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TITLE

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ABSTRACT

Diagnostic systems in advanced D-T-burning fusion devices will be subjected to intense fluxes and fluences of high-energy neutrons and gamma rays. Materials used in these systems may suffer significant degradation of structural, optical, and electrical properties, either promptly upon irradiation or after accumulation of structural damage. Of particular concern are windows, optical fibers, reflectors, and insulators. Many materials currently specified for these components are known to degrade under anticipated operating conditions. However, careful materials selection and modification based on an appropriate irradiation testing program, when combined with optimization of design-sensitive factors such as location, shielding, and ease of replacement, should help to alleviate these materials problems.

1. Introduction

Magnetically-confined fusion devices require diagnostic facilities in order to analyze plasma performance and to control the plasma through feedback systems. As fusion devices begin to employ deuterium-tritium (D-T) fuel mixtures, radiation fluxes will increase greatly and the materials that make up the diagnostic facilities can be expected to suffer significant degradation of physical properties.

Physicists and materials scientists in many countries are beginning to address materials problems associated with radiation effects in diagnostic systems. This paper summarizes the U.S. view of materials issues for diagnostic systems in next-step burning plasma devices such as the Burning Plasma Experiment (BPX) in the United States and the International Thermonuclear Experimental Reactor (ITER), both of which will generate radiation fluxes characteristic of a fusion powerplant.

The wide variety of diagnostic systems currently in use or proposed for BPX and ITER translates into a complex set of performance requirements and materials needs (see, for example, ref.[1]). This paper summarizes critical materials requirements for four major applications: windows, optical fibers, reflectors, and insulators.

2. Irradiation fluxes and fluences

Neutron and gamma fluxes and fluences for BPX and for the physics and technology phases of ITER are shown in Table 1. Values are given both at the first wall and behind the cryostat; most diagnostics will be located at or between these two locations.

Radiation fluxes are severe in both devices, with fluxes actually being somewhat higher for BPX than for ITER. However, fluences are much greater for ITER, reflecting the greater duty factor for that machine. Neutron fluences can readily be converted into estimated displacements per atom (dpa), given a knowledge of the energy spectrum. However, the conversion factor varies with material and spectrum (which softens with increasing distance from the first wall or proximity to penetrations), so that a simple approximation of 1 dpa per 10^{25} n/m^2 is often used. This means that at the end of the technology phase in ITER every atom in a solid will have been displaced 20 times. However, the majority of the damage is quickly recovered, so that in less than one microsecond the dpa level from a given nuclear collision event is significantly reduced.

The ionizing energy represented by gamma irradiation must be converted to energy absorbed, in order to estimate the effect on materials parameters. This conversion is dependent on energy of the gamma rays and composition and density of the material in question. A useful approximation for a low atomic number material such as Al_2O_3 is that 5×10^{18} fusion gamma/m^2 (of energy about 2 MeV) is equivalent to approximately 10^4 Gy of energy absorbed, where 1 Gy = 100 rad.

It should be noted that a significant fraction of ionizing energy absorbed results from the stopping within the material of ions knocked from their lattice positions by neutron bombardment. A useful approximation by Dell and Goland [2] for Al_2O_3 is that 6.1×10^{15} first wall n/m^2 deposits 1 Gy. This comprises about a tenth of the ionizing energy absorbed from accompanying gamma rays in ITER, although damage effects are not necessarily comparable since energy is deposited more locally in the case of neutrons.

3. Materials applications in diagnostic systems

Windows

Candidate window materials for BPX and ITER will be subjected to radiation that can degrade the transmission characteristics, induce luminescence, cause dimensional changes, and alter the mechanical properties. Proposed candidate materials for windows are, according to Taylor [3]:

- Crystalline quartz for the far infrared region
- ZnSe for the infrared
- Fused silica for the visible and near ultraviolet
- Sapphire and magnesium fluoride for the ultraviolet.

Approaches to development of windows for near-term designs include selection of materials that exhibit the greatest resistance to radiation damage, operation of windows at elevated temperatures (T 300 C) where irradiation-induced defects can continuously anneal out of the material, periodic annealing of defects following low-temperature operation, and judicious design of windows to accommodate material changes without failure. The following discussion emphasizes the effect of dimensional changes in SiO_2, with optical damage in this material being discussed in the section on optical fibers.

Primak and co-workers [4-7] have shown that both fused silica and crystalline quartz change dimensions when irradiated with low fluences of fast neutrons or gamma rays at ambient temperature. Three mechanisms have been identified that contribute to dimensional changes in fused (vitreous) silica during reactor irradiations: compaction due to collision damage, contraction but later expansion due to gamma rays, and radiation-induced stress relaxation. Figure 2 shows trend lines for dimensional changes in these materials [3,4,6,7]. Inhomogeneities in the original material can result in localized stress centers as well as macroscopic dimensional changes.

Small dimensional changes in window materials can result in high stress levels in window assemblies. It is estimated that the upper limit for the radiation-induced interference strain for window assemblies of current design is $5x10^{-4}$; design optimization may improve this limit by a factor of two [3]. This leads to the conclusion that windows of current design should not be subjected to a dose in excess of $5x10^{21}$ fusion n/m^2. Larger dimensional changes could be tolerated if sliding seal assemblies can be developed.

Optical fibers

Silica-based optical fibers are the leading candidates for BPX/ITER diagnostic applications operating in the range -0.4-2.0 microns. These materials are mechanically viable, thermally stable, and less susceptible to radiation-induced attenuation than are other types of glasses. To preserve their mechanical and thermal characteristics these fibers must be metal-coated rather than polymer-jacketed, but the technology to do this exists. Radiation-induced color centers can never be eliminated, but thanks to recent research these defects are becoming understood, and it is known that they can be controlled to a degree (for a review, see ref. 8).

Figure 2 shows the spectral dependence of induced absorption in a commercial high-purity fused silica of low water content, after irradiation with 2 MeV electrons [9]. Also shown are Gaussian resolutions of several of the distinct color center bands that have been isolated in the course of correlated optical and electron spin resonance (ESR) experiments. (ESR gives information about the atomic-scale structure of the color centers [10].)

The bands centered at 5.85, 4.7, and 2.0 eV are known to result from structural defects that can be introduced by irradiation. The 5.85 eV band results from a hole trapped at the site of an oxygen vacancy [11], while that at 2.0 eV is contributed by the nonbridging-oxygen hole center [12]. The largest peak, near 4.7 eV, has been shown [13] to be due to the presence of interstitial ozone molecules (O_3), and is correlated with dissolved O_2 in the as-manufactured material [8,13]. However, even in the absence of pre-dissolved oxygen, interstitial O_2 and O_3 molecules can be anticipated to form from radiation-displaced oxygen [14].

A striking dependence on dose rate has been reported for the 5.85 eV band [15], indicating the importance of in-situ experiments and tests employing rates characteristic of BPX and ITER. Onset of saturation for this band is near 10^{10} Gy [16], or 1000 times the ionizing dose represented in Fig. 2; thus transmissivity of the SiO_2 fibers may be expected to be severely degraded by the end of the technology phase of ITER (Table 1).

Other absorption bands in the infrared region have been tentatively ascribed to alkali and hydrogen impurities [17]. If this interpretation is correct, pickup of hydrogen isotopes from a fusion reactor environment could prove to be a problem.

Construction of an optical fiber involves core and cladding glasses of different compositions, so that 10% dopants must be introduced into one or the other in order to achieve waveguiding. With the exception of fluorine, the ususal dopants employed for this purpose lead to greater radiation-induced attenuation. Thus a pure-silica-core, F-doped-silica-clad fiber would seem to be the best for BPX/ITER diagnostic applications, although Be-doped-silica-core, pure-silica-clad telecommunications fibers should also be tested.

Finally, in addition to the radiation-induced attenuation bands, there are also radiation-induced luminescence bands that may be excited either by the radiation itself or by light propagating in the fiber. The spurious light could mask the true optical data from the plasma. In particular, an emission band near 2.7 eV is intrinsic to pure silica and may arise from any or all of the following: self-trapped excitons [18], oxygen vacancies [19], or two-coordinated silicon ions [20]. In diagnostic applications, it is likely that the luminescence emissions will have to be removed from the data stream by computer processing, perhaps by making use of the light output of reference fibers exposed to the same radiation fluxes but prevented from propagating the signal light. Similar approaches may be required for the optical absorption bands.

Reflectors

Reflectors (mirrors) are specified for use at wavelengths from 300 to 11000 nm and 0.1 to 5 mm, and at temperatures of 100 to 350 C. These diagnostic elements may be made of a variety of materials or

materials combinations, depending on the wavelength to be reflected. Possibilities include:

all metal
all ceramic or all glass
ceramic with metal coating
ceramic or glass with dielectric coating
metal with dielectric coating
metal with metal coating.

Transient damage may be in the form of temporary luminescence or darkening. Permanent degradation could result from darkening, deposition of contamination layers, sputtering, microcracking, spalling, swelling, or structural damage. Some of these topics have previously been discussed with respect to SiO_2, in the sections on windows and optical fibers; discussion of structural damage to ceramics is deferred to the following section on insulators.

Many of these same problems may be encountered with metals, although materials with significant ductility should show adequate resistance to such brittleness-related problems as microcracking and spalling. Metals are of course also immune from luminescence and darkening effects.

Insulators

Bulk dielectrics will be used for a number of applications in fusion diagnostics, including magnetic probes, cables, and feedthroughs. The most severe environment is that for magnetic probes, whose operating conditions include:

- frequency from DC to 1 MHz
- DC bias voltage from zero to 1000 V/mm, with higher voltage spikes during plasma disruption
- temperatures from 600 to 1200 C
- vacuum, with possible tritium contamination
- voltage transients during disruptions.

Degradation of these insulators can be permanent, as from neutron damage or dielectric breakdown, or transient, as a result of absorption of ionizing energy or generation of a high concentration of defects during irradiation.

Transient damage, which takes the form of a temporary decrease in insulating properties during irradiation, is of special concern because such degradation can occur as soon as the fusion device begins to generate radiation fields. The effect can be large: Farnum et al. [21] have observed a dramatic increase of room-temperature ac conductivity in single-crystal Al_2O_3 during irradiation with 3 MeV protons, as ionizing energy produces an excess number of charge carriers. Much of the increase dissipates with time as damage dose builds up; this effect is attributed to trapping and recombination of electrons and holes at defect sites.

Recently, Hodgson [22] has identified another, perhaps more serious problem: degradation of electrical and perhaps even structural properties when insulators are irradiated while under an imposed electric field. This phenomenon, which is not well understood, is currently under study at several laboratories around the world.

The lifetime neutron fluence in BPX is not sufficient to cause significant structural degradation in most ceramics. However, Macor machinable glass-ceramic [23], one of a family of materials that lends itself to inexpensive production of complex insulator configurations, has been shown [24] to swell significantly at 4×10^{22} 14 MeV n/m^2. Since the net swelling observed is attributed to growth of the crystalline mica phase and densification of the glassy phase, a large reduction of strength due to internal stresses is likely.

At the much larger lifetime neutron fluence characteristic of ITER, other ceramics can undergo significant swelling and strength loss. Fission reactor irradiation tests of BeO conducted at 100 C by Hickman [25] have shown that most strength is lost at a fluence about fifty times less than that characteristic of ITER lifetime fluence. Strength loss results from anisotropic swelling of individual grains in this non-cubic ceramic, leading to severe internal stresses and microcracking. A similar problem can affect polycrystalline Al_2O_3, although usable strength may be retained to ITER end-of-life fluences [26]. On the other hand, cubic $MgAl_2O_4$ spinel actually strengthens under high-dose fission neutron irradiation [27], and so this ceramic may be a good choice for fusion applications.

4. Data base for materials in diagnostic systems

No comprehensive database exists for radiation effects in diagnostic materials for fusion applications. Supportive information can be obtained from the literature in areas such as communications, space, fission power and nuclear weapons programs, and in professional journals. However, the focus is often on long-term damage effects, whereas fusion instrumentation is most vulnerable to transient effects. There is also a requirement for data on activation of diagnostic materials and effects of tritium exposure. Such information is for the most part unavailable.

While the database is incomplete, assessments of radiation effects on fusion diagnostics have been made for the Joint European Torus (JET) in 1980 [28] and for the Tokamak Fusion Test Reactor (TFTR) in 1981 [29]. These reports contain extensive information on diagnostic materials and systems, as well as discussions of shielding and hardening techniques. An important goal of the ITER diagnostic program is to create an updated database of radiation effects in diagnostic materials for that device.

5. Irradiation testing

Investigators of structural radiation damage effects in fusion reactor materials have traditionally been concerned with the question

of simulation of cumulative structural damage from fusion neutrons. Such studies require the use of other types of radiation, since no intense source of fusion neutrons presently exists.

Study and qualification of diagnostic materials impose additional simulation needs beyond those required for studies of structural damage, because of the requirement that electrical and optical properties also be assessed. Further, some materials specified for diagnostic applications can be altered structurally by absorption of ionizing energy. Thus testing of diagnostic materials may, depending on the material and its application, require simulation of some or all of the following:

1. Cumulative knock-on damage events
2. Cumulative displacive or disordering events that result from absorption of ionizing energy
3. An appropriate combination of (1) and (2)
4. Prompt knock-on damage rates
5. Prompt ionizing energy absorption rates
6. An appropriate combination of (4) and (5).

Simulation of damage with particles other than fast neutrons (e.g., light ions) will usually involve deposition of a ratio of ionizing to displacive energy that is quite different from that to be encountered in a fusion device. Work by Zinkle [30] has shown that the result can be significant differences in damage microstructure; thus extrapolations to fusion conditions must be made with due caution, and must be based on a thorough understanding of the basic damage effects involved.

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Table 1.

ITER AND BPX FLUXES AND FLUENCES

	BPX (500 MW)	ITER Physics	ITER Technology
FIRST WALL			
Neutron Flux (n cm^{-2} s^{-1})	2.0×10^{15}	2.5×10^{14}	2.5×10^{14}
Neutron Fluence (n cm^{-2})	$<<2.0 \times 10^{19}$	2.0×10^{20}	2.0×10^{22}
Gamma Flux (γ cm^{-2} s^{-1})	8.0×10^{14}	2.0×10^{14}	2.0×10^{14}
Gamma Fluence (γ cm^{-2})	$<<8.0 \times 10^{18}$	1.6×10^{20}	1.6×10^{22}
BEHIND CRYOSTAT			
Neutron Flux (n cm^{-2} s^{-1})	8.0×10^{13}	2.0×10^{5}	2.0×10^{5}
Neutron Fluence (n cm^{-2})	$<<8.0 \times 10^{17}$	1.5×10^{11}	1.8×10^{13}
Gamma Flux (γ cm^{-2} s^{-1})	3.0×10^{13}	1.0×10^{6}	1.0×10^{6}
Gamma Fluence (γ cm^{-2})	$<<3.0 \times 10^{17}$	7.5×10^{11}	9.0×10^{13}

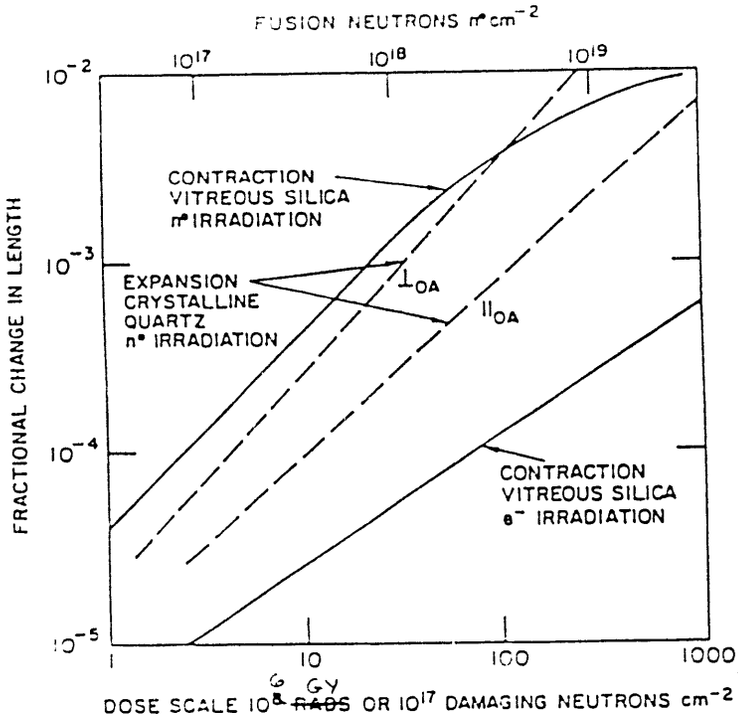

Fig. 1. Fractional contraction of vitreous silica and expansion of crystalline quartz as a function of fluence of fission neutrons and ionization dose, at ambient temperature. The upper scale shows equivalent fluence of fusion neutrons. [References 3,4,6,7].

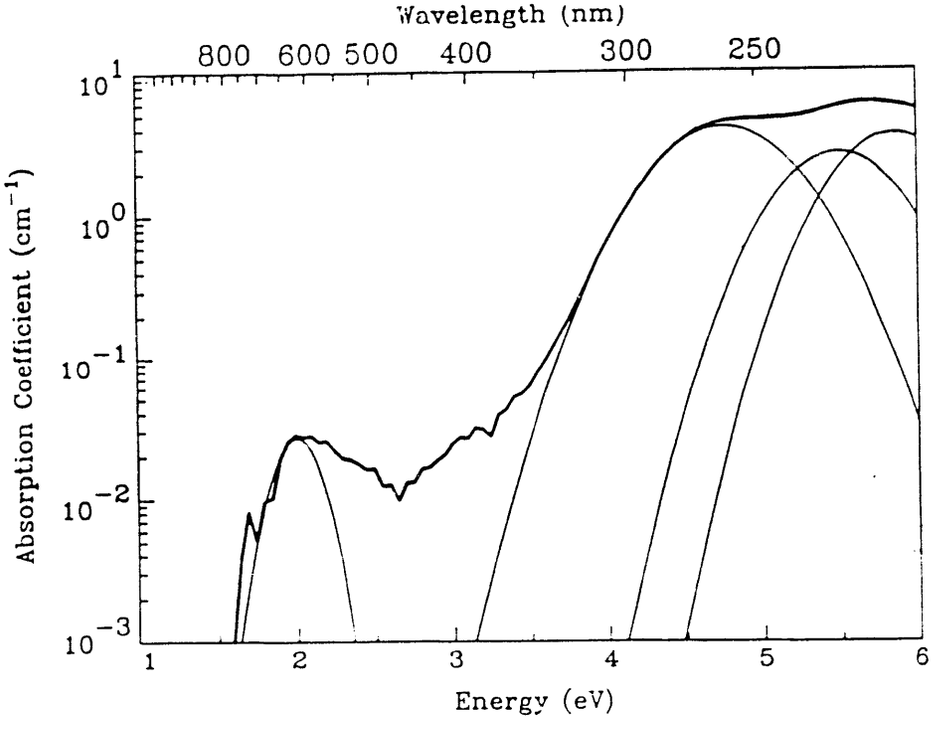

Fig. 2. Optical absorption in Suprasil W2 Fused silica after irradiation with 2 MeV electrons to 10 MGy [Reference 9].

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