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THE EFFECTS OF RADIATION ON TFTR COIL MATERIALS

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The Coupled Fast Reactivity Measurements Facility (CFRMF) at the Idaho National Engineering Laboratory was used to irradiate coil insulation specimens provided by the Princeton Plasma Physics Laboratory. Exposure times were chosen as to be representative of expected lifetime doses in the TFTR. Shear bond and flexure tests were performed on irradiated samples; identical unirradiated samples were tested as controls. A general loss of strength (10-20%) was seen on the majority of specimens.

1. INTRODUCTION

The Tokamak Fusion Test Reactor (TFTR) will be the first fusion plasma experiment to attain near-reactor conditions. Concurrent with its design objective of demonstrating breakeven ($Q=1$) will be the associated problems of operating a plasma physics experiment in a radiation field. Aside from the radiation effects to the active diagnostics, radiation damage to the insulation materials must be considered in the design of the machine. The magnetic field coil insulation will be the most sensitive and serious indicator of permanent radiation damage for several reasons:

- (1) The total neutron fluence expected in TFTR over a four year lifetime is $10^{20} - 10^{21} \text{ n/m}^2$, well below that which would cause appreciable damage to structural metals. However, the coil insulation material, a composite of fiberglass impregnated with epoxy, will be far more sensitive to radiation effects than metals.
- (2) The TFTR coils will be normally conducting with no planned shielding, and will absorb a substantial fraction of the energy of the fusion neutrons emanating from the plasma.
- (3) In the TFTR, the large toroidal field (TF) coils cannot be replaced without cutting and rewelding a segment of the vacuum vessel (remotely since the TFTR will be activated). Thus, it is extremely important that accommodation of the radiation effects on coil materials be incorporated in the design.

Knowledge concerning radiation damage to fiberglass-composite insulators with regard to fusion applications is noticeably sparse when compared to metals and other "first wall" materials, due in part to the more complex nature of damage mechanisms in such materials. However, the effects of various radiation sources upon epoxy [1-4] and glasses [5-10] have

been studied. It is generally concluded that irradiation (neutron as well as gamma) induces cross-linking of polymeric chains and a depolymerization which results in embrittlement of epoxy materials [1]. The degree of embrittlement is a function of dose [1-2]. Aromatic hardeners generally have better radiation damage resistance than their aliphatic counterparts due to the energy absorptive benzene resonance [3].

The effect of irradiation upon glasses is dependent upon the type and dosage of irradiation as well as the composition of the glass [8]. Most glasses exhibit coloration and an increase in optical density [10]. The changes in physical properties due to irradiation tend to be less severe than for other ceramics [11]. However, there is evidence that as exposure is increased, displacement and transformation of ions in glass can form a critical flaw which, when placed in a stress field, will initiate cracking leading to catastrophic failure. This is especially true in the presence of water vapor [11]. Glasses containing boron are especially susceptible to thermal neutron radiation due to the $B^{10}(n,\alpha)Li^7$ reaction, which releases a high energy alpha particle producing a damage cascade area [11]. Johnson [7] describes glasses with large amounts of boron (>10%) exhibiting large fissures and cracks after irradiation.

The above data are of marginal value for estimating the degree of damage suffered by a composite material such as the TFTR coil insulation materials. In support of TFTR, Smith and Punchard [12] investigated the static and fatigue shear strengths of fiberglass-epoxy composites. The present work extends that study to include the effects of radiation.

2. IRRADIATION PROCEDURE

2.1 TFTR Coil Radiation Doses

The TFTR coils will be composed mostly of three materials: copper, epoxy (an approximate formulation, suitable for calculating absorbed

dose, is $C_{10}H_{13}O_2$), and E-glass (approximately 60% SiO_2 , 20% CaO , 10% B_2O_3 , and 10% Al_2O_3). The composition of the coil as a whole will be approximately 30% water (for cooling), 12% insulation (itself 35% epoxy and 65% glass), and 85% copper. The approximate doses to the TF coil materials expected from 4,000 D-T pulses of 0.5 sec duration were calculated, using the photon and neutron spectra provided by the Princeton Plasma Physics Laboratory (PPPL), and are given in Table 1.

TABLE I

APPROXIMATE TFTR RADIATION DOSES FROM 4000 D-T
0.5 SECOND PULSES

Neutron Fluence: $6.2 \times 10^{20} \text{ n/m}^2$
Neutron Average Energy: 4.5 MeV
Photon Fluence: $1.8 \times 10^{20} \text{ gamma/m}^2$
Photon Average Energy: 1.75 MeV

	NEUTRONS (Gy.)	PHOTONS (Gy.)	ALPHA ₀ ($B^{10}n, \alpha$) (Gy.)
E-Glass	9×10^4	2×10^5	6×10^5
Epoxy	7×10^5	1×10^5	3×10^5

Doses of from 10^6 to 10^7 Gy. will damage most organic compounds, and neutron fluences on the order of 10^{25} n/m^2 will damage copper such that self-annealing will not occur at room temperature. The insulation materials (especially the epoxy) will be on the threshold, while the copper should not suffer permanent damage.

It is often possible to extrapolate the damage produced from a fission neutron spectrum to that expected in a fusion reactor. This is especially true when the fusion neutrons undergo several collisions prior to reaching the point of interest. Through inelastic scattering, the high-energy (14 MeV) neutrons produced in the D-T reaction will be moderated to the range found in a fast fission spectrum.

Before neutrons reach the TF coils, they must travel at least through the stainless-steel vacuum vessel (12.5 mm) and coil case (30 to 70 mm). In addition, many of the 14 MeV neutrons will be further moderated by striking assorted diagnostic ports and equipment before traveling into the coils. The inelastic scatter (including n, 2n) mean free path for 14 MeV neutrons in copper and iron is approximately 0.1 m. Thus, at some point not too far inside the coils, the spectrum will resemble that found in a fission reactor.

2.2 Coupled Fast Reactivity Measurement Facility (CFRMF)

The Coupled Fast Reactivity Measurements Facility (CFRMF) at the Idaho National Engineering Laboratory (INEL) was used for the present irradiation experiments. This is a pool reactor with a maximum power level of 100 kW (th) and a peak flux of $8 \times 10^{15} \text{ n/m}^2 \text{ sec}$. The CFRMF experiment area contains a boron filter which removes most of the thermal flux and correspondingly, problems of excessive heating from neutron activation. In addition, its relatively low gamma flux allows easy cooling of the specimens. A 38 mm ID stainless-steel dry tube provides access to the CFRMF experiment area.

A comparison of CFRMF and TFTR neutron spectra is shown in Figure 1. The TFTR spectrum was calculated with two-dimensional transport theory (DOT), and it represents a point just inside the coil. The CFRMF spectrum was calculated and confirmed by measurements. The correlation in the energy range of from 10 keV to 5 MeV is quite good, and it is suggested that the bulk of neutron-induced damage occurs in this range. A comparison of spectrum-averaged damage energy cross sections supports the suggestion. For copper, this parameter is 6.0×10^4 eV-barns for the TFTR spectrum and 4.3×10^4 eV-barns for the CFRMF spectrum. The numbers for aluminum, assumed to be a neutronically representative constituent of the E-glass are 6.7×10^4 eV-barns (TFTR) and 6.0×10^4 eV-barns (CFRMF). Energy deposition coefficients ($\text{erg-g}^{-1}/10^7 \text{ n-m}^{-2}\text{sec}^{-1}$), important for comparing damage to the epoxy, were also spectrum averaged. These numbers are: carbon, 0.25 (TFTR) and 0.19 (CFRMF); and C_2H_2 , 1.16 (TFTR) and 1.20 (CFRMF).

Fig. 1 Comparison of CFRMF and TFTR neutron spectra

Such calculations confirm the applicability of the CFRMF for radiation damage tests of TFTR coil materials. The 14-MeV spike present in the TFTR contributes little to the above parameters, simply because it is so narrow. The majority of the neutrons are in the energy range of a fission spectrum. Besides the 14-MeV spike, the TFTR develops a significant

thermal tail outside the plasma region, which is missing in the CFRMF. These thermal neutrons do not directly cause many displacements or deposit much energy, and this is reflected in the cross-section calculations given above. However, the thermal neutrons do contribute to the total energy deposition indirectly due to $B^{10}(n,\alpha)$ reaction as shown in Table I.

2.3 Irradiation

Test specimens (described in the next section) were placed in the CFRMF experiment area. Air was circulated around the specimens, and the temperature continuously monitored by means of thermocouples inserted within the epoxy. The peak temperature (at reactor centerline) was held to 335 K, which is representative of the maximum temperature in the actual TFTR coils.

The bulk of the specimens were irradiated for 28 hours yielding an average neutron fluence of 7×10^{20} n/m², representative of that expected in the TFTR design. A group was irradiated for 56 hours (1.4×10^{21} n/m², which is representative of the fluence which would be received if the TFTR is upgraded to longer neutral beam pulse lengths. The radiation doses corresponding to a 28-hour exposure time are shown in Table II (the 56-hour values are a factor of 2 greater).

TABLE II
APPROXIMATE RADIATION DOSES FROM A 28-HOUR
IRRADIATION IN CFRMF

	NEUTRONS (Gy.)	PHOTONS (Gy.)	ALPHAS (Gy.)
E-Glass	1×10^5	7×10^5	1×10^4
Epoxy	9×10^5	4×10^5	7×10^3

The CFRMF radiation time was selected such that the TFTR neutron dose would be reached or exceeded in the materials. This conservatism is important for two reasons:

- (1) The geometry of the TFTR is very complex and many penetrations exist. Neutronics calculations are subsequently difficult, and have not been benchmarked. It is doubtful that the doses for TFTR can be predicted within a factor of two.
- (2) It is likely that the neutral beams for TFTR will be upgraded to longer pulse lengths; an increase in radiation levels of up to an order of magnitude is possible.

Comparison of Table I and Table II show that the neutron dose for E-glass is matched, and exceeded for the epoxy resin. Photon doses are exceeded by a factor of three in the CFRMF environment, but alpha irradiation due to the $B^{10}(n,\alpha)$ reaction is much lower due to the

considerably lower thermal tail. It is felt by some that radiation damage to organic-type materials is not dependent on the source; if this is true, the doses are additive. One finds that the total doses (neutron, gamma, and alpha) received by CFRMF irradiated specimens match quite well with TFTR expected doses: approximately 8×10^5 Gy. to the E-glass and 1×10^6 Gy. to the epoxy. However, one must remember that these specimens are composites of fiberglass and epoxy. It is not clear that the effect of radiation to such composites is independent of the source. In addition, it is unlikely that the highly localized energy deposition of the alpha particle will cause damage identical to that caused by neutrons and photons. However, these CFRMF irradiations reasonably match neutron energy spectra over a broad range, neutron fluence, and total energy deposition with those values expected in TFTR. The subject of source dependence regarding radiation effects to these materials will be addressed in future work.

3. MECHANICAL TESTING

Composite bars (100 x 13 x 50 mm) composed of layers of E-glass cloth tape in an epoxy matrix (similar to the materials selected for TFTR insulation) were provided by the Princeton Plasma Physics Laboratory (PPPL). They were prepared by standard impregnation techniques. The basic formulation of the epoxy resin was 100 pbw "Dow" #332 resin, 90 pbw NMA hardener, and 1 pbw BDMA accelerator, with exceptions as noted. G-10 circuit board, a commercially produced fiberglass epoxy composite was also tested.

The bars were tested in a flexure mode in an Instron-Model TT-D testing apparatus per ASTM specification D-790. Three point loading over a 83 mm span was utilized with a cross-head speed of 2.5 mm/min. Moduli of rupture were calculated from the data. Results from the above tests were compared with flexure data taken on identical unirradiated specimens to determine the extent of radiation damage. It is assumed that the flexure strength of the composite reflects directly upon the extent of damage in these materials.

In conjunction with the above tests, the effects of irradiation upon the static shear-bond strength of the glass epoxy composite to copper bond were determined for various epoxy compositions, bond surface preparations, and wrapping configurations. The shear bond specimens were machined from fabricated insulation test bundles prepared by PPPL. The specimens were irradiated in a similar fashion to that described above. The configuration of the samples is shown in Figure 2. Tests were performed using an Instron TT-D testing apparatus with a crosshead speed of 1.3 mm/min. The fiberglass-epoxy composites were formulated in the same manner as their counterparts in the flexure tests.

Fig. 2 Shear Bond Test Specimen

4. RESULTS AND DISCUSSION

The average flexure strengths of the unirradiated and irradiated specimens are shown in Table III. It is observed that for all groups of specimens there was a loss of flexure strength upon irradiation. Furthermore, the loss increased as the fluence was augmented. At a fluence of 7×10^{20} n/m², sample groups A, B and C exhibited losses of 20, 15, and 28% respectively. The loss of flexure strength of the commercial G-10 composite was relatively low, 6%, at this fluence. However, at a higher fluence, 1.4×10^{21} n/m², the G-10 had flexural strength loss of 30% with a corresponding loss of 17% on the "B" specimens.

The initial strengths of the laboratory prepared unirradiated specimens were identical, implying that subsequent data reflects directly upon radiation effects. The use of the plasticizer in the "A" samples appears to have a deleterious effect, as evidenced by the greater loss in strength (20%) when compared to the similarly prepared B group (15%). The air-poured epoxy samples (non-vacuum impregnated) exhibited the greatest loss in strength (28%). It cannot be determined at this time if this greater loss is attributable to method of preparation or to the aluminum trihydrate addition.

The G-10 specimens, obviously superior in their initial unirradiated strength, exhibited a small decrease in flexural strength after the initial fluence. However, a 30% degradation was observed after the larger fluence, indicating a damage threshold for this material. The threshold for the prepared samples (A, B and C) is probably at an even lower fluence than 7×10^{20} n/m².

The average results of the shear bond strength tests are shown in Table IV. The shear bond strengths of the double primed specimens (Group A) exhibit a greater strength in both the irradiated and unirradiated condition than those with

just one primed surface (B) or those with two sandblasted surfaces (C). The average loss of shear strength upon irradiation of the Group A specimens (20%) is approximately equal to those with one primed surface (15%) at an equal fluence (7×10^{20} n/m²). The loss in bond strength appears to vary proportionately with fluence as indicated by a further decrease (25%) of the Group B specimens when exposed to a fluence of 1.4×10^{21} n/m².

TABLE III
FLEXURE STRENGTH

Specimen I.D.	No. of Specimens	Exposure Time (Hours)	Average Modulus of Rupture/Std Deviation (X10 ⁶ Pa)	Average Change
A	1	0	141/-	
	2	28	112/5.7	-20%
B	1	0	141/-	
	2	28	121/2.7	-15%
	2	56	118/5.5	-17%
C	1	0	141/-	
	2	28	101/0	-28%
G-10	3	0	291/9	
	2	28	273/9	-6%
	2	56	203/0	-30%

A denotes standard wrapping, 5 pbw Goodrich #7

"Hycar" plasticizer, 394 K/9 hr. cure.

B denotes standard wrapping, no plasticizer, 372 K/36 hr. cure.

C denotes standard wrapping, no plasticizer, 25 pbw, alumina trihydrate, atmospheric pour of epoxy, 378 K/36 hr. cure.

The G-10 specimens were cut from commercially available circuit board material.

The low shear bond strengths of the surfaces that were only sandblasted (Group C) are indicative of a generally poor bonding between the copper and the composite. It is noted in Table IV that in those materials which had one primed surface and one sandblasted surface (Group B) the shear always took place on the sandblasted surface. Again, this indicates an inferior bond obtained when primer is not applied to the copper surface.

5. CONCLUSIONS AND RECOMMENDATIONS

1. There is a substantial loss (15-30%) in flexure strength of fiberglass-epoxy composites upon irradiation at fluences of 7×10^{20} and 1.4×10^{21} n/m².
2. The addition of a plasticizer ("Hycar" 77) to the epoxy induced a greater loss in flexural strength upon irradiation.
3. The shear bond strength of the copper-insulation interface is degraded upon irradiation. The amount of degradation does not appear to depend on surface preparation of the copper. Although the utilization of a primer in the laminate

preparation enhances the general shear bond strength, primed specimens exhibit a similar loss in shear bond strength upon irradiation to unprimed specimens.

4. An increase of the fluence increases the loss of strength.

It is not claimed that these tests are conclusive of damage that will be seen in TFTR. They were designed as screening tests to determine the necessity of further investigating the effects of radiation with regard to the design of TFTR. The results given indicate that the TFTR radiation doses will be near the threshold for measurable damage in the coil insulation materials. The proposed upgrade of the neutral beam injectors would increase the probability that the doses will be over that threshold; operation of the machine could be restricted. It is recommended that the selection process of the TFTR coil insulation materials include radiation resistance, and the data base be extended by actual experiments. This will aid in the design of future machines, as the shielding required to maintain cryogenic temperatures may allow some use of organic insulation materials in future fusion experiments.

TABLE IV
SHEAR STRENGTH

Spec.No. of I.D. Samples	Exposure Time (Hours)	Average Load Shear Area/Std. Deviation (X10 ⁶ Pa)		Average Change
+A	2	0	29.6/3.8	
	2	28	23.7/0.1	-20%
B-H*/P	3	0	19.8/1.0	
	2	28	16.8/1.9	-15%
	1	56	14.8/0	-25%
++C	4	0	8.5/0.7	
	3	28	8.5/0.2	
	2	56	8.0/0	-6%

*Denotes side on which shear occurred.

H - Denotes sandblasted copper surface.

P - Denotes primed surface (Ciba DZ-80).

+ - All A samples were primed on both shear surfaces.

++ - All C samples were sandblasted but unprimed.

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