RADIATION PROBLEMS FOR INSULATORS IN ITER AND BEYOND

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INTRODUCTION

Present plans envisage that ITER (International Thermonuclear Experimental Reactor) will come into operation during the second decade of this new 21st century, with the purpose of bridging the gap between the present day large "physics" machines and the pre-commercial DEMO reactor. Commercial reactors could then become available by the middle of the century. Although ITER will help to solve many problems remaining in the field of plasma physics, it will present additional operational and experimental problems due to radiation damage effects as a result of the intense radiation field from the "burning" plasma. The ignited plasma will give rise to a high energy neutron and gamma flux, extending well beyond the first wall, from which one foresees a serious materials problem which has to be solved. In the initial physics phase radiation flux will be of concern, whereas in the later technology phase both flux and fluence will play important roles as radiation damage builds up in the materials. For metallic materials the problem of radiation damage is expected to be severe, although tolerable, only near to the first wall, however the problem facing the insulating components is more serious due to the necessity to maintain not only mechanical, but also the far more sensitive physical properties intact. The need to carry out inspection, maintenance, and repair remotely due to the neutron induced activation of the machine is also of concern. Remote Handling will require machines which use standard components ranging from simple wires, connectors, and motors, to optical components such as windows, lenses, and fibres, as well as electronic devices such as cameras and various sophisticated sensors. All these components use insulating materials. We face a situation in which insulating materials will be required to operate under a radiation field, in a number of key systems from plasma heating and current drive, to diagnostics, as well as remote handling maintenance systems. These directly affect not only operation, but also safety, control, and long term reliability of the machine. In the long term, beyond ITER, the solution of the materials problem will determine the viability of fusion power.

FUSION RELEVANT RADIATION DAMAGE

Radiation will modify to some degree all of the important material physical and mechanical properties. Unfortunately in general these changes do not improve the materials. Some of the changes are flux dependent, while others are modified by fluence. Flux dependent processes are of concern from the on-set of operation, while fluence affects component and material lifetime. The insulator properties of concern include electrical resistance, dielectric loss, optical absorption and emission, as well as thermal and mechanical properties. Papers discussing general and specific aspects of radiation damage in insulating materials for fusion applications are included [1-11].

The study of intense radiation effects in metals has been closely associated with the development of nuclear fission reactors, aso by the 1980's when the urgent need to consider radiation damage aspects of materials to be employed in future fusion reactors was fully realised, a considerable amount of data existed for metallic materials [12]. This was not so for insulators, due to the fact that insulators in fission type reactors are limited to low radiation regions. However despite this considerable progress has been made in assessing the possible problem areas and finding viable solutions. Several general reviews give a good introduction to radiation damage in insulators [13 - 17].

The materials in ITER and beyond will be subjected to fluxes of neutrons and gammas due to the ignited plasma. The intensity will depend not only on the distance from the plasma, but also in a complex way on the position within the machine due to streaming along numerous penetrations required for cooling systems, blanket structures, heating systems, and diagnostic and inspection channels, as well as radiation from the cooling water due to the $^{16}O(n,p)^{16}N$ nuclear reaction. However models are available which enable the neutron and gamma fluxes to be calculated with confidence [18 - 20]. At the ITER first wall the primary displacement dose rate will be about 10^{-6} dpa/s, and the ionizing dose rate 10^4 Gy/s.

The polyatomic nature insulators make them far more sensitive to radiation damage than metals. While stainless steel can withstand several dpa and GGy with no problem, some properties of insulators can be modified by as little as 10^{-6} dpa or a few kGy. Radiation damage results in a change in the electrical and thermal conductivity, dielectric loss and permittivity, optical properties, and to a lesser extent the mechanical strength and volume. Hence insulators may suffer Joule heating due to increased electrical conductivity or lower thermal conductivity, windows become opaque from the microwave to the optical region, and in addition they may become more brittle and swell. Of the numerous insulating materials the refractory oxides and nitrides show the highest radiation resistance. MgO, Al_2O_3, $MgAl_2O_4$, BeO, AlN, and Si_3N_4 have received specific attention. In addition SiO_2, and diamond and silicon have been examined for window and optical transmission applications.

Finally one should mention transmutation. Nuclear reactions in the materials will give rise to transmutation products [21]. These build up with time and represent impurities in the materials which may modify their properties. Physical properties of insulators are particularly sensitive to impurities. Some of these transmutation products are radioactive and give rise to the

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need for remote handling and hot cell manipulation in the case of component removal, repair, or replacement. For the structural materials, in the present concepts mainly steel alloys, considerable work has been carried out on the development of so-called reduced activation materials (RAM) for use in DEMO and future commercial fusion reactors [22]. For insulating materials no equivalent study or development has been carried out, due in part to the small fraction of the total material volume represented by the insulators, but also because the important physical properties of these materials will have degraded before the transmutation products become of concern. Certainly for ITER transmutation products, with the possible exception of hydrogen and helium, are not expected to present a serious problem.

SIMULATION EXPERIMENTS

At present no entirely suitable irradiation testing facility exists so experiments are being performed in nuclear fission reactors and particle accelerators, as well as gamma and X-ray sources, to try to simulate the real operating conditions of the insulating materials and components. This can be justified as long as the influence of the type of radiation on the physical parameter of interest is known. This in certain cases is true for radiation induced electrical conductivity and radioluminescence for example, where for low total fluences it is the ionizing component of the radiation field which is important. The experiments must simulate the neutron and gamma radiation field i.e. the displacement and ionization damage rates, the operating environment i.e. vacuum and temperature, and also the operating conditions such as applied voltage, or mechanical stress. It is essential that in-situ testing is carried out to determine whether or not the required physical properties are maintained during irradiation. Examples of this include electrical conductivity which can increase many orders of magnitude due to the ionizing radiation, or optical windows which may emit intense radioluminescence.

Fission reactors have the advantage of producing both neutrons and gammas, although the neutron energy spectrum and the displacement to ionization ratio are not those which will be experienced in a fusion reactor. The main difficulties with in-reactor experiments come from the inaccessibility of the radiation volume and are concerned with the problem of carrying out in-situ measurements and achieving the correct irradiation environment. While considerable success has been attained in the in-situ measurement requirement, with parameters such as electrical conductivity, optical absorption and emission, and even radiofrequency dielectric loss being determined, the problem of irradiating in vacuum still remains, with most experiments being performed in a controlled He environment. Also nuclear activation generally means that post irradiation examination (PIE) has either to be carried out in a hot cell, or postponed until the material can be safely handled. Particle accelerators are ideal for carrying out in-situ experiments in vacuum at controlled temperatures due to easy access and localised radiation field. High levels of displacement and ionization can be achieved with little or no nuclear activation. However the non-nuclear aspect of the radiation field is a problem. A further disadvantage is due to the limited irradiation volume and particle penetration depth. This means that only small thin material samples or components can be tested.

ELECTRICAL INSULATOR DEGRADATION

Electrical resistance, generally discussed in terms of electrical conductivity (inverse of resistance), is an important basic parameter for numerous systems and components including the NBI (Neutral Beam Injection) heating system, ICRH (Ion Cyclotron Resonant Heating) windows and supports, magnetic coils, feed-throughs and stand-offs, MI cables and wire insulation. Reduction in electrical resistance of the insulators in these components may give rise to Joule heating, signal loss, or impedance change. The main candidate for these applications is Al_2O_3, and has been extensively studied, in the polycrystalline alumina form and as single crystal sapphire. Four types of electrical degradation in a radiation environment are recognised and being investigated, these are; Radiation Induced Conductivity (RIC), Radiation Induced Electrical Degradation (RIED), Surface Degradation, and Radiation Induced Electro-Motive Force (RIEMF).

Fig. 1. Schematic RIC as a function of irradiation time (dose) and dose rate.

RIC, RIED, and surface degradation are fully discussed elsewhere [8]. RIC is a flux dependent enhancement of the electrical conductivity due to excitation of electrons from the valence to the conduction band. Figure 1 shows schematically the RIC as a function of irradiation time and ionizing dose rate (flux). The increase to saturation depends on the dose rate and in a complex way on temperature and sample impurity content, see figure 2 where RIC for MgO:Fe at 0.1 Gy/s is given [23]. The complex behaviour is well predicted by theory [24].

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Fig. 2. RIC as a function of irradiation temperature and impurity content for MgO:Fe. 1.8 MeV Bremsstrahlung irradiation at 0.1 Gy/s [23].

For the dose rates of interest for fusion, approximately 1 Gy/s to 1000 Gy/s, saturation is reached within seconds to minutes and it is the saturation level which is of concern. From available data, one can safely say that RIC is sufficiently "well understood" to allow this type of electrical degradation to be accommodated by the design, and that materials exist which give rise to electrical conductivities $\leq 10^{-6}$ S/m for ionizing dose rates of up to 10^4 Gy/s. One only expects possible problems near the first wall. Unfortunately this is the region where magnetic coil diagnostics, which can tolerate only very low leakage conductivity, will be employed. RIC is a flux dependent effect and will be present from the on-set of operation of ITER. Hence devices which are sensitive to impedance changes, which will occur for example in MI cables, must take RIC into account. Furthermore RIC is strongly affected by impurity content, figure 2 and [8], hence the build-up of transmutation products will modify RIC with irradiation time (fluence), although this is not expected to be of serious concern for ITER.

RIED, see figure 3, is more serious, not only from the point of increasing the electrical conductivity beyond that of the RIC, but also because this type of degradation is still not fully understood, nor even is there general agreement as to whether RIED exists as a real volume degradation [8, 11]. The most recently completed in-reactor RIED experiment in HFIR at ORNL [25 - 27] helps to throw light on the complex RIED problem. Initial results indicated no significant increase in electrical conductivity for the 12 different samples. However moderate to substantial electrical degradation was observed in some of the sapphire and alumina samples, so material type may be an important parameter [27]. Despite the purely academic distinction, for the insulating components, surface degradation is just as serious as volume degradation. Two types of surface degradation have been reported, one related to surface contamination caused by poor vacuum, sputtering, or evaporation [28 - 30] and real surface degradation of the material related to surface vacuum reduction and possibly impurity segregation [31 - 33]. To illustrate all these problems, figure 4 shows the leakage current measured for a vacuum gauge 99.7 % alumina insulated feedthrough component electron irradiated at 300 C, 700 Gy/s [34]. The initial large increase in conductivity is due to RIC, and the slow permanent increase is due to either RIED or surface degradation.

Fig. 3. Schematic RIC and RIED as a function of irradiation time (dose), showing the underlying permanent degradation.

Fig. 4. 99.7 % alumina feed-through leakage current as a function of irradiation time, with 1.8 MeV electrons, 700 Gy/s, 300 C. Leakage is due to RIC, and RIED and/or surface degradation.

Strictly speaking RIEMF is not a degradation, but an induced voltage / current which "degrades" the signal quality carried by the mineral insulated (MI) coaxial cables in a radiation field. RIEMF can produce several volts between the inner and outer conductors, or supply tens of microamps of current, and has been known and employed in reactor control since the early 70's [35]. The effect is due to electron producing reactions such as (n, β), (n, γ, e) etc. causing an unbalanced charge distribution between the inner conductor and the outer sheath of MI cables. Judicious choice of the inner and outer materials together with their diameter and thickness can minimize the effect for a given neutron and gamma flux and spectrum, however the rapidly varying radiation field expected for next step fusion devices means that RIEMF will have to be tolerated rather than eliminated.

While considerable concern has been expressed about the possible radiation induced degradation of solid insulating materials under a fusion radiation environment, and by implication in those required for the ITER NBI accelerator system, little or no attention has been paid until very recently to the problem of the insulating gas which will be required around the NBI high voltage feed line, ion source and accelerator. This gas, in the present design SF_6, will be in a radiation field of the order of 1 Gy/s due to the fusion plasma and the NBI accelerator itself. The radiation will cause ionization in the gas, and hence an increase in the gas electrical conductivity. As this is a source of power loss due to the corresponding leakage current which in addition will produce heating and possibly breakdown, the radiation effect must be quantified and taken into account in the engineering design of the NBI system. Results show that the gas does not behave like a solid insulator, but that the leakage current is a function of the gas volume due to the possibility of collecting all the generated charge carriers. For the 1 MV ITER NBI system this implies that up to megawatts of power could be lost due to this radiation induced leakage current [36]. To limit this the use of vacuum insulation is being considered.

DEGRADATION OF OPTICAL PROPERTIES

Finally quick mention should be made of another area of concern related to the effects of radiation on the optical properties of materials to be used as transmission components (windows, lenses, and optical fibres) for the UV, visible, and IR wavelengths [11, 37, 38].

Fig. 5. Radioluminescence for KU1 and KS-4V. 1.8 MeV electrons, 700 Gy/s, 70 C

For remote handling applications the optical components are expected to maintain their transmission properties under high levels of ionizing radiation (1 - 10 Gy/s) during many hundreds of hours. Here radiation induced optical absorption imposes the main limitation. However in the case of diagnostic applications, in addition to a higher level of ionizing radiation (tens to hundreds Gy/s), the material will be subjected to atomic displacements of the order of 10^{-10} dpa/s. For these applications both radiation induced optical absorption and light emission (radioluminescence) impose severe limitations on the use of SiO_2 and sapphire, present day ITER candidate materials, making it extremely difficult to separate out the plasma emission from the window emission and absorption [39]. Work on KU1 and KS-4V quartz glasses provided by the Russian Federation for the ITER programme has shown that suitable materials do exist in which the radioluminescence can be reduced to a minimum, as may be seen in figure 5 where the radioluminescence from KU1 is almost at the Cherenkov limit [40]. However one must remember that with irradiation displacement dose the optical absorption related to oxygen vacancies in SiO_2 quickly renders this material opaque in the UV and visible range [41 - 44]. Of course some radiation effects can be put to good use and this is the case of radioluminescence, which while a problem for optical windows can be employed as a detector / converter for X-ray and UV emission from the plasma. This is illustrated in figure 6 where the intense radioluminescence from Al_2O_3 : Cr is shown. Such emission has been used for many years in ceramic fluorescent screens for accelerator beam alignment [45], and is now being developed for improved radiation resistance and rapid decay times for fusion applications.

CONCLUSIONS

The problems of electrical and optical degradation in insulating materials for next step fusion devices have been briefly presented. Although the task ahead is difficult, important advances are being made not only in the identification of potential problems, but also in the understanding of the radiation effects as well as materials selection and design accommodation to enable the limitations to be tolerated or even employed.

Fig. 6. Intense Cr radioluminescence for Al_2O_3:Cr. 1.8 MeV electrons, 700 Gy/s, 30 C.

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