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CHARTS FOR SPECIFYING LIMITS ON COPPER STABILIZER DAMAGE RATE

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Charts that simplify the task of specifying the damage rate limit in the copper stabilizer of fusion reactor superconducting magnets are presented. Partial damage recovery with annealing is accounted for. Applications to the MARS magnets are discussed.

1. INTRODUCTION

Fusion reactors require using superconducting magnets for plasma confinement.[1,2] Shielding must be provided to protect the magnets from excessive radiation effects. Recently, insulators that can stand doses up to 10^8 Gy have been considered[3] leaving the radiation damage to the stabilizer as the main shield design driver. Because of its strength, fabricability, and small radiation induced resistivity, copper is the leading stabilizer candidate. Neutron irradiation of Cu results in a radiation induced resistivity which impacts the total magnetoresistivity at the operating field.

For the magnet to be cryostable the stabilizer resistivity is limited such that the I^2R heat can be removed by the coolant and temperature kept below the critical temperature. Charts based on the Kohler plot for Cu are generated to determine the limit on radiation induced resistivity for any given magnet design. This limit can then be translated into a limit on atomic displacements (dpa). For magnet shielding neutronics calculations, the maximum allowable damage *rate* must be specified. Charts are presented for determining the minimum allowable time between anneals that accounts for the partial recovery with annealing[4,5] and availability requirements. The charts are applied to the coils of MARS[2].

2. MAGNETORESISTIVITY OF COPPER

The relation between the resistivity at field and initial resistivity at zero field is usually presented in the form of a Kohler plot which gives the fractional change in resistivity at field versus the field divided by the initial resistivity. A single Kohler plot, shown in Fig. 1, was obtained by Fickett.[6] The temperature dependence can be omitted as the resistivity is independent of temperature in the range of interest.

The curve in the Kohler plot can be represented as

$$\{\rho(B) - \rho(0)\}/\rho(0) = C\,\{B/\rho(0)\}^{\alpha}\ , \qquad (1)$$

where C and α vary slightly with $B/\rho(0)$. Upon irradiation at cryogenic temperatures, immo-

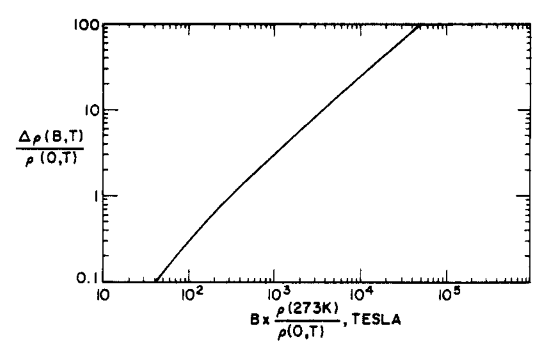

FIGURE 1
Kohler plot for copper obtained by Fickett.

bile point defects are produced and the resistivity at zero field will increase by the radiation induced resistivity $\Delta\rho_r(0)$. $\rho(0)$ in Eq. (1) must be replaced by $\rho_0(0) + \Delta\rho_r(0)$, where $\rho_0(0)$ is the residual resistivity. The slope α in Fig. 1 varies from 0.9 to 1.15 implying that the contribution of $\Delta\rho_r(0)$ to $\rho(B)$ depends on the field and initial resistivity and the frequently used assumption of adding different resistivity components[7,8] is not valid. Recently, experiments on irradiated Cu[5,9] indicated deviations up to ~ 20% from the original Kohler plot with Fig. 1 tending to overestimate the magnetoresistivity at small values of $B/\rho(0)$.

3. LIMIT ON RADIATION INDUCED RESISTIVITY

If cryogenic stabilization is required, the coolant must be capable of removing the resistive heat generated in the stabilizer. This sets an upper limit on the total resistivity at field given by

$$\rho(B) < q''_{max} A_{Cu} P/I^2 , \qquad (2)$$

where A_{Cu} is the Cu cross sectional area, P is the wetted perimeter and I is the current. q''_{max} is the allowable heat flux that can be removed by the coolant. One must insure that $\rho(B)$ will not exceed the limit at any time during the reactor life.

Based on the Kohler plot, we generated the radiation induced resistivity chart given in Fig. 2. The chart can be conveniently used to determine $\Delta\rho_r(0)$ that corresponds to a specified $\rho(B)$ given the field B and the residual resistivity ratio RRR of the copper used. This chart is based on Fig. 1 and gives conservatively low limits for $\Delta\rho_r(0)$ compared to charts based on other plots.

4. LIMIT ON ACCUMULATED DAMAGE

The limit on $\Delta\rho_r(0)$ can be translated into

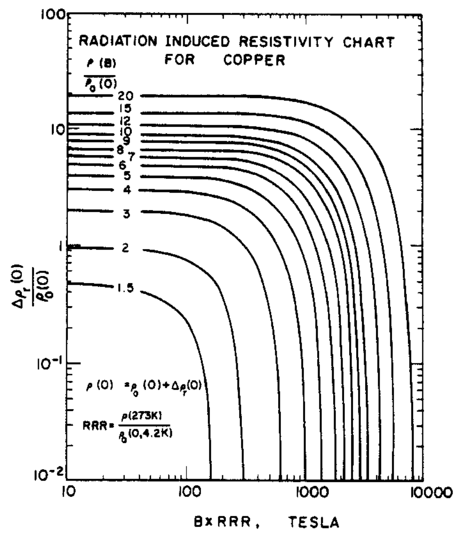

FIGURE 2
Radiation induced resistivity chart for Cu.

a limit on dpa or neutron fluence using simple analytic expressions obtained by fitting experimental data. They have the general form

$$\Delta\rho_r(0) = \Delta\rho_r^\infty(0)\ [1 - \exp(-aD)] , \qquad (3)$$

where $\Delta\rho_r^\infty(0)$ is the saturation resistivity and D is the accumulated dose represented in terms of dpa or neutron fluence. Values for $\Delta\rho_r^\infty(0)$ in the range 300-440 nΩcm have been proposed.[8-10] The coefficient a is given by the initial resistivity damage rate $[\partial\Delta\rho_r(0)/\partial D]_0$ divided by $\Delta\rho_r^\infty(0)$.

Extensive resistivity measurements in Cu at 4.2 K have been performed.[9-12] The initial resistivity damage rate with respect to neutron fluence has a strong energy dependence.[11] Hence, the coefficient a is sensitive to the neutron spectrum at the magnet if D is used to represent the neutron fluence.

The initial resistivity damage rate with respect to dpa can be obtained by dividing the rate with respect to neutron fluence by the dpa cross section. This rate has less energy dependence and the coefficient a in Eq. (3) will be less sensitive to the neutron spectrum if D is used to represent the accumulated dpa. However, the value of this coefficient will depend on the assumed displacement energy E_d. Values of 30 and 40 eV have been used. Values for a in the range 162 to 563 were derived by different researchers.[5,8,9] Given the limit on $\Delta\rho_r(0)$, the maximum allowable dpa, D_{max}, can be obtained using the appropriate $\Delta\rho_r(0)$ versus D formula.

5. DAMAGE RATE LIMIT

In order to design the shield the limit on the dpa rate in the stabilizer must be specified. Experimental results indicate that 80-90% of the radiation induced defects can be recovered[4,5,10] by room temperature annealing.

For the accumulated damage not to exceed the limit D_{max} with the time between anneals being at least Δt_{min} determined from availability and cost considerations, different irradiation-annealing schemes can be adopted. In one approach illustrated in Fig. 3 equal times, measured in full power years (FPY), are used between anneals. The dpa limit, D_{max}, will not be reached until the end of reactor life and is given by

$$D_{max} = (dD/dt)\ \Delta t\ \{1 + (m-1)\ (1-r)\}\ , \quad (4)$$

where r is the recovery fraction. The limit on damage rate is, hence, given by

$$dD/dt < D_{max}/[\Delta t_{min}\{1+(\frac{t_\ell}{\Delta t_{min}} -1)(1-r)\}]\ . \quad (5)$$

Another schedule, illustrated in Fig. 4, can be used with the reactor operating until the dpa limit is reached before each anneal. The annealing frequency will increase as one approaches the end of reactor life. The total reactor life is related to Δt_1 via

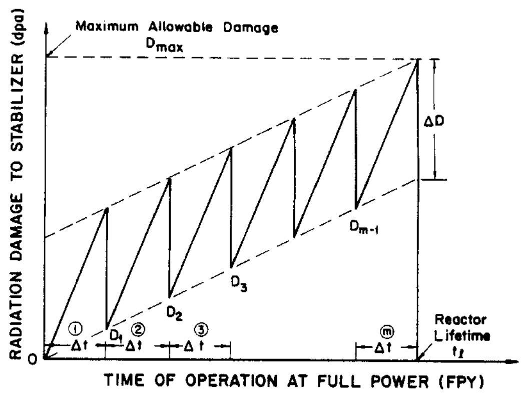

FIGURE 3
Irradiation-annealing schedule with equal time between anneals.

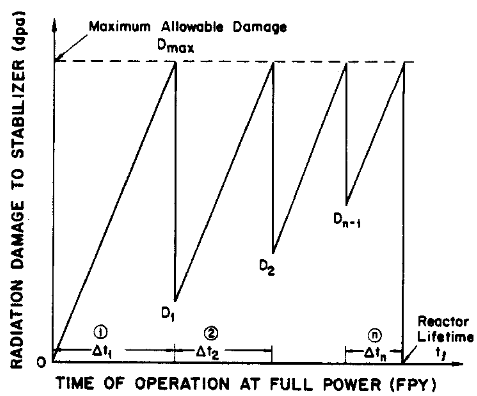

FIGURE 4
Irradiation-annealing schedule with damage limit reached before each anneal.

$$t_\ell = \Delta t_1\ (1 - r^n)/(1 - r)\ . \quad (6)$$

The time for the final irradiation cycle Δt_n is given by

$$\Delta t_n = r^{n-1}\Delta t_1 . \quad (7)$$

Setting $\Delta t_n = \Delta t_{min}$, Eqs. (6) and (7) can be solved to yield the minimum time required before the first anneal. The solution is represented by the chart given in Fig. 5. The corresponding number of cycles is given by

$$n = \ln\{1 - \frac{t_\ell}{\Delta t_1}(1 - r)\}/\ln r . \qquad (8)$$

Once Δt_1 is determined the limit on the damage rate can be obtained by dividing D_{max} by Δt_1. One can easily show that exactly the same damage rate limit as that given by Eq. (5) is obtained, implying that these charts can be used to determine the dpa rate limit regardless of the schedule used. The second scheme is preferred because it results in the least number of anneals for the same D_{max} and Δt_{min}.

6. APPLICATIONS TO THE MARS MAGNETS

Superconducting magnets of different shapes and conductor designs are used in MARS.[14] While all coils use NbTi, the central cell and end cell coils are cooled by normal helium (LHeI) at 4.2 K and superfluid helium (LHeII) at 1.8 K, respectively. Among the end cell coils, the plug yin-yang coils are exposed to the largest neutron irradiation. The charts developed in this work have been used to determine the dpa rate limits in the stabilizer of the central cell and plug yin-yang coils.

6.1. Central cell coils

The composite conductor at the innermost

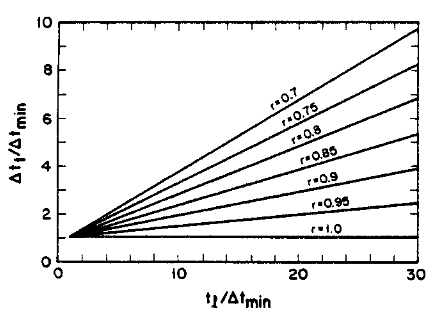

FIGURE 5
Chart for determining minimum time required before first anneal.

layers of the magnet is 2.38 by 2.185 cm. The conductor current is 5830 A and the maximum field is 7.14 T. The working current density for NbTi is considered to be 4.9 x 10^4 A/cm^2 implying that the required NbTi cross section area is 0.119 cm^2. This yields a Cu area of 5.08 cm^2. The wetted perimeter represents half the actual conductor perimeter. The maximum allowable heat flux for LHeI is taken to be 0.2 W/cm^2. Using Eq. (2) yields a limit on the total resistivity at field of 136.5 nΩcm.

Half hard copper with RRR = 80 is used in both central cell and end cell magnets, with a residual resistivity $\rho_0(0)$ of 19.31 nΩcm. Figure 2 yields a limit on $\Delta\rho_r(0)$ of 81.1 nΩcm. Guinan et al.[5] used the neutron spectrum in the central cell coil of MARS to derive values of 300 nΩcm and 240 for $\Delta\rho_r^\infty(0)$ and a, respectively in Eq. (3). Using this formula a corresponding damage limit of 1.3 x 10^{-3} dpa was obtained.

Availability considerations for MARS require the time between anneals to be at least 1 FPY. Assuming 85% recovery with annealing and 24 FPY reactor lifetime, Fig. 5 yields a minimum required time of 4.45 FPY before the first magnet anneal. The corresponding number of irradiation cycles is 11. Hence the limit on damage rate in the stabilizer is 2.95 x 10^{-4} dpa/FPY. The calculated peak dpa rate in the stabilizer is 1.6 x 10^{-5} dpa/FPY implying that no magnet annealing is needed.[14]

6.2. Plug yin-yang coils

The conductor is 1.889 by 1.0 cm with a current of 6518 A and a maximum field of 10.7 T. The working current density for NbTi is taken to be 5.39 x 10^4 A/cm^2 implying that the copper cross section area is 1.77 cm^2. With half of the actual conductor perimeter cooled by LHeII that can handle a heat flux of 1 W/cm^2, Eq. (2) yields a limit on $\rho(B)$ of 120.4 nΩcm. Figure 2 gives a limit of 38.6 nΩcm for $\Delta\rho_r(0)$. The value of a in Eq. (3) obtained using the spectrum in the yin-yang coil of MARS was found to be 231. This yields a dpa limit of 5.96×10^{-4} implying that the dpa rate should not exceed 1.34×10^{-4} dpa/FPY.

The neutronics calculations for a steel shield indicate that the peak dpa rate is 2.1×10^{-4} dpa/FPY.[14] If cryogenic stabilization is utilized the first anneal is needed after 2.84 FPY. An infinite number of anneals would have been required after only 18.9 FPY. Using a tungsten shield the peak dpa rate reduces to 5.8×10^{-5} dpa/FPY implying that the first magnet anneal is needed after 10.3 FPY. Two magnet anneals will be required during the whole reactor life. For cost considerations, the tungsten shield can be used only at locations where high radiation effects are expected.

7. SUMMARY

Charts have been generated to determine the maximum allowable damage rate for the copper stabilizer in fusion reactor superconducting magnets that are required to be cryostable. These charts are based on the Kohler plot and account for the partial recovery of radiation induced defects by room temperature annealing. The charts provide the shield designer with a tool that greatly simplifies the task of specifying damage rate limits in the stabilizer for given magnet design and reactor availability considerations and facilitate the subsequent shield design. These charts are also useful in trade-off studies.

ACKNOWLEDGEMENT

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