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FOR FUSION-REACTOR MAGNETS

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ORGANIC INSULATORS AND THE COPPER STABILIZER
FOR FUSION REACTOR MAGNETS*

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ABSTRACT

The materials which compose the large composite superconducting fusion reactor magnets are subjected to mechanical stress, neutron and gamma-ray radiation with broad energy spectra, high magnetic fields, and thermal cycling from 4 to 300 K. Of the materials now considered for use in the magnets, results show that the organic insulators and the Cu stabilizer are the most sensitive to this environment. In response to the need for stabilizer data, magnetoresistivity changes were studied in eight variously prepared specimens of Cu throughout five cycles of an alternate neutron irradiation (4.0 K) and annealing (14 h @ 307 K) program. The results were combined with those on the radiation behavior of epoxy and polyimide organic insulators to provide a preliminary assessment of their comparative radiation resistance in a typical magnet location of the Experimental Power Reactor (EPR). It was found that insofar as the chosen conditions typify the mix of gamma-ray and neutron dose rates in fusion-reactor magnet locations, the radiation resistance of the stabilizer is at best equal to that of the epoxies and much less than that of the polyimides. The poor performance of the Cu stabilizer suggests that additional shielding for magnet protection or serious magnet-design changes are needed. Several needs for further organic insulator and stabilizer research are described.

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ORGANIC INSULATORS AND THE COPPER STABILIZER FOR FUSION REACTOR MAGNETS

R. R. Coltman, Jr.

1. INTRODUCTION

The plasma of a fusion reactor will be contained by an intense magnetic field produced by large composite superconducting magnet coils. The radiation emitted by the plasma through the first wall to the coils is reduced by geometrical factors and by absorption in the intervening heat-producing blanket. It was found at the outset that this reduction was not sufficient to meet two essential criteria. First, the power required for the refrigeration necessary to remove nuclear heating in the coils at 4 K must be less than some small fraction (typically 10%) of the total power produced by the reactor. Second, the degradation by radiation of the magnet materials must be sufficiently small so that acceptable performance can be expected over the life of the coils. To meet these criteria, additional shielding will be used. This is a costly step, not only because of the shielding expense, but also because of the increase in coil size necessary to accommodate the shield. It becomes complicated, however, to determine final shield and magnet configurations because of cost minimizing "trade-offs" which can be made between materials and designs.

Over the last ten years various authors have written assessments of radiation effects in magnet materials [1,2,3,4]. As reactor concepts and designs change due to advances in plasma physics, reassessments of materials uses are needed to maintain continuity in the progress of fusion technology.

It has been customary in these assessments to divide magnet materials into four groups:

1. Structural materials -- magnet support members, vacuum jacketing, etc. -- usually stainless steel.
2. Superconducting matrix -- NbTi or Nb₃Sn.
3. Normal metal stabilizer -- Cu or Al.
4. Electrical insulators -- organic and inorganic (in some locations insulators must provide mechanical support).

A recent comprehensive assessment of magnet materials prepared by Brown [1] found that for probably all applications structural materials do not present a radiation tolerance problem. The second most radiation-resistant component is the superconductor, for which there is concern in some applications. The least radiation-resistant materials are the stabilizer and organic insulators, with no clear distinction as to which is the weakest. This report summarizes current information on the last two groups and compares them for service in a typical magnet location. In addition, needed new research is identified for each group.

The information given in this report is applicable mainly to radiation conditions present in the main body of the magnet. It is very important to note that the use of neutral beam injection tubes and possibly some vacuum piping provide line-of-sight penetrations into the plasma along which intense radiation streaming can occur. As a result, radiation "hot spots" will be found at some magnet locations. While the presence of a "hot spot" may still allow the overall refrigeration power criterion to be met, the materials radiation tolerance criterion becomes difficult to meet. At these spots of high radiation intensity, which can be twenty times that in

the main body of a magnet [5], fluence values are reached during the life of the magnet which can (1) seriously affect the performance of the superconductor, (2) produce large increases in stabilizer resistivity which would require drastic changes in composite superconductor design, and (3) exceed the radiation tolerance of even the most resistant organic insulators known. For these reasons consideration is needed for the use of protective shielding around penetrations or, if possible, orientation changes which direct penetrations further away from the superconducting coils.

2. ORGANIC INSULATORS

In superconducting magnetic coils constructed for purposes other than fusion technology, organic insulators have achieved wide application in many forms such as rigid sheets, tapes, films, potting, and casting. It is reasonable for designers to anticipate that the familiar materials and established techniques now in use could be applied as well to fusion-magnet designs, or at least that substitute materials with similar properties can be found. Doubts concerning the use of organic insulators for fusion magnets arise from uncertainties about their tolerance for the radiation present at the magnets. While inorganic insulators have a greater tolerance for radiation, their use is thought to be more costly than organic insulators. For example, in some fusion magnets large quantities of sheet stock will be used to provide inter-turn electrical insulation and mechanical support. The sheets must be accurately machined to provide He-coolant-flow channels. Further, in this use the organics have sufficient flexibility so that installation between curved surfaces is not difficult. In contrast, the

use of inorganics would probably require the development of new fabrication techniques and special handling for installation. In addition, the use of inorganics for film applications could be difficult, especially for multi-layered metal-coated films used as "superinsulation" (radiant-heat reflectors).

Although many studies on the effects of irradiation on organic insulators exist, there are few on the most recently developed materials or on the simultaneous effects of radiation and low temperatures. In the discussion which follows, a summary is given of the main results of recent studies for two groups of organic insulators; epoxies which are in present use and more recently available polyimides which show greater radiation tolerance.

2.1 Epoxies

Epoxies are used in a variety of forms in the construction of superconducting magnets, and presently their use is being considered for one of the first test reactors, the Fusion Engineering Device (FED). In response to the need for radiation-tolerance information on these materials, a program was carried out at the ORNL Low Temperature Irradiation Facility (LTIF) [6].

Tests were made after irradiation at 4.9 K and warmup to room temperature. This is a meaningful procedure, since it is expected that over their lifetime fusion-reactor magnets occasionally will be warmed to 300 K. Knowledge of the strength of insulators under cyclic conditions is just as essential as that under static cold conditions. Since the cost of testing at liquid-He temperature after irradiation without warmup is many times greater than with warmup, tests of the first type were excluded in an effort to maximize the information we could obtain with available funds.

The following list gives the material designation as used in this report and a brief description of each.

1. Stycast 2850 FT (Blue) -- Epoxy, with 7% 24 LV hardener; Emerson and Cuming, Inc.; an inorganically filled room-temperature-curing epoxy.
2. EPON 828 -- Epoxy, with 20-pph-Z curing agent, 0.5% Z6020 Silane couplant; Shell Chemical Company; filled with 40 wt % 400-mesh SiO_2 (80°C cure, followed by 150°C post-cure).
3. G-10 CR -- National Electrical Manufacturers Association (NEMA), a heat-activated amine-catalyzed bisphenol solid type epoxy resin laminate reinforced with continuous filament E Glass fabric, silane finished; designated for cryogenic use; Spaulding Fibre Company.
4. G-10 CR (BF) -- Same as No. 3, except made with boron-free E Glass.
5. G-11 CR -- Same as No. 3, except that an aromatic amine-hardened bisphenol liquid-type epoxy resin is used in its fabrication.

Several property changes were studied for two gamma-ray doses, 0.24 and 1×10^8 Gy (10^{10} rads). Overall, the electrical properties (resistivity and voltage breakdown strength) showed detectable changes at the higher dose, but the values remained well into the usable range for all materials. In contrast, the mechanical properties showed drastic changes. Figures 1 and 2 show, respectively, the results for flexure and compressive fracture strength tests. The castable types, Stycast and EPON, which initially are much weaker than the glass fabric filled (gff) materials, retain usable strength after the lower dose, but not after the higher dose. On the other hand, the gff types (G-10 CR, G-10 CRBF and G-11 CR) which may be used extensively in the FED, probably do not have usable strength even after the lower dose, and they continue to lose strength up to the high dose. Other results reported in [6] but not given here include bond strength, linear flexure modulus, dimensional changes, radioactivity, weight loss and gas evolution.

2.2 Polyimides

While the gff epoxies may serve the magnet needs for the FED, it is clear that materials with better radiation tolerance are needed for advanced reactors having higher radiation levels.

The superior radiation resistance of pure polyimide, Vespel, at room temperature has been known for some years; however, its strength is insufficient for magnet application. Only recently have gff polyimide materials become available that have a strength in the unirradiated condition comparable to gff epoxies and sufficient to meet design needs. For these reasons, a study of the electrical and mechanical properties of pure and gff polyimides was made on specimens irradiated at 4.9 K to various gamma-ray doses up to 10^8 Gy (10^{10} rads). The irradiation and testing conditions were identical to those used for the epoxies. While the complete results of this research have been reported [7], only the main features are given here, as with the epoxies above.

Gff materials were especially prepared by cooperating manufacturers, while the unfilled polyimide, Vespel, is available commercially. The following list gives the material designation as used in this report and a brief description of each.

1. Vespel -- (SP-1) unfilled polyimide; E. I. DuPont de Nemours and Company.
2. Spaulrad (formerly called Spauldite) -- SPAULDITE[®] SPAULRADTM;
Spaulding Fibre Company; a high-pressure laminate composed of aromatic polyimide resin reinforced with continuous filament E glass-woven fabric 70-71% by weight.
3. Norplex (formerly called Kerimid) -- Norplex NP 530; Norplex Division, UOP, Inc.; a balanced resin of bismaleimide and aromatic diamines reinforced with E glass-woven fabric 40-60% by weight.

4. Kapton H -- Film; E. I. DuPont de Nemours & Company; polyimide film frequently used in magnets.
5. Aluminized Kapton -- Type NRC-2, King-Seeley Thermos Company, used for multilayer superinsulation.

In the case of the polyimide film, Kapton, no significant changes could be detected in either resistivity or voltage breakdown strength for a dose of 10^8 Gy (10^{10} rads). In similar fashion aluminized Kapton, which can be used for multilayer superinsulation (radiant-heat reflectors) showed no tendency for peeling or brittleness during repeated flexing after the same dose. The mechanical-testing results for flexure and compressive fracture strength are shown for 10^8 Gy (10^{10} rads) and two intermediate doses in Fig. 3. Overall, the gff materials, Spaulrad and Norplex, show on the average only $\sim 35\%$ reduction in strength at the highest dose. It is important to note that the composition of the gff polyimides in terms of glass type and content is very similar to that of gff epoxy G-10 CR and further that their initial strengths are quite similar. Thus at 10^8 Gy (10^{10} rads) the gff polyimides retain a useful strength, while comparably prepared epoxies are weakened beyond practical use at one-fourth that dose.

3. FURTHER NEEDS FOR ORGANIC-INSULATOR RESEARCH

3.1 Additional Epoxy Data

Although gff polyimide and epoxy materials can be prepared with similar initial strengths, the polyimides are more costly than the epoxies. For this reason, it may be prudent to use the less radiation-resistant epoxies at lower-dose-rate locations in magnets. To make effective use of the

epoxies, however, more data are needed over the dose range in which the change in strength is most responsive. From earlier work, we know that at 2×10^6 Gy (2×10^8 rads) the mechanical properties of the gff epoxies are unaffected [8]. When this result is added to the survey results given above, we find the range in which new data are needed is 2 to 20×10^6 Gy.

3.2 Fast-Neutron Effects in Organic Insulators

While some fast neutrons were present in the radiation used to obtain the foregoing epoxy and polyimide results, their possible contribution to damage production was small compared to that produced by the gamma rays. At magnet locations in both the FED [9] and in the more advanced Experimental Power Reactor (EPR) [5], calculations show that energy deposition by fast neutrons will be comparable to that by gamma rays -- a ratio a few hundred times that in the ORNL-LTIF.

While energy deposition has long been used as the gamma-ray dose unit to be correlated with property changes, there is little evidence that the same correlation holds for fast-neutron irradiation, for which the damage mechanisms are different. For these reasons, it is essential that correlations between fast-neutron fluence and property changes be studied in applicable organics. When such results are combined with gamma-ray data, it will be possible to make more accurate predictions of the behavior of organics in the fusion-magnet environment. An important tool for such studies is the new Intense Pulsed Neutron Source (IPNS) now operating at ANL [10]. It will provide a broad spectrum of fast neutrons with little accompanying gamma-ray intensity. In addition, extensive low-temperature capabilities are available.

3.3 Tests After Irradiation Without Warmup

As indicated earlier, the testing of specimens irradiated near 4 K without warmup is costly. Usually the test devices are massive compared to the specimens, and they impose heavy nuclear heat loads on the irradiation cryostat. In addition, the experimental volume in most cryostats is limited, and the volume occupied by testing devices displaces valuable sample space. Nevertheless, tests without warmup after irradiation on candidate materials selected from present studies are essential in future work. Takamura and Kato recently studied the pure polyimide, Vespel, and various preparations of one epoxy, EPON 828, after reactor irradiation at 5 K to 11 MGy (1.1×10^9 rads) [11]. They made postirradiation tests at 4.2 and 77 K without prior warmup. In the case of Vespel, they observed virtually no change in compressive strength at 77 K, in agreement with the results presented in this report, which were obtained with prior warmup to 300 K. A further comparison with our earlier epoxy study [6] is difficult to make because of the dissimilarity in material preparation. In general, however, there is qualitative agreement between the two studies for filled EPON 828. While the Takamura work provides valuable insight into this question, the need for similar studies in the gff epoxies and polyimides remains.

3.4 Cyclic Irradiation and Annealing

In earlier work [6], evidence of gas bubbles was seen in some of the irradiated samples. It was speculated that the nucleation and growth of bubbles may occur during postirradiation warmup when gas atoms (mostly H) freed by the irradiation become mobile. It was thought that a possible buildup of gas pressure in bubbles could produce internal microcracks which would reduce mechanical strength. The periodic warmups of the magnet expected during its life will provide the opportunity for freed gas atoms to diffuse at concentrations lower than those that would be present

after a lifetime dose without warmup. If diffusion of gas atoms out through surfaces (see 3.5 below) competes with bubble nucleation and growth, then the fraction of atoms participating in the latter process may be less at lower concentrations. Strength tests on specimens irradiated to the same dose with and without cyclic annealing should be compared to look for possible gains in radiation tolerance due to the anneals.

3.5 Possible Effects of Surface-to-Volume Ratio

In the epoxy study [6], it was found that weight loss due to irradiation was greater in specimens with a higher surface-to-volume ratio. This result supports the speculation made in 3.4 above; however, further testing is needed to quantify the effects and to correlate them with strength changes. If definite correlations are found consideration could be given to fabrication methods which would control the surface-to-volume ratio in cases where other required specifications could still be met.

3.6 Compression Fracture Strength Normal to the Laminations in gff Material

In the case of the gff polyimide, Norplex $\perp$ (see Fig. 3), which was tested in compression with the load perpendicular to gff layers, no loss in strength was observed for 10^8 Gy (10^{10} rads). Within the scatter of the data, a constant-strength line might represent the behavior nearly as well as the indicated concave-up curve that connects average values. Since present reactor designs show some material stressed perpendicular to the laminations, further study to doses greater than 10^8 Gy (10^{10} rads) to determine the radiation tolerance for this orientation could give useful results. Such testing of gff epoxies in this orientation might also give fruitful results.

4. THE COPPER STABILIZER

The stabilizer (normal metal) of a composite superconductor safely carries the current during a localized momentary normalization of the superconducting matrix. The amount of normal metal needed for safe operation increases with increasing resistivity of the metal. As a result, the design of large composite superconducting magnets for fusion reactors will depend sensitively upon increases in the resistivity of the stabilizer produced by irradiation during its lifetime. To minimize these increases and hence the cost of magnets and their radiation shielding, consideration is given to periodic warming of the magnets to remove annealable portions of the radiation-produced resistivity. For large power reactors such warming cycles are costly, and the frequency of these operations becomes an economic "trade-off" parameter with various capital-cost parameters such as shield thickness and amount of normal metal. It is important to point out that a fusion magnet will be rated for safe operation according to a stabilizer resistivity value which cannot be exceeded. If cyclic annealing is chosen as an economy measure, as it now appears, it becomes essential to magnet design to be able to predict accurately the resistivity of the stabilizer under service conditions throughout its life.

Presently, Cu stands as the choice candidate for the stabilizer, although some consideration is given to Al. While there have been many radiation experiments on Cu, none have been made under the combination of conditions present in fusion-reactor magnets. These include magnetic fields up to 10T, the use of commercial-grade Cu containing various

amounts of cold work, irradiation near 4 K by a broad spectrum of fast neutrons, and the cyclic annealing just mentioned. Although there is presently no irradiation facility which can precisely simulate the range of conditions projected for a fusion-reactor magnet, some such as the new IPNS facility [10], and the ORNL - LTIF can provide conditions which make it possible to observe trends of behavior needed by magnet designers.

In response to these needs, resistivity changes were studied in eight specimens of Cu throughout five cycles of an alternate irradiation (4.0 K) and annealing (14 h @ 307 K) program carried out in the LTIF. At each step, measurements were made at 0 and six transverse magnetic field strength values up to 3.8 T. Six specimens were prepared from a commercial OFHC-type Cu now in use for large magnets. The states of preparation were high-temperature internal oxidation and low-temperature recrystallization treatments from each of which one fully annealed and two states of cold-worked specimens were made. This assembly produced zero field resistance ratio values which encompass those now found in large magnets. In addition, one fully annealed and one cold-worked specimen of ASR research-grade Cu were studied for comparison.

The operational mode chosen for the LTIF gave a mix of neutron-flux components consisting of a fast spectrum (slightly harder than fission) which produced 55% of the damage and thermal neutrons which produced 45% of the damage by means of low-energy recoils resulting from an (n,γ) reaction. For comparison, it is calculated that the neutron spectrum present at a fusion-reactor magnet typically will be softer than a fission-reactor spectrum [12]. Since the LTIF (n,γ) damage component is equivalent to that produced by collision with neutrons having a soft spectrum, the LTIF neutron conditions may

bear a reasonable equivalence to a magnet spectrum. The irradiation dose given in the first cycle was based upon an average consensus among designers of a 25% allowable increase in the initial field-on resistivity. All samples were irradiated until the allowed increase was reached for one representative sample, while increases in the other samples were greater or smaller depending upon their initial condition. The irradiation increments for succeeding cycles were terminated when the resistivity of the chosen sample again reached the allowed value.

The experiment yielded a large multidimensional body of data which is now being analyzed. The results will be reported in the near future. The following are some results and trends which have emerged so far. They should be considered from the designers' view of the three most desirable field-on properties of a stabilizer; a minimum initial resistivity, a minimum incremental damage resistivity increase, and the minimum damage resistivity retained after an annealing cycle.

1. In the commercial Cu the incremental damage resistivity increases were greater ($\sim 9\%$ at 0 T and 10 - 18% at 3.8 T) in the cold-worked samples compared to the annealed samples. The increment measured at 3.8 T for any one sample was about 18% less than at 0 T.
2. During the first annealing cycle the cold worked specimens showed a smaller percent retention of the damage than the annealed specimens; i.e. 6 and 16% respectively, at 0 T. At 3.8 T the values decreased slightly by 1 to 2%. During subsequent cycles all samples showed progressively less damage retention, with the annealed samples approaching but not exceeding that of the cold-worked samples.

3. Using an extrapolation of the field-on data to 10 T it was found that during a cyclic program having a fixed field-on resistivity value after each irradiation increment the approach to a prescribed accumulated fluence required fewer annealing cycles for the lightly cold-worked samples than either the heavily cold-worked or fully annealed samples.

The results given above show from the designers' viewpoint that a given material can exhibit both beneficial and adverse effects from neutron irradiation which must be carefully sorted out in a data analysis involving several samples with different initial conditions.

5. FURTHER NEEDS FOR STABILIZER RESEARCH

5.1 Measurements at High Magnetic Fields

In the ORNL experiment described above, the highest attainable field was 3.8 T, whereas fields in fusion-magnet service conditions will reach 12 T in some designs. In earlier ORNL data [13], in this work, and in recent measurements of 14-MeV-neutron-irradiated Cu by Van Konynenburg et al. [14] deviations from Kohler's rule were found. In analyzing the ORNL data, we found that over the same range in H , Kohler plot deviations occur when the resistivity is changed due to different defect states; i.e., deviations occur between annealed and cold worked states and between annealed and unannealed damage states. It was found, however, that extrapolations on Kohler plots of a single defect state where only H is varied provide limited accuracy sufficient to study trends of behavior. This method is used in an analysis given below. Nevertheless, care must be taken in the use of Kohler-plot extrapolations to obtain field-on resistivity values for copper in states for which there are no other corroborating experimental data.

For magnet-design information, measurements up to 10 or 12 T on cyclic-irradiated and annealed specimens are needed for a variety of initial conditions. Such a body of data can be used to select optimum starting material and to provide sufficient accuracy so that tradeoffs between shield thickness, the quantity of stabilizer, and the number of annealing cycles can be made with confidence.

5.2 The Role of Resistivity Recovery During Annealing

The fraction, r , of the irradiation resistivity which recovers during annealing cycles plays an important role in determining the number of cycles, n , which are needed to reach the lifetime fluence, Φ , at a reactor magnet. As indicated above, n is an important economic "trade-off" parameter. The value of r is affected by several conditions including magnetic-field strength, impurities, dislocations, number of previous cycles, temperature and length of anneals, and the energy spectrum of the incoming neutrons. In the ORNL experiment, studies were made of variations in all but the last two items. A need remains to study r with variations in annealing time and temperature as the other items are varied parametrically. For large power reactors, designers suggest an uppermost annealing temperature of 373 K and times up to three months. The sixth item, the neutron-energy spectrum at the magnet, is not a controllable parameter as are the other five items, but, instead, is a condition which results from the reactor design. Since it is unlikely that such spectra can be produced exactly we must first carefully analyze the proposed neutron spectra at the magnet, and then find those radiation sources which most nearly simulate the type of damage they would produce. Then, studies of r can be made in which the other parameters are varied.

Since we do not yet have in hand from the ORNL data an analysis which shows experimentally a range of dependence of n upon r , it is worthwhile to examine this dependence using a simplifying approximation which is easy to derive.

When r is constant for all cycles;

$$\Phi = \frac{(1 - r^n)}{1 - r} \Delta\Phi_1 \quad (1)$$

$$\rho_n = \rho_I (f - 1)(1 - r^n) = \rho_I (f - 1)(1 - r) \frac{\Phi}{\Delta\Phi_1} \quad (2)$$

where ρ_I is the initial field-on resistivity, ρ_n is the field-on resistivity values after each annealing cycle, and f is the factor (typically 1.25) by which ρ_I is allowed to increase during the first irradiation cycle ($\Delta\Phi_1$) to reach the established resistivity safety limit. It may be noted in Eqn. (2) that ρ_n has a simple linear dependence on Φ since all other quantities are constant.

To show the influence of r upon n , we first take the results from this experiment for cold-worked commercial copper irradiated in the mixed neutron spectrum described above. Up to $n = 5$ cycles the average value observed for r was 0.95. If, for comparison, we choose a value of $r = 0.80$ as is found for fission-neutron damage in annealed copper, we find from Eqn. (1) for the same values of Φ and $\Delta\Phi_1$ that $n = 10$; a costly increase.

5.3 The Role of Damage Efficiency

In addition to the information needed on damage resistivity recovery, the designer also needs to be able to predict the initial neutron fluence, $\Delta\Phi_1$, required to increase the initial resistivity of the

stabilizer to the established safety limit. In general terms, to study "trade-offs" in design with confidence, the designer needs to know the dependence of field-on resistivity increase upon neutron fluence, Φ .

Neutronics calculations for fission- and fusion-reactor configurations as well as accelerator-based neutron sources are commonly made using the modified Kinchen-Pease relation [15], to find theoretical values of defect production, expressed as displacements per atom,

$$D(\text{dpa}) = \frac{0.8 \langle \sigma T \rangle}{2 E_d} \Phi \quad (\text{n/m}^2) \quad (3)$$

where Φ is the neutron fluence in the units indicated, E_d is the effective displacement threshold energy, and $\langle \sigma T \rangle$ is the damage-energy cross-section calculated with a damage-computer code such as RECOIL [16]. Unfortunately, the relationship between resistivity increase and $D(\text{dpa})$ is not fixed, but varies in the fashion now described.

For some neutron spectra experimental values of defect production, ΔC , have been found by combining zero-field measurements of damage-resistivity increases, $\Delta \rho$, and the specific Frenkel-pair resistivity, ρ_F , to give

$$\Delta C = \frac{\Delta \rho}{\rho_F} (0 \text{ T}) \quad (4)$$

The ratio of experimental to theoretical defect production values for the same neutron spectrum and fluence is called the damage efficiency.

$$\eta \equiv \frac{\Delta C}{D(\text{dpa})} \quad (5)$$

Values of η have been found for several metals including Cu and for irradiating particles having widely different energy spectra from barely-above threshold electrons to 14-MeV neutrons [17, 18, 19, 20]. Using energetic

ions, Averbach et al. [17] made a thorough investigation of η over a wide energy range. They summarized the results for Cu and found that at very low primary knock-on (pko) energies (a few E_d), $\eta = 1$. With increasing pko energy η decreased to near 0.35 for energies in the range produced by moderated reactor fast neutrons. At higher particle energies up to 14-MeV neutrons, η remained constant at 0.35. Speculations on the origin of the dependence of η upon particle energy are given in the references just cited.

The damage resistivity increase can now be expressed analytically by combining Eqns. (4) and (5) to give

$$\Delta\rho = \rho_F \eta D(\text{dpa}) \quad (0 \text{ T}) \quad (6)$$

Unfortunately, the neutron spectra at the magnet are not so energetic as to have a value of η which lies in the range where $\eta = \text{constant} = 0.35$. Santoro et al.'s neutronics calculations show, instead, that magnet spectra for the EPR are quite soft (large neutron populations with low energies) [12]. To calculate $\Delta\rho$, then, it is necessary to determine values of η for neutron spectra at the magnet. At the moment, we know only that η values for magnet spectra lie between 0.35 and 1, and, as a result, that predictions of damage resistivity bear a corresponding uncertainty. Averbach et al., however, have developed a criterion for characterizing particle energy spectra which can be correlated with values of η [17]. It is hoped that this criterion, or some other, will provide a reliable method for predicting η values for magnet spectra which in turn can be extracted from neutronics calculations. Then values of zero-field resistivity increases, $\Delta\rho$, can be related to calculated fluence values, $D(\text{dpa})$. It remains, then, to convert zero-field resistivity values to field-on values.

At this time there does not appear to be an exact analytic method to convert zero-field resistivity values to field-on values, however, an empirical approach can be used. In Section 5.1 it was recommended that

a new body of resistivity data is needed for field strengths up to 12 T. This body of data would certainly include zero-field values. If the body of data were further expanded to include data obtained using different radiation sources with known values of η , then by interpolation or limited extrapolation the needed conversions from zero-field to field-on resistivity values pertinent for magnet spectra could be made.

6. A COMPARISON OF RADIATION TOLERANCE BETWEEN ORGANIC INSULATORS AND THE COPPER STABILIZER

While the separate responses of these materials to radiation dose are needed information, there is a further need by designers to compare the materials performances as a function of time in the mix of radiation present at the magnet. To give an example of how this need can be met, use was made of the neutronics calculations by Santoro et al. [5]. They determined nuclear heating rates (gamma and neutron) in units of W/cm^3 and neutron dose rates in units of dpa/y at five typical locations in the toroidal field coils of the EPR. For this example, position #3 (without penetrations), which has about 2/3 the highest values calculated, was chosen as typical. Santoro et al.'s gamma-ray-heating values correspond to a dose rate of 2×10^6 Gy/y (2×10^8 rads/y). (An additional 20% nuclear heating by neutrons at this position was added although its effect on property changes is uncertain.) G-10CR epoxy and Spaul-rad polyimide were chosen as typical insulators. For the copper stabilizer at the same position, they calculated a neutron dose rate of 4×10^{-4} dpa/y using the RECOIL code.

The comparative behavior of the materials is shown in Figure 4 in which the scales of operating time, gamma-ray dose and neutron dose were adjusted to fit the radiation conditions at position #3 [5]. Data plotted in Figure 4 for the

organic insulators were taken directly from the results in Figs. 1, 2, and 3. To make a comparison with copper, results chosen as typical were taken from the ORNL experiment for a lightly cold-worked commercial material of the type now in use for magnet construction. First, the experimental data for each point in the five-cycle irradiation and annealing program were extrapolated in the manner given in Section 5.1 to give an equivalent body of data for 10 T. Then, a value of $f = 1.25$ [see Eqn. (2)] was assigned as a typical factor by which the initial 10 T resistivity was allowed to increase to reach the safety limit.

Fol-

lowing this, the experimental values for the fraction recovered after each cycle were used to construct the response of the resistivity at 10 T throughout the five cycles. To complete the picture, increments of neutron dose as dpa were found for each cycle by applying the corresponding zero-field resistivity measurements and a value $\rho_F = 2 \times 10^{-6} \Omega\text{m/dpa}$ to Eqn. (6). For this assessment, a value of damage efficiency, $\eta = 0.5$, was estimated for use in Eqn. (6) as that which might be characteristic of Santoro et al.'s neutron spectrum at position #3. As mentioned above, it is recognized that for the relationship between zero-field and field-on resistivity values the neutron spectrum present in this experiment (see Section 4) may not be the same as those for the position #3 spectrum, although this is not expected to be a large source of error, nor are those related to the extrapolations of field strength and the value of f mentioned above. Clearly, the major source of error is in the choice of η which cannot be

greater than unity or less than 0.35.

To expand the range of comparison between the organic insulators and the stabilizer, eqns. (1) and (2) and the experimental value of $r = 0.95$ measured for the fifth cycle were used to estimate stabilizer behavior up to an infinite number of cycles. These results are shown by the dashed-line construction in the lower graph of Figure 4.

7. CONCLUSIONS

In Sections 3 and 5, descriptions were given of several needs for further research which is expected to provide the means to make accurate assessments of materials uses and to study the economic trade-offs in various designs with confidence. Without this new information, assessments such as that given here are largely limited to uncovering trends of behavior. It is with this view that the following conclusions drawn from the results in Figure 4 are made.

1. The value of five cycles chosen for the ORNL stabilizer experiment was based on an average consensus by designers as a feasible number over the possible 20-year lifetime of a power reactor. For the typical conditions that were applied to the EPR design it is seen in Fig. 4 that five cycles would be required in only the first two years of operation.

If a damage-efficiency value of $\eta > 0.5$ (this indicates a softer magnet neutron spectrum than that for $\eta = 0.5$) had been chosen, the operating time for five cycles would be reduced still further. For the very unlikely possibility that, instead, the lower limit applies ($\eta = 0.35$) the five-cycle operating time would be extended to only about 2.9 years.

If the constraint on the number of cycles were relaxed to allow ten, it is estimated that this limit would be reached in about 3.7 years. (The

time may be slightly longer if the fractional recovery, r , continues to increase slowly as indicated by the ORNL data obtained for five cycles — see Section 4).

If the initial damage-resistivity increase $\Delta\rho_1 = \rho_I(f - 1)$ were allowed to be four times larger than that chosen (this corresponds to an increase in f from 1.25 to 2.0), then to a first approximation $\Delta\Phi_1$ would also increase by a factor of four, and the operating time to utilize five cycles [Eqn. (1)] would increase to about eight years. Uncertainties in this extrapolation are the possible effect of irradiation annealing at higher fluence (possibly a beneficial effect) and the effect of higher fluence on the fraction of damage resistivity recovered, r (possibly an adverse effect). Nevertheless, since the factor by which the added amount of stabilizer needed to accommodate the damage resistivity is about equal to f (this assumes that a linear stabilizer resistance along a coil must be maintained in a particular design) an increase from 1.25 to 2.0 would require design changes in the magnet.

The assessment of the stabilizer given in this report combines recent experimental data, some design parameters based on consensus, interpolations and extrapolations. As a result, it cannot serve as a basis for final design studies. Nevertheless, it indicates trends which suggest that for EPR-type power reactors reconsideration of shield and magnet designs may be necessary. Such reconsiderations can best be made from a stronger data base of stabilizer behavior than we now have.

2. Although data on the response of mechanical strength of epoxies to dose are not available over the pertinent dose range, it can be estimated from Fig. 4 that for the conditions applied in this assessment the

radiation tolerance of the stabilizer is probably equal to or less than that of the epoxies. In more general terms, insofar as the results of Santoro et al.'s neutronic calculations [5] typify the mix of gamma-ray and neutron dose rates to be found at fusion-reactor magnet locations, the radiation resistance of the stabilizer is at best equal to that of the epoxies, and both are far less than that of the polyimides. The polyimides appear to maintain serviceable strength for more than thirty years in the EPR design. Overall, the Fig.-4 results suggest that additional shielding is necessary and that, if possible, consideration should be given to types which provide additional moderation[†] or absorption of neutrons rather than those which reduce gamma-ray intensity. If additional shielding is added to protect the stabilizer, it most certainly will also provide added protection for the organic insulation as well. A reduced dose rate for the organic insulators could then place the less costly epoxies in a stronger position for use. This enhances the need for detailed information on the epoxies' radiation behavior.

3. The assessment presented in this report is based on a body of organic insulator and stabilizer data which is too deficient to be used for detailed design studies. Further, the assessment relies on neutronics calculations for one power reactor configuration when, instead, it would be desirable to consider at least a few other design options. Finally, the assessment uses values for important parameters obtained from an average consensus of designers views (largely unpublished) which shift with time

[†]While neutron moderation (reducing particle energy) may increase the damage efficiency, η , it also reduces the damage-energy cross-section, $\langle\sigma T\rangle$, and hence the value of $D(\text{dpa})$ [see Eqn. (3)]. A study of the trade-offs between changes in η and $\langle\sigma T\rangle$ would be needed.

as fusion reactor technology moves forward. While these limitations restrict the accuracy of this assessment, it is believed that they do not obscure a major result: the radiation tolerance of the stabilizer is sufficiently low that significant changes in shield and/or magnet designs may be necessary.

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LIST OF FIGURE CAPTIONS

- Fig. 1. Flexure strength of epoxies as a function of irradiation.
- Fig. 2. Compressive strength of epoxies as a function of irradiation.
- Fig. 3. Results of fracture strength tests on pure and glass-fabric-filled (gff) polyimides after irradiation at 4.9 K followed by warmup to 307 K. Each data point shows the average value of three tests, and error bars indicate avg. dev. Points without error bars indicate data scatter was too small to show.
- Fig. 4. A comparison of the flexure fracture strength of G-10CR epoxy and Spaulrad polyimide with the resistivity (4 K) of lightly cold-worked commercial copper at 10 T. The radiation conditions chosen as typical were Santoro et al.'s magnet position #3 for the EPR [5]. The dashed line for the G-10CR epoxy serves only to connect related data points and indicates the dose range over which further studies are needed. The solid lines indicate known behavior based on experimental results that lie outside the range of the graph.

IRRADIATION AT 4.9K - TEST AT 78K AFTER WARMUP TO 307K.

Fig. 2

Fig. 3

ORNL-DWG 81-19690

Fig. 4