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RELATIVE RADIATION SENSITIVITY OF INSULATORS,
STABILIZERS, AND SUPERCONDUCTORS

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January 15, 1982

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Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under Contract W-7405-Eng-48.

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**3.1 RELATIVE RADIATION SENSITIVITY OF INSULATORS, STABILIZERS, AND SUPERCONDUCTORS - R. A. Van Konynenburg and M. W. Guinan
(Lawrence Livermore National Laboratory)**

3.1.1 SPM Task

IV.G.2 Radiation Damage in Superconducting Composites

3.1.2 Objective

The objective of this work was to compare the radiation sensitivity of the various parts of superconducting magnet systems.

3.1.3 Summary

Using the radiation spectra calculated by Engholm for the Engineering Test Facility (ETF) toroidal field magnet inboard leg¹ and available data on radiation effects, commonly used magnet components were ranked in order of radiation sensitivity. It was found that epoxy-based insulators and copper and aluminum stabilizers were the most sensitive parts of the magnets, more sensitive than the superconductors. Use of polyimide-based insulators would make the insulators less vulnerable than the stabilizers and superconductors.

An experiment is planned to study the effects of various degrees of cold work on the radiation-induced magnetoresistance of copper, since this will be an important factor for fusion magnet stabilizers.

3.1.4 Progress and Status

3.1.4.1 Introduction

When radiation effects on superconducting magnet systems were first considered, attention was directed primarily toward the superconductors themselves. As superconductor radiation effects data became available, researchers began to suspect that other parts of the magnets, namely the stabilizers and the insulators, might be more radiation-sensitive. In the ETF study, a model magnet and shield design coupled with neutronics calculations and new experimental data made it possible to test

these suspicions. An ad hoc meeting was convened at D.O.E. Headquarters on December 2-3, 1980, to examine the problems associated with electrical insulators for fusion magnets, at which the authors were requested to compare the radiation sensitivity of insulators, stabilizers, and superconductors. The main features of the resulting analysis will be reported here. A more complete discussion can be found in the proceedings of that meeting.²

3.1.4.2 Operating Conditions

The operating temperature for present designs of superconducting magnets is 4-6 K, but studies are also underway to test the feasibility of operating at 1.8 K, using superfluid helium-II.

Engholm¹ has calculated the neutron and gamma spectra for the in-board shield of the ETF, and they are shown in Tables I and II. These spectra are similar to those calculated for other D-T machines with shielded magnets.

3.1.4.3 Materials and their Functions

Superconducting magnets are made up of four main components: the superconductor, the stabilizer, insulators, and the magnet case and structure. The two candidate superconductor materials are Nb-Ti and Nb₃Sn. Copper appears to be the favored material for stabilizers, but aluminum is also a candidate. Up to the present, the insulators have been made of organic materials. The case and structure are generally made of steel.

The superconductors themselves are intended to carry large currents with low resistance. Accordingly, their important property is the critical current density, which is the maximum current per unit area they can carry and still remain superconducting. In the presence of equal gamma and neutron fluxes, only the neutrons produce significant changes in critical current density.

The stabilizer is used to carry current in the event that a portion of the superconductor "goes normal", thereby preventing a catastrophic release of energy and restoring the magnet to superconducting operation.

Table I - Neutron Spectrum¹ at Inboard Leg of ETF Toroidal Field Coil,
Assuming 2.4 MW/m² Wall loading and 82-cm Thick SS-BH₂O Shield.

<u>Lower Energy</u>	<u>Flux</u>
(MeV)	(n/cm ² -sec)
13.5	5.76E+7
12.2	4.32E+7
11.05	1.18E+7
10.0	1.41E+7
9.05	1.40E+7
8.19	1.32E+7
7.41	1.19E+7
6.70	1.14E+7
6.07	1.08E+7
5.49	9.6E+6
4.49	1.94E+7
3.68	2.27E+7
3.01	2.92E+7
2.47	4.05E+7
1.35	2.11E+8
0.74	6.8E+8
0.41	5.1E+8
0.166	9.84E+8
0.032	9.17E+8
3.35E-3	7.35E+8
3.54E-4	1.48E+8
3.73E-5	1.53E+8
3.9E-6	1.39E+8
4.1E-7	5.1E+7
Total	4.84E+9

Table II - Gamma Ray Spectrum¹ at Inboard Leg of ETF Toroidal Field
Coil, Assuming 2.4 MW/m² Wall Loading and 82-cm-Thick SS-BH₂O
Shield.

<u>Lower Energy</u>	<u>Flux</u>
(MeV)	(/cm ² -sec)
8.0	5.46E+7
7.5	1.0E+8
7.0	5.07E+7
6.5	4.17E+7
6.0	4.44E+7
5.5	4.89E+7
5.0	5.31E+7
4.5	5.66E+7
4.0	6.82E+7
3.5	7.97E+7
3.0	9.82E+7
2.5	1.21E+8
2.0	1.53E+8
1.5	2.04E+8
1.0	3.27E+8
0.4	1.43E+9
0.2	1.08E+9
0.1	4.49E+8
Total	4.46E+9

The resistivity at the operating magnetic field and temperature is thus the important parameter, and neutrons again are the only significant agents.

The insulators are intended to carry the Lorentz forces on the conductors, provide space for liquid helium coolant, and prevent shorting or breakdown between turns of the magnet or to the magnet case. Several properties are therefore important, including strength, resistivity, and others. For organic insulators, both neutrons and gamma rays produce damage. For silica-based inorganics both are also important. For other inorganics, neutrons are probably the only significant damaging radiation.

The magnet case and structure provide mechanical support. Since the other components are more radiation-sensitive, the case and structure will not be discussed further here.

3.1.4.4 Dose Conversion Factors for Insulators

In order to estimate the effects of combined neutron and gamma fields on insulators, it is necessary to convert them to a common dose basis. At the present state of knowledge, the best approach appears to be to convert to the absorbed energy measured in grays (or rads). The neutron doses were determined by dividing the ETF neutron spectrum into six groups. The energy deposited into each chemical element in the insulators was then calculated for each group using cross section and local energy deposition data from the ENDL library.³ These were then summed according to the fraction of each element present, using the chemical compositions shown in Table III. The resulting conversion factors are shown in Table IV.

The gamma ray dose conversion factor was estimated by using a mean gamma ray energy of 0.8 MeV for the whole spectrum, and a mass absorption coefficient of $0.029 \text{ cm}^2/\text{g}$ for all the insulators. The resulting gamma dose conversion factor was $3.7 \times 10^{-10} \text{ rad gamma/cm}^2$.

3.1.4.5 End-of-life Criteria

In order to compare the various components according to radiation

Table III - Chemical Compositions Used for Six Insulators (Wt. %)

<u>Element</u>	<u>Insulator</u>				
	G-10	G-10 (BF)	Polyimide - Fiberglass (BF)	MACOR	Al ₂ O ₃
H	2.02	2.02	1.56		
B	1.74			2.51	
C	21.8	21.8	28.2		
N	1.0	1.0	3.13		
O	39.41	37.86	35.05	45.08	47.1
F	.070	.077	.066	6.18	
Na	.312	.343	.294		
Mg	1.90	2.09	1.79	8.60	
Al	5.19	5.7	4.89	7.54	52.9
Si	17.7	19.4	16.7	22.2	
K				7.89	
Ca	8.76	9.6	8.23		
Ti					
Fe	.098	.108	.09		

Table IV - Conversion Factors (rads per n/cm^2) Using Engholm's
ETF Spectrum¹.

<u>Material</u>	<u>Factor</u>
Al_2O_3	1.0×10^{-10}
MACOR	2.0×10^{-10}
Polyimide-Fiber- glass(BF)	3.3×10^{-10}
G-10 (BF)	3.8×10^{-10}
G-10	4.4×10^{-10}

sensitivity, it is necessary to establish criteria for the end of life of each part. This is difficult to do, because it involves system trade-offs such as the frequency of warm-ups to room temperature, the allowable excess stabilizer which can economically be designed into the magnet, the difficulty in coping with foreign gases in the refrigeration system, the assumed failure mode of the magnet system, and others. Nevertheless, criteria must be proposed to serve as a basis for discussion, and we therefore propose the following limits:

For Nb-Ti, we have chosen the criterion of a 10% decrease in the critical current density between annealing periods. A 10% limit, though somewhat arbitrary, seems reasonable, since the critical current density decreases rather slowly with fluence, and since considerable annealing takes place at room temperature.

For Nb₃Sn, we used a 1% decrease in critical current density for the lifetime dose. This more conservative criterion is established because Nb₃Sr will not recover significantly on annealing and because the drop in J_c with fluence is more rapid in this material (after the initial J_c increase due to enhanced flux pinning occurs).

For the stabilizers, a criterion of 25% increase in resistivity (at the operating field and temperature) between anneals seems like an appropriate estimate. There are a number of uncertainties in the radiation effects on commercial material which should be resolved, such as the fraction of damage recovery for successive anneals. Experiments at LLNL and ORNL are planned to study these effects. Another important consideration is the economic trade-off between the cost of extra stabilizer and increased magnet thickness as over against the cost of additional shielding and resulting increased magnet inside diameter. These issues must be addressed by the reactor designers.

For fiber-reinforced organic insulators, we used a criterion of 20% decrease in compressive strength perpendicular to the plane of the laminate as the lifetime dose. The choice of a strength criterion is based on the available data,⁴ which indicate that the mechanical properties degrade at a lower dose than do the electrical ones. Furthermore, we believe that radiolysis gases evolved during warm-up can be

removed by purifying the helium. The type and direction of loading are based on the main type of loading present in the magnets. The 20% choice is somewhat arbitrary, and will depend on the cross sectional area of the interlayer insulation (less the liquid helium slots), the presence of load bearing material such as steel filaments in the conductor, which would decrease the magnetic compressive forces on the insulation, and other factors. This is another area in which advantages must be traded off by reactor designers.

For inorganic insulators, we used a criterion of 0.1% lifetime swelling. This is based on the need to avoid strains in the superconductors, and the belief that swelling would be the earliest deleterious effect in materials of this type.

Although these criteria are somewhat arbitrary, we are of the opinion that varying them over a plausible range of values will not strongly affect the results in terms of relative radiation sensitivity. This comes about because of the rather large differences in the radiation doses at which property degradation occurs in some cases, and the rather steep decline in properties once this dose is reached in other cases.

3.1.4.6 Estimates of Lifetimes

Based upon the work of Soll,^{5,6} of Birtcher, Brown, and Scott,⁷ and of Van Konynenburg, Guinan, and Kinney,⁸ and using damage energy scaling, we estimate that Nb-Ti would undergo a 10% decrease in J_c at a fluence of about 3×10^{18} n/cm² in the ETF spectrum, which corresponds to 6×10^8 seconds. Assuming that ten or more anneals were performed during the life of the reactor, and that 70% recovery occurred during each anneal, as observed in small-scale experiments,⁹ the lifetime of Nb-Ti would be 1.6×10^9 seconds.

Using the results of Soll,⁶ Brown et al.,¹⁰⁻¹² Scanlan and Raymond,¹³ Snead et al.,¹⁴ Parkin and Schweitzer,¹⁵ and Snead and Parkin,¹⁶ with damage energy scaling, we estimate the lifetime fluence of Nb₃Sn in the ETF spectrum to be 4×10^{18} n/cm². The lifetime would be 8×10^8 seconds.

Based on the experiments which have involved cryogenic irradiation

and testing of relevant organic insulators^{4,17-22} we estimate the lifetime dose of G-10 epoxy-fiberglass laminate to be 1×10^9 rads and that of polyimide-fiberglass laminate to be 1×10^{10} rads. For G-10 the lifetime is then about 2.6×10^8 seconds, and for polyimide-fiberglass it is about 3×10^9 seconds.

Although little is known about cryogenic effects in inorganic insulators, higher temperature irradiations generally have shown them to be considerably more resistant than organic insulators. Machinable glass-ceramic would probably be the easiest type of inorganic insulator to use for magnets. Fowler et al.²³ report no swelling in MACOR irradiated to 10^{18} n/cm² (14 MeV) at room temperature. We estimate that for the ETF spectrum, which is softer, the 1% swelling criterion would be reached in no less than 5×10^{19} n/cm², which leads to a lifetime of about 10^{10} seconds.

The International Annealed Copper Standard resistivity at 20°C is 1.724 microhm-cm. If copper having a residual resistivity ratio of 215 is used, the unirradiated resistivity at 4-5 K would be 8.0 nanohm-cm. Using the extensive magnetoresistance data of Fickett²⁴ for copper the resistivity in an 8T field would be 45.6 nanohm-cm. A 25% increase at field due to irradiation would mean an increase at zero field of 9.8 nanohm-cm. At 12T, the unirradiated resistivity would be 63.4 nanohm-cm. A 25% increase at field would mean an increase of 13.3 nanohm-cm at zero field.

In the neutron spectrum of Table I, the damage energy cross-section for copper²⁵ is 39.1 b-keV compared to 81.3 b-keV in a pure fission spectrum for which the resistivity damage rate is²⁷ $.723 \times 10^{-6}$ nanohm-cm /n/cm². We therefore expect a 25% increase in resistivity at field to occur at fluences of 2.8×10^{17} and 3.8×10^{17} at 8T and 12T respectively, in times of 5.8×10^7 seconds and 7.9×10^7 seconds. Annealing over 10 or more cycles with 80% recovery would allow an increase of a factor of 4 in lifetimes to 2.3×10^8 seconds and 3.2×10^8 seconds at 8T and 12T respectively.

The magnetoresistive behavior of aluminum differs greatly from that of copper, for which the change in resistivity at field is, to first

order, the same as the change at zero field. For aluminum the resistivity at high fields is roughly two to three times that at zero field. In order to compare aluminum with copper we estimated the fluence at which the resistivity of aluminum is equal to that of copper at the end of life. Magnetoresistance data for aluminum at 4 K covering a wide range of purity^{28,29} as well as radiation induced defects³⁰ indicate that the resistivity will reach the copper values of 57 nanohm-cm at 8T and 79.2 nanohm-cm at 12T when the zero field values reach 27.0 nanohm-cm and 30.7 nanohm-cm.

The resistivity of aluminum at 20°C is 2.824 microhm-cm. With a residual resistivity ratio of 215 the resistivity at 4.5 K would be 13.1 nanohm-cm thus allowing radiation-induced zero-field changes of 13.9 nanohm-cm and 17.6 nanohm-cm, respectively, at 8T and 12T.

For the neutron spectrum of Table I, the damage energy cross-section for aluminum²⁵ is 47.2 b-keV compared to 98.3 b-keV for a pure fission spectrum for which the resistivity damage rate is²⁷ 2.19×10^{-16} nanohm-cm /n/cm². The changes given above would be reached at fluences of 1.3×10^{17} n/cm² and 1.7×10^{17} n/cm² for 8T and 12T, respectively, corresponding to times of 2.7×10^7 and 3.5×10^7 seconds. Since less than 1% of the radiation-induced resistivity remains after room-temperature annealing in aluminum, the times to failure would be reached in 2.7×10^8 and 3.5×10^8 seconds if ten annealing cycles were carried out. However, unlike Nb-Ti and copper, for which little can be gained by increasing the number of annealing cycles, in aluminum the lifetime will be directly proportional to the number of annealing cycles. With ten annealing cycles the performance of aluminum is nearly the same as copper of comparable purity. For a reactor designed for a thirty year life with yearly anneals, aluminum could operate in a neutron flux three times larger than copper could accommodate.

3.1.4.7 Comparison of Radiation Sensitivities

The relative radiation stability of various components of superconducting magnets in the neutron and gamma spectra of the ETF design are summarized in Table V. Each material is listed with its estimated

Table V - Relative Radiation Sensitivity of Magnet Materials at
Inboard Leg of ETF Toroidal Field Coil

<u>Material</u>	<u>Lifetime</u>	
	Seconds	MW-y/m ²
Inorganic insulators	1.0×10^{10}	761
Polyimide-based insulators	3.0×10^9	228
*Nb-Ti	1.6×10^9	122
Nb ₃ Sn	0.8×10^9	61
*+Aluminum stabilizer	$2.7-3.5 \times 10^8$	21-27
*+Copper stabilizer	$2.3-3.2 \times 10^8$	18-24
Epoxy-based insulators	2.6×10^8	20

*Assuming 10 annealing cycles to room temperature.

+Values are for 8T and 12T respectively.

lifetime in seconds at full power of 2.4 MW/m^2 wall loading. For convenience, the lifetimes are also given in MW-y/m^2 . The materials fall into four groups, each separated by about a factor of three in lifetime. Inorganic insulators are the least sensitive to irradiation with lifetimes of 1×10^{10} seconds, followed by polyimide-based insulators at 3×10^9 seconds, superconductors at 1×10^9 seconds and in the most sensitive group, stabilizers and epoxy-based insulators with lifetimes of 3×10^8 seconds.

It is important in a comparison of this nature to make an estimate of precision. In the case of copper stabilizers, Guinan² has estimated an uncertainty of nearly a factor of two in the lifetime. Because it is important for designers to have more precise information, experiments are planned to measure the changes in magnetoresistance of copper under neutron irradiation and annealing, using a range of purity and cold-work.

3.1.5 Conclusions and Recommendations

1. In view of the fact that organic insulators appear to be the most vulnerable part of present magnet systems from the radiation damage standpoint, we recommended that more effort be put into irradiation and testing of (preferably, organic) materials having more radiation tolerance. This should be done under conditions of temperature, stress, and radiation type and spectrum which are closer to the proposed application than the testing performed heretofore. Polyimide-fiberglass materials appear to be promising candidates. It would be desirable to perform fast neutron irradiations at 4-5 K. The samples should be placed in compression and shear, in directions that correspond properly to the orientation of the fiber reinforcement. Loading during irradiation would be desirable. Post-irradiation mechanical tests should be performed both without warming up and after warming to room temperature and cooling back to 4 K. If organic insulators are found to be inadequate, inorganic materials should be studied.

2. The changes in high-field magnetoresistivity of stabilizer materials under repeated low-temperature neutron irradiations and room-temperature anneals should receive further study. It is particularly

important to make measurements on materials that have the same species and amounts of impurities and degree of cold work as would actually be present in magnet material, and to assess the effects of variation in these parameters over the ranges expected for magnet material.

3. Nb-Ti should be irradiated with neutrons at 4-6 K, and critical current measurements up to 10 T should be performed, without warming the samples. Both 14 MeV and lower energy neutron irradiations are needed. Repeated irradiations and room temperature anneals should be performed, to see how the damage accumulates.

4. Nb₃Sn should be irradiated with neutrons at 4-6 K, and critical current measurements up to 12 T should be performed without warming the samples. Both 14 MeV and lower energy neutron irradiations are needed, to fluences high enough to cause J_c to decrease to less than its initial value.

5. System studies should be continued in order to determine the best trade-offs of factors that affect shielding thickness. In particular, the effects of operation with superfluid helium-II on these trade-offs should be studied to see whether refrigeration power or radiation damage is the limiting factor in this case.

Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

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