EFFECT OF FAST NEUTRON IRRADIATION AT LOW TEMPERATURE ON NbZr COIL PERFORMANCE*

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Summary

The effects of exposure to fast neutron radiation on the performance of a superconducting NbZr solenoid are reported. The irradiations and tests were carried out with the coil held near its operating temperature. Performance was determined by measuring the maximum current at which the coil quenched.

Secondary irradiation from the 60-in ANL Cyclotron (1.2×10^9 neutrons/cm^2/s at 3-13 MeV, peaked at 8 MeV) had no measurable effect upon the operation of the coil. At the ANL CP-5 reactor, a total dosage of 7.2×10^{17} neutrons/cm^2 (fission neutrons above 0.7 MeV) caused no deterioration in the coil. A slight enhancement (2 to 3%) of coil performance was observed but this annealed out at room temperature. An exposure rate of 8.3×10^{11} neutrons/cm^2/s produced sufficient nuclear heating to give severe degradation in coil performance to 20% of the initial quench current.

Introduction

Superconducting magnets have many potential applications in accelerator facilities, fusion devices, and in space, most of which require operation in a radiation environment. Therefore, the effects of nuclear irradiation on the superconducting properties of magnets should be understood. Several studies have been performed to assess these effects.[1-8] Many of them have been carried out with the specimen at room temperature. While these studies have yielded valuable information on the nature of superconductivity, they may not be sufficient in themselves to determine the effects of irradiation on superconductors operating near 4.2°K.

It is well known that in the bombardment of solids with energetic particles, the bombarding particles collide with the atoms of the solid imparting kinetic energy to them and displacing them from their equilibrium position. While the vast majority of the kinetic energy is dissipated in heat ($>90\%$), vacant lattice sites and interstitial atoms are important consequences of the atomic displacement event. Small clusters of these defects as well as small dislocation loops can also be formed depending upon the displacement energy and the temperature of bombardment. These defects may improve or degrade superconducting magnet performance. The experiment described here was designed to assess whether or not these changes occur and consisted of tests in which a superconducting coil was irradiated in a bath of liquid helium with fast neutrons. The effect of this environment was then measured by determining the quenching current before and after the irradiation. It is important to bombard and to measure at liquid helium temperatures without warm-up as it is well known that the defects created by the bombardment are highly mobile at temperatures well below 80°K in many metals.

In the case of reactor irradiations, the absorption of gamma rays and thermal neutrons will introduce a heating effect. Internal ionizations during charged particle bombardment will generate heat. In an operational coil, this heat must be extracted with a minimal increase in coil temperature which requires that careful consideration be given to the coil design. This effect, however, was not the primary consideration of these tests.

Experimental

The test coil consisted of 1200 turns of 0.010-in diameter Nb25%Zr wire with a 0.001-in thick copper coating wound on a stainless steel core. Its winding dimensions were 0.25-in i.d., 0.75-in o.d. and 0.88-in length. The wire insulation was a 0.0001-in thick coating of lead acetate and the interlayer insulation was 0.003-in thick fiberglass cloth. The initial quench current was 40.8 A for a field strength of 22.4 kG at 4.2°K.

The operating characteristics of the coil were studied during a one hour's exposure to a radiation intensity of 1.2×10^9 neutrons/cm^2/s in a secondary beam from the ANL 60-in Cyclotron. The beam was obtained from the 22 MeV deuteron reaction on beryllium and contained a broad energy spectrum of neutrons with a particle maximum at 8 MeV. The accelerated life test with the coil under large radiation doses was performed at the ANL CP-5 reactor. This irradiation facility[9] (Fig. 1) is surrounded by 600 gms of enriched Uranium which absorbs about half of the incident thermal neutrons to yield a spectrum within the converter of 6×10^{11} fission neutrons/cm^2/s (>0.7 MeV) with a peak at 1.7 MeV. The transmitted thermal neutrons are absorbed by a water-cooled cylinder of boron carbide which is located inside the converter plate and reduces the thermal neutron intensity in the cryostat to less than 10^8 neutrons/cm^2/s. The closed circuit refrigeration system external to the sample copper chamber was used to maintain the chamber at liquid helium temperature throughout the irradiation.

Because of nuclear heating, the exact temperature of the coil is not known during an irradiation. The temperature in some parts of the winding at full reactor power may rise to between 10

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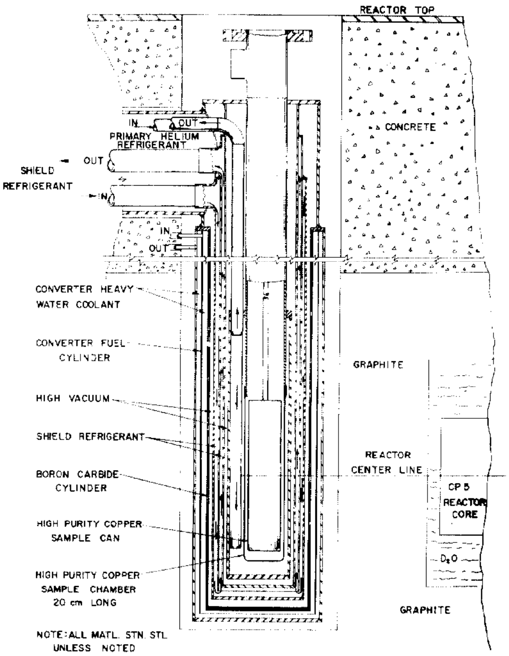

FIGURE I - FAST NEUTRON SAMPLE FACILITY

and 15°K. Carbon resistors were placed at the top and bottom of the coil and were constantly monitored so that the temperature difference, if any, could be detected. The quench current, I_c, was determined by increasing the coil current at 0.4 A/s until the coil was driven into the normally conducting state.

Results

Figure 2 and the following table relate each phase of testing and radiation exposure in chronological order. All quench currents listed in the table were either obtained at or extrapolated to 4.21°K.

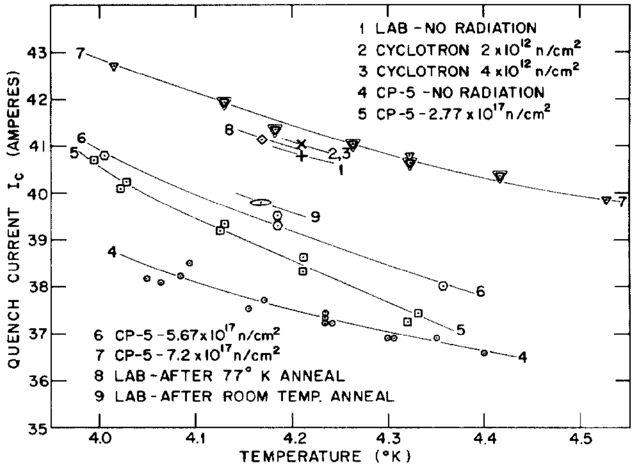

Fig. 2. Quench Currents at Various Phases of the Irradiation.

In the cyclotron tests, the coil was kept in a bath of liquid helium and was run continuously at 40 A, only 0.8 A below the quenching current, I_c, observed in the initial laboratory tests. During and after the bombardment, which lasted about one hour, the interactions did not produce heat spikes in the coil capable of causing a transition to the normal state. There was practically no difference between the initial I_c and those during the cyclotron irradiation (see runs 1, 2 and 3).

The CP-5 measurements were made during shutdown periods of the reactor. The initial coil checks at the facility before the irradiation show a 9% reduction in I_c which is due to residual nuclear heating from the reactor. (See run 4.)

The dose rate due to residual reactor power was found to be higher than that existing during the cyclotron irradiation. The rate at quench was calculated by assuming that 6% maximum dosage

Table - Radiation Test Results in Chronological Order

Run No.	Comments	Location	Total Dosage (n/cm^2)	Residual Reactor Power (kW)	Dosage Rate at Quench (n/cm^2/s)	I_c (A)
1	Initial quench	Lab	0	--	0	40.8
2		60-in Cyclotron	2×10^{12}	--	1.2×10^9	41.0
3		"	4×10^{12}	--	"	41.0
4	Anneal 300°K	CP-5	"	10	1.4×10^9	37.3
5		"	2.77×10^{17}	50	7.0×10^9	38.4
6		"	5.67×10^{17}	50	7.0×10^9	39.1
7		"	7.2×10^{17}	20	2.8×10^9	41.7
8	Anneal 77°K	Lab	"	--	0	40.9
9	Anneal 300°K	"	"	--	0	39.5

rate was still present when the reactor was initially shut down and the dosage rate thereafter is proportional to $t^{-0.2}$, where t is time in s. Since the exact temperature of the superconductor is not known when nuclear heating, due to residual power in the reactor, is present, some of the differences in I_c during the CP-5 tests can be attributed to the differences in nuclear heating present in the coil. For example, the coil was still superconducting at a dose rate of 3.0 x 10^{11} neutrons/cm^2/s but quenched at 8.6 A. The trend was towards an increase in I_c as the radiation dose increased. The total dosage was 7.2 x 10^{17} neutrons/cm^2/s and the corresponding coil current and dose rate during quench were 41.7 A and 2.8 x 10^9 neutrons/cm^2/s, respectively. (See run 7.)

After irradiation, the coil was annealed at 77°K and retested. The I_c of 40.9 A obtained was very close to the initial quench current. A further anneal at room temperature, however, showed a very slight deterioration of the coil from the original condition as is shown in Fig. 2.

In summary the experiment described here shows that a Nb25%Zr coil radiated with 7.2 x 10^{17} neutrons/cm^2 at a coil temperature of approximately 10°K results in a few percent increase in I_c. This enhanced quench current is annealed out when the coil is pulse annealed at 77°K. A further pulse anneal at room temperature results in a slight decrease in I_c.

Future tests are being planned to include Nb_3Sn and NbTi coils.

Acknowledgments

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