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MATERIALS CONSIDERATIONS FOR HIGHLY IRRADIATED NORMAL-CONDUCTING MAGNETS IN FUSION REACTOR APPLICATIONS

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A detailed study has been performed to identify deleterious material radiation effects in unshielded highly-irradiated normal-conducting magnets. Application of the study to the design evolution of the normal-conducting hybrid coils in the MARS tandem mirror reactor resulted in the identification of several potential radiation-induced failure mechanisms and enabled coil lifetimes to be reasonably predicted. In the present optimized coil design, lifetime under a peak neutron wall loading of 4.5 MW m^{-2} is limited by swelling of the Spinel ceramic insulation to ~ 1.5 full power years. The effect of radiation damage on high strength copper alloy conductors at these fluences (> 10^{22} ncm^{-2}) remains an area of urgent data need.

1. INTRODUCTION

The last two years or so has seen an increasing requirement in the fusion community for very high axial magnetic fields in the range 7-24 T.[1-5] Because the operation of present day superconductors is limited by the maximum critical field at the conductor, production of these high axial magnetic fields requires a hybrid approach where an outer shielded superconducting coil surrounds an inner unshielded (or lightly shielded) normal-conducting coil. The total field on axis is then a superposition of the separate contribution from each coil. Recent examples of the requirements for high field hybrid solenoids can be found in the following fusion devices: MARS (24 T),[1] TDF (15 T),[2] TASKA (20 T),[3] MFTF/B upgrade(s) (~ 12-18 T),[4] and TFCD (7 T).[5]

In the case of the MARS tandem mirror reactor,[1] the on-axis field of 24 T is comprised of 14 T from an outer Nb_3Sn superconducting magnet operating at 1.8 K and 10 T from an inner normal-conducting coil with water-cooled copper windings. Table 1 lists the key design parameters of the normal-conducting coil. For economic reasons, this coil is operated with no intervening shielding between the first wall and its inner windings. In the interim version of MARS,[1] the peak wall loading under the coil is 4.5 MWm^{-2} and it is evident that the magnet will be operating in a severe neutron and gamma radiation environment. It was important, therefore, to recognize potential radiation-induced failure mechanisms so that coil lifetimes could be reasonably predicted. Accordingly, five potential radiation problem areas were identified as follows:

TABLE 1

Design Parameters of the Normal-Conducting Insert Coil for The Mirror Advanced Reactor (MARS)

Number of coils	2
Axial magnetic field	24 T
Conductor copper alloy	MZC (Cu, Mg, Zr, Cr)
Insulator	Spinel ($MgAl_2O_4$)
Coolant	De-ionized water
Maximum conductor temp.	150°C
Conductor design/yield stress	357/570 MPa
Conductor (unirradiated) conductivity	~ 75% IACS
Peak/average neutron wall loading	4.5/2 MWm^{-2}
Power consumption (Joule losses) at start of life	41 MW

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- Resistivity degradations in the ceramic insulation under instantaneous neutron and gamma absorbed dose-rates.
- Mechanical and structural degradations in the ceramic insulation under long-term neutron fluences.
- Radiolytic dissociation of the coolant water leading to conductor corrosion product formation.
- Resistivity increases in the copper conductor due to neutron-induced transmutations.
- Neutron-induced mechanical and structural degradations in the copper conductor.

It should be noted that the results of this study are not necessarily specific to MARS and have general applicabilities to highly irradiated normal-conducting magnets in fusion reactor applications.

2. DOSE-RATE RESISTIVITY DEGRADATION IN CERAMIC INSULATION

Under neutron and gamma dose-rates typical of fusion reactor first wall conditions, common ceramic insulators such as Al_2O_3, MgO, $MgAl_2O_4$, etc., exhibit a significant and instantaneous decrease in their DC resistivity.[6,7] Ceramics in the form of a compacted powder typically show a greater effect than those in solid form.[7] Unlike long term fluence effects, this phenomenon is dependent on the instantaneous neutron and gamma dose-rate and is, therefore, a potential problem as soon as the fusion plasma reaches operating power.

The extent to which the performance of a normal-conducting magnet is degraded due to this effect depends rather critically on magnet design and power supply voltage.[7] In particular, for internally cooled magnets of the extruded winding design (i.e., inner conductor and outer grounded-case separated by compacted powdered insulation), the resulting dose-rate-induced leakage currents flowing across the insulation are potentially capable of Joule heating rates sufficient to lead to insulator destruction via thermal runaway effects. In view of this phenomenon and the large peak dose-rates of ~ 1.4×10^4 Gy/s (1.4×10^6 rads/s) absorbed in the ceramic insulation in the inner layers of the coils, it was decided not to employ magnets of the extruded winding design in MARS. Instead, a magnet design with windings having turn-to-turn solid insulation rather than turn-to-ground powdered insulation was specified.[1] Such designs do not suffer the same deleterious heating effects when their ceramic resistivity degrades.[7]

3. STRUCTURAL DEGRADAION IN CERAMIC INSULATION

To assess the mechanical and structural degradations in the ceramic insulation under elevated neutron fluences, it is necessary to consider whether the insulator is a compacted powder or a polycrystalline solid, and, if it is the latter, whether it has a cubic or non-cubic crystal structure. For compacted powder ceramics, neutron damage has no effect on the strength of the material since each grain is affected individually. Accordingly, the fluence limit is set only by the swelling limit of the bulk material. Since compacted powder ceramics have typical void fractions of at least 30%, the lifetime of this insulation is not usually the limiting factor in irradiated normal-conducting magnets.

In the case of solid ceramics with cubic structures (e.g. MgO or $MgAl_2O_4$), swelling is isotropic under neutron irradiation.[8] In fact, the fracture toughness of these materials actually increases under elevated fluences.[6,8] The fluence limit for cubic ceramics is, therefore, determined only by the maximum swelling limit which a particular magnet design can tolerate. However, for non-cubic materials (e.g. Al_2O_3), swelling proceeds anisotropically which leads to the onset of structural microcracking even at modest fluences.[6] These factors dictated the choice of Spinel ($MgAl_2O_4$) for the insulation in the normal-conducting coils. A reasonable experimental data-base on swelling exists for this material[8] and, to date, appears to offer the lowest degree of swelling among its class of cubic ceramic insulators.

4. WATER RADIOLYSIS AND CORROSION PRODUCT FORMATION

Under irradiation, radiolysis of the coil coolant water will occur. Water molecules are split to form H^+ and OH^- radicals which can recombine as H_2, O_2, and H_2O_2. Radiolytic corrosion via H_2O_2 might be expected to erode ~ 0.33 mm of copper conductor per full power year of operation of the magnet.[1]

The original design of the normal conducting coil employed an externally-cooled conductor where bulk water flow was directed across the conductor layers. Since each layer was at a different electrical potential, buildup of radiolytic corrosion products would eventually lead to arcing or shorting. Accordingly, in view of these electrochemical failure mechanisms, the coil was reconfigured with an internally-cooled winding design with water flowing entirely within the conductor. The disadvantages of the internally-cooled coil, i.e., its lower current density and separate water passages, are more than compensated by its increased electrical reliability and lifetime.

5. RESISTIVITY INCREASES IN THE COPPER CONDUCTOR

Resistivity of the copper conductor will increase under neutron irradiation from two mechanisms, namely the production of defects and dislocations from neutron damage and the production of neutron-induced transmutation impurities. It is, however, expected that damage-induced resistivity will be only a second order consideration compared with transmutation impurity production since effects of the former will be self-annealed at the operating temperature of the coil (413 K). Further details on this may be found in Reference 9. Accordingly, concentrating on neutron-induced transmutations of the two stable isotopes of copper, ^{63}Cu and ^{65}Cu, the reactions of interest are (n,p), (n,α), (n,2n) and (n,γ), the latter two resulting in unstable isotopes of copper which subsequently decay to other elements. After a given irradiation time, the copper matrix will contain a mixture of radioactive Co, Ni and Cu isotopes and stable Ni, Zn and Cu isotopes.

Full details of the computation of resistivity changes due to neutron-induced transmutations in the coil may be found in Reference 9. Briefly, the neutron spectrum in the coil, computed via a 1-D neutron transport analysis, was fed to the DKR code to compute time dependent inventories of radioactive nuclides. Subsidiary calculations were made of stable impurity nuclides. After two full power years (FPY) of operation, maximum impurity concentrations at the inner windings were found to be 1750 ppm Ni, 971 ppm Zn and 33 ppm Co per MWm^{-2} of wall loading, with resulting fall-off of these concentrations with radial distance through the coil. Relating the conductor resistivity changes to these impurity product concentrations,[9] we obtain Figure 1 which shows the resistivity increase as a function of radial distance through the coil per MWm^{-2} and after 2 FPY of operation. With peak and average wall loadings under the coil of 4.5 MWm^{-2} and 2 MWm^{-2}, respectively, this translates to a peak local resistivity increase in the inner winding of 54% and an average increase of ~ 24%. The average increase in resistivity in the outer winding is only ~ 0.2% and the composite volume-averaged resistivity increase through the whole coil is ~ 5.4%. On-going studies of resistivity changes in copper alloys with neutron irradiation are in progress.

Increasing resistivity with time means increasing power dissipation in the coil since the current must be held constant to preserve the required ampere-turn conditions. Coil lifetime due to transmutations is, therefore, dependent on either the maximum design reserve capacity in the magnet power supply or the maximum tolerable increase in operating costs for magnet recirculating power. In this context, note that the Joule heating losses in each of the MARS normal-conducting coils are 41 MW at start of life. The economic consequences of radiation-induced resistivity increases are evident in Figure 2, where the additional power requirements and corresponding increase in integrated operating costs are shown as a function of the operating life of both coils. Note that operating the same coils for 20 FPY would result in an extra 200 M$ in operating costs! There is thus a strong economic incentive to change out the coils after only a few FPY of operation.

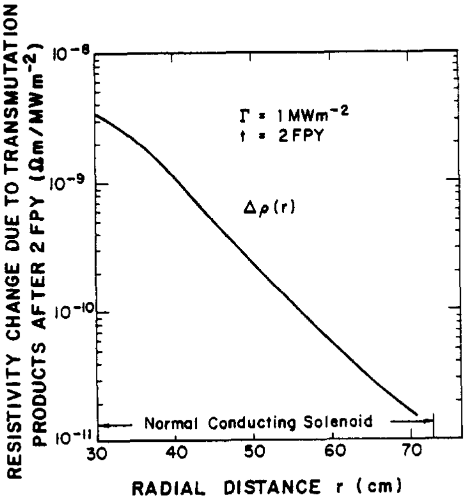

FIGURE 1
Radial dependence of resistivity increases in the MARS normal-conducting coil due to neutron-induced transmutations

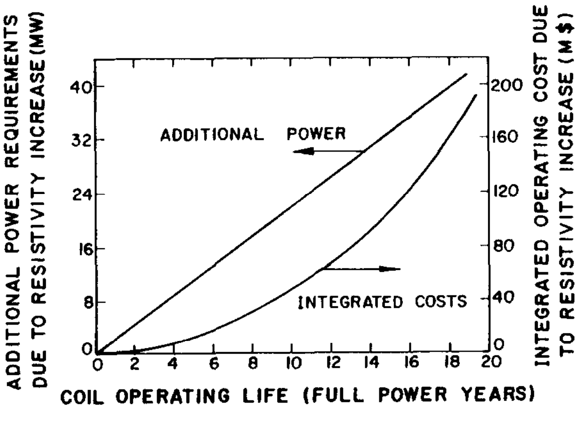

FIGURE 2
Economic consequences of radiation-induced resistivity increases in the MARS normal-conducting coils

6. MECHANICAL AND STRUCTURAL DEGRADATIONS IN THE CONDUCTOR

The MZC copper alloy conductor in the normal-conducting coils in MARS has to satisfy two rather conflicting requirements, namely high yield strength against hoop stresses and high electrical conductivity. Radiation transport calculations yield maximum helium production rates in the inner winding of 315 ppm after 2 FPY of operation with a corresponding average dpa of 63. However, the effects of these damage parameters on the mechanical and structural properties of the copper alloy is unknown. There is, at present, no adequate irradiation data for copper alloys for neutron fluences > 10^{22} ncm^{-2}. Probable effects will include high void formation, swelling, loss of ductility, change in yield strength (up or down?) and irradiation creep. Clearly, appreciable decreases in yield strength and ductility and/or high swelling and irradiation creep rates will be detrimental to lifetime. There is, therefore, an urgent need for high fluence irradiation tests of the high strength copper alloys at relevant temperatures (~ 50-200°C).

7. CONCLUSIONS - COIL LIFETIMES

With regard to the five radiation mechanisms likely to degrade the performance of the MARS normal conducting coil, dose-rate resistivity degradation in the ceramic insulation and problems of corrosion product formation from radiolysis of the coolant water have been circumvented by judicious coil design. Of the remaining three mechanisms, neutron-induced transmutations increase the bulk volume-averaged resistivity of the coil by 5.4% after 2 FPY irradiation time. This could certainly be accommodated by specifying sufficient reserve margin in the magnet power supply and should be no problem given the swelling limit for the Spinel insulation (see below).

Therefore, of the five mechanisms, only two are seen as determining the minimum coil lifetime, namely neutron damage to the copper alloy conductor and neutron-induced swelling in the ceramic insulation. The first of these is rather an unknown area and it is important here to reiterate the urgent need for high fluence irradiation data for copper alloys. At present, the lifetime of the MARS normal-conducting insert coils is determined by swelling of the Spinel ceramic insulation. The local swelling tolerance for the insulation in the present coil design[1] is 3 v/o. For a peak wall loading of 4.5 MWm^{-2} under the coil, neutron transport calculations yield a peak fluence to the Spinel insulation of 2.74 x 10^{22} n cm^{-2} per FPY of operation ($E_n > 0.2$ MeV). The reported irradiation swelling data for this material indicates a swelling of ~ 0.8 v/o for a fast fission irradiation of 2.1 x 10^{22} n cm^{-2} at 430 K.[8] Therefore, with the rather conservative assumption that the harder 14 MeV fusion spectrum will enhance the swelling rate by a factor of two, we obtain a lifetime of ~ 1.44 FPY before the 3 v/o swelling tolerance limit of the coil insulation is reached.

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REFERENCES

1. B.G. Logan et al., "Mirror Advanced Reactor Study (MARS) - Interim Design Report," UCRL-53333, Lawrence Livermore National Laboratory (1983).
2. J. Doggett et al., "Fusion Technology Demonstration Facility (TDF)," UCID-19328, Lawrence Livermore National Laboratory (to be published 1983).
3. B. Badger et al., "TASKA - A Tandem Mirror Fusion Engineering Facility," UWFDM-500, University of Wisconsin Fusion Engineering Program (1982).
4. K.I. Thomassen and J.N. Doggett (Eds.), "Options to Upgrade the Mirror Fusion Test Facility," UCID-19743, Lawrence Livermore National Laboratory (1983).
5. J.A. Schmidt and C.A. Flanagan, "Next Tokamak Facility," in Proc. of 5th Topical Meeting on Technology of Fusion Energy, Knoxville, TN, April 1983.
6. F.W. Clinard, "Ceramics for Applications in Fusion Systems," J. Nucl. Mater., 85 & 86 (1979) 393.
7. L.J. Perkins, "Radiation Dose-Rate Resistivity Degradation in Ceramic Insulators and Assessment of the Consequences in Fusion Reactor Applications," UWFDM-469, University of Wisconsin Fusion Engineering Program (1982).
8. G.F. Hurley, J.C. Kennedy and F.W. Clinard, "Structural Properties of MgO and $MgAl_2O_4$ After Fission Neutron Irradiation Near Room Temperature," LA-UR 81-2078, Los Alamos Scientific Laboratory (1981).
9. B.G. Logan et. al., "Mirror Advanced Reactor Study (MARS) - Final Design Report," Lawrence Livermore National Laboratory (to be published 1984).