15</td>
<td>1.42</td>
</tr>
<tr>
<td>135</td>
<td>4.5</td>
<td>1025</td>
<td>-0.09</td>
<td>0.20</td>
<td>0.09</td>
<td>1.68</td>
</tr>
</tbody>
</table>

\(^{(a)}\) E_n > 0.1 MeV.

\(^{(b)}\) Diametral change – corresponds to a axis change.

\(^{(c)}\) Length change – corresponds to c axis change.
### TABLE 7a

**Characteristics of commercial alumina products**

<table>
<thead>
<tr>
<th>Type of Alumina</th>
<th>Source</th>
<th>Bulk Density (g/cm³)</th>
<th>Average Grain Size (microns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I Coors AD-995</td>
<td>Coors Porcelain Co.</td>
<td>3.86</td>
<td>13</td>
</tr>
<tr>
<td>II Wesgo Al-995</td>
<td>Western Gold and Platinum Co.</td>
<td>3.85</td>
<td>25</td>
</tr>
<tr>
<td>III GE Opaque Lucalox</td>
<td>General Electric Co.</td>
<td>3.91</td>
<td>6</td>
</tr>
<tr>
<td>IV GE Translucent Lucalox</td>
<td>General Electric Co.</td>
<td>3.96</td>
<td>25</td>
</tr>
</tbody>
</table>

### TABLE 7b

**Analysis of commercial alumina products**

<table>
<thead>
<tr>
<th>Type of Alumina</th>
<th>Total Impurities (wt.%)</th>
<th>Major Impurities (wt.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I Coors AD-995, 13 µm</td>
<td>0.42</td>
<td>Mg 0.1 Si 0.06 Fe 0.06</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Cu 0.06) (Cr 0.1)</td>
</tr>
<tr>
<td>II Wesgo AL-995, 23 µm</td>
<td>0.25</td>
<td>Mg 0.1 Si 0.1 Fe 0.03</td>
</tr>
<tr>
<td>III GE Opaque Lucalox, 6 µm</td>
<td>0.06</td>
<td>Mg 0.02 Si 0.007 Fe 0.01</td>
</tr>
<tr>
<td>IV GE translucent Lucalox, 25 µm</td>
<td>0.14</td>
<td>Mg 0.08 Si 0.02 Fe 0.003</td>
</tr>
</tbody>
</table>

-35-
<table>
<thead>
<tr>
<th>Irradiation Temperature (°C)</th>
<th>Dose (nvt ≤ 1 MeV)</th>
<th>As-irradiated</th>
<th>Temperature (°C) of 1 h anneals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>800 to 1000 in argon</td>
</tr>
<tr>
<td>≤ 150</td>
<td>$2 \times 10^{19}$</td>
<td>15 Å dots resolved in flakes</td>
<td>damage still not resolved</td>
</tr>
<tr>
<td></td>
<td>$5 \times 10^{19}$</td>
<td>damage not resolved in thinned single crystals</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$10^{20}$ to $4 \times 10^{20}$</td>
<td>damage resolved as dots in flakes and dots of 20-00 Å dia. in thinned single crystals</td>
<td>similar to as-irradiated</td>
</tr>
<tr>
<td></td>
<td>$10^{20}$ to $5 \times 10^{20}$</td>
<td>50-75 Å dots and 50-600 Å loops in flakes</td>
<td></td>
</tr>
<tr>
<td>650</td>
<td>$10^{20}$</td>
<td>150-500 Å dia. loops</td>
<td>similar to as-irradiated</td>
</tr>
<tr>
<td>1000</td>
<td>$4 \times 10^{20}$</td>
<td>300-500 Å dia. loops, tangles $10^{14}$ to $10^{15}$/cm² 50-200 Å cavities of indefinite shape</td>
<td></td>
</tr>
</tbody>
</table>
The figure shows the neutron flux $\Phi$ (neutrons cm$^{-2}$ s$^{-1}$) as a function of the radial distance from the plasma centre (m). The flux decreases significantly with increasing distance from the plasma. The labels indicate different materials and regions:

- Plasma
- Nb Wall
- Li-Nb Blanket
- Graphite, etc.
- Magnet Shield $Fe, H_2O$ (B)
- Superconducting Coil Cu, Nb, Fe

The 20-yr dose is approximately $10^{16}$ neutrons cm$^{-2}$ ~ $10^9$ rad.

1a. Some typical neutron fluxes calculated for a conceptual Tokamak reactor rated at 10 MW m$^{-2}$. (51)
1b. Calculated values of the 70- year radiation dose in rads in the vicinity of the magnet of the CHELLM for a power rating of 1 kWm⁻² (48)

Dose Rate (rad sec⁻¹ gm⁻¹)

Photon Dose (7 and X)

Total Dose

Distance from Minor Axis (cm)

Total Dose (rad gm⁻¹)

Manifold Space

Module Shield (Steel & Boron Carbide)

Fixed Shield (Steel and Water)

Magnet Windings
2a. Primary events occurring after the interaction of radiation with polymer molecules (after Van de Voorde).
2b. Processes resulting from bond dissociation.
3. Possible processes for radical migration

\[
\begin{align*}
\text{CH}_2 - \text{CH}_2 & \xrightarrow{\text{reaction}} \text{CH} - \text{CH}_2 + \text{He} \\
\text{CH} - \text{CH}_2 + \text{O} - \text{O} & \xrightarrow{\text{reaction}} \text{CH} - \text{CH}_2 - \\
\text{CH} - \text{CH}_2 & \xrightarrow{\text{reaction}} \text{C} = \text{O} + \text{O} - \text{CH}_2 - \\
\end{align*}
\]

4. Illustration of the influence of oxygen on chain scission and resulting degradation (after Van de Voorde\(^{(13)}\)).
5. Variation of conductivity (plotted logarithmically) as a function of time when the material is subjected to a pulse (shaded rectangle) of radiation of dose rate $\dot{\gamma}(15)$. 
Polystyrene
Polyvinyl carbazole
Acrylonitrile/butadiene/styrene (ABS)
Polyimide
Polyvinyl chloride
Polyethylene
Polyvinyl formal
Polyvinylidene chloride
Polycarbonate
Ethylene propylene polyallomer
Kel-F
Polyvinyl butyral
Cellulose acetate
Polypropylene
Polymethyl alpha-chloroacrylate
Polymethyl methacrylate
Polyamide
Vinyl chloride-acetate
Teflon TFE
Teflon FEP
Teflon TFE and FEP (vacuum)

Gamma dose, rad.

Damage

Incipient to mild
Mild to moderate
Moderate to severe

Utility
Nearly always usable
Often satisfactory
Limited use

7. Radiation resistance of thermosetting resins (13).
8. The effects of radiation on the mechanical properties of polyethylene (cable insulation) (79).
9. Three forms of Frenkel defect concentration growth kinetics in NaCl. (28)
10. Macroscopic growth of Al₂O₃ as a function of neutron dose at 150^0(37).
11. Macroscopic growth of $\text{Al}_2\text{O}_3$ as a function of neutron dose at $650^\circ\text{C}$ (37).
12. Lattice parameter changes in $\text{Al}_2\text{O}_3$ as a function of neutron dose at 75-100°C (31).
13. Recovery of X-ray and macroscopic growth of irradiated Al₂O₃ during isochronal (1 hour) annealing. (32)
Figure 14. Volume increase of polycrystalline alumina during reactor irradiation.
15. The effect of neutron dose and irradiation temperature on the thermal conductivity of polycrystalline Al₂O₃\(^{(34)}\).
16. Electrical conductivity of single and polycrystalline aluminium oxide. 
$S_0$: single crystal, c-axis in plane of sample; $S_{90}$: single crystal, c-axis perpendicular to plane of sample; $P_1$: polycrystalline aluminium oxide, mean grain size 12 μm, bulk density 3880 Kg m$^{-3}$; $P_2$: polycrystalline aluminium oxide, mean grain size 20 μm, bulk density 3900 Kg m$^{-3}$. 
17. Theoretical and experimental photoconductivities versus dose rates for various insulators (45)