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FUSION-NEUTRON EFFECTS ON
MAGNETORESISTIVITY OF COPPER
STABILIZER MATERIALS

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February 24, 1983

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Livermore
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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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3.4 FUSION NEUTRON EFFECTS ON MAGNETORESISTIVITY OF COPPER STABILIZER MATERIALS -- M. W. Guinan and R. A. Van Konyenburg (Lawrence Livermore National Laboratory)

3.4.1 SPM Task

IV.G.2 Radiation Damage in Superconducting Composites

3.4.2 Objective

The objective of this work is to quantify the changes which occur in the magnetoresistivity of coppers (having various purities and pretreatments, and at magnetic fields up to 12 T during the course of sequential fusion neutron irradiations at about 4 K and anneals to room temperature. In conjunction with work in progress by Coltman and Klabunde of ORNL, the results should lead to engineering design data for the stabilizers of superconducting magnets in fusion reactors. These magnets are expected to be irradiated during reactor operation and warmed to room temperature periodically during maintenance.

3.4.3 Summary

Eight copper wires were repeatedly irradiated at 4.2-4.4 K with 14.8 MeV neutrons and isochronally annealed at temperatures up to 34°C for a total of five cycles. Their electrical resistances were monitored during irradiation under zero applied magnetic field. After each irradiation the magnetoresistances were measured in applied transverse magnetic fields of up to 12 T. Then the samples were isochronally annealed to observe the recovery of the resistivity and magnetoresistivity. After each anneal at the highest temperature (34°C) some of the damage remained and contributed to the damage state observed following the subsequent irradiation. In this way, we were able to observe how the changes in magnetoresistance would accumulate during the repeated irradiations and anneals expected to be characteristic of fusion reactor magnets. For each succeeding irradiation the fluence was chosen to produce approximately the same final magnetoresistance at 12 T, taking account of the accumulating residual radiation damage. The increment of magnetoresistivity added by the irradiation varied from 35 to 65% at 12 T and from 50 to 90% at 8 T for

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the various samples.

3.4.4 Progress and Status

3.4.4.1 Introduction

Magnetic fusion reactors are expected to require superconducting magnets for economical operation. These magnets will be subject to neutron and gamma irradiation arising from the plasma and reactor blanket regions. Since radiation is deleterious to the properties of the magnet materials, a sufficient amount of shielding must be used to protect them and preserve their properties for a practical reactor lifetime. On the other hand, excess shielding increases magnet size and structural loads and, hence, cost. It has therefore been necessary to accurately measure radiation effects on magnet components and to compare their vulnerabilities in order to determine the driving factors in producing an economical design.

There are four major components in a superconducting magnet system from a materials standpoint: the superconductor, the stabilizer, the insulators, and the magnet case and structural support. Past work^{1,2} has shown that of these, the most radiation-sensitive components are the insulators and the stabilizer. Other experimenters are studying radiation effects on the insulators, and it appears that alternative materials to the commonly-used fiber-reinforced epoxies and aluminized mylar are available if increased radiation tolerance is needed, albeit at greater cost. In the case of the stabilizer, however, it appears that copper is virtually the only choice, for reasons of economics, fabricability of superconducting composite conductors, and radiation effects on magneto-resistivity. It therefore appears that radiation effects on the copper may be the fundamental limit on allowable radiation dose to superconducting fusion reactor magnets. Hence it is important to quantify these effects, and this work was directed to that end.

The purpose of the stabilizer in a superconducting magnet is to protect the magnet from "going normal" during high-current operation due to flux jumps or other causes. For this function, its most important

radiation-sensitive property is its electrical conductivity in the presence of the magnetic field, or magnetoresistivity. Since the magnetoresistivity is known to depend on a host of parameters, including material purity, state of internal oxidation of impurities, cold work, temperature, magnetic field level, radiation type, energy spectrum, dose, and time history of delivery and annealing, it is necessary to control all of them, and duplicate as closely as possible the conditions expected in fusion reactor magnets. As is usual in situations of this sort, these conditions are not completely defined and are subject to change as successive conceptual fusion reactor designs are developed. In addition, the experimental facilities available have characteristic limitations. As a result, some judgment and compromise are necessary. In particular, there are no facilities available in which samples can be subjected to high neutron fluxes while simultaneously being held in the presence of a high magnetic field. This is not thought to present problems since the cyclotron radius of recoiling copper ions in a 12 T field is very long compared to their range in the material, and once displacements have occurred, they are "frozen in" at liquid helium temperature, and can be preserved until the samples are transferred to a magnet.

The present work was performed with an essentially "pure" 14.8 ± 0.3 MeV neutron spectrum, whereas fusion reactor magnets will be subjected to a broad spectrum of neutron energies, only a small fraction having energies near this value. Accordingly, we plan to combine our results with those to be produced by Coltman and Klabunde of ORNL, using different neutron spectra, in order to obtain design data generally applicable to various fusion reactor designs.

Finally, we have delivered lifetime doses to the copper in a few days, compared to the several-year period over which it will be used in a fusion reactor. This is also not thought to be a serious problem because the defects are not able to anneal significantly at the magnet operating temperature.

3.4.4.2 Sample Material and Preparation

The copper materials used in this work were obtained from Charles

Klabunde of ORNL, and are the same materials which Coltman and Klabunde have used for irradiations in the Bulk Shielding Reactor at ORNL and will use in the Intense Pulsed Neutron Source at ANL. The materials included both OFHC copper and high purity copper having different treatments in regard to internal oxidation, cold work, and annealing. The following description of the material preparation procedure was provided by Klabunde³:

"OFHC copper stock as used for stabilizer and matrix in large composite superconductors was supplied by Bruce Zeitlin of Inter-magnetics General Corporation (Guilderland, New York). It is designated 'CDA-101' and described as OFHC copper with a minimum of 99.99% purity and a resistance ratio of at least 180. It was supplied to us as 1/8" wire in a partially cold-worked state.

A portion of this stock was processed through swaging, drawing, etching, annealing, and more drawing to produce six different sample materials with various degrees of cold-work after anneal and with or without an internal oxidation treatment in its history. The internal oxidation treatment consisted of a three-hour anneal at 1000°C in a dynamic-leak air atmosphere of 1×10^{-4} torr as indicated at a liquid-nitrogen trapped gauge. (The vacuum annealing furnace system used may be described in essence by the sequence of its elements as: air leak, hot zone, liq. N₂ trap, gauge, diffusion and mechanical pumps.) This treatment is known to produce the lowest residual resistivity attainable in any given piece of reasonably pure copper (with adjustment of the time according to the cross-section of the sample, this having been done at a 0.031" diameter in this case).

The swaging operations (from 1/8" to 0.0375") left some folded-over (flash) material on the surface which was removed by etching and digging or cutting between drawing until examination by stereo-microscopy (up to 40x) revealed clean, pit-free surfaces before the first annealing stage. This microscopic examination was also applied in cleaning the diamond dies used to draw the wires. The set of dies used gives very nearly a 7.5% reduction in area at

each pass. The final passes were 0.0054, 0.0052, and 0.0050" diameter.

The final states of cold-work were achieved by further subdividing the oxidized and unoxidized batches into three pieces, each of which was given a 'recrystallizing anneal' at a different point in the drawing schedule: (0) after the last pass to yield zero cold work, (1) before the last pass to yield one-pass of C.W., and (2) before the next-to-last pass to yield two passes of C.W. (14.3% area reduction). This anneal, done on all pieces simultaneously, was 3 hours at 400°C in a vacuum of $< 1 \times 10^{-5}$ torr.

A piece of single crystal grown from Asarco 99.999% pure copper in high vacuum or reducing atmosphere was swaged and drawn to 0.010". Its resistivity ratio was tested at that point (after a high vacuum, non-oxidizing anneal at 600°C) to be 1240. This stock wire (made in 1977) was processed for the present work in a similar manner to the OFHC stock, except that only internally oxidized material was produced and only in zero and two-pass states of cold work. The oxidizing anneal was done at a size of 0.0059" using a 2-hour, 950°C, 1×10^{-4} torr air-bleed treatment (adequate at this size; temperature and time reduced to minimize sinter-sticking of the wire loops to one another). The recrystallizing anneal was 3 hour at 500°C."

Table 3.4.1 summarizes the size and resistance data provided by Klabunde for the materials used in this work.

Experimental samples were cut from this material at LLNL and two copper strips (0.13 mm wide by 0.025 mm thick) were spot welded to each sample for use as voltage measurement leads, thus defining the gauge section of each sample. Some of these connections were later reinforced by soldering with indium metal after the samples were mounted on the cryostat. Final gauge lengths for our samples are also given in Table 3.4.1.

Table 3.4.1. Sample Specifications

Sample	Treatment	Diameter (mm)	Gauge Length (mm)	ρ^d (4.2K)	RRR ^e
CUUNO ^a	Recrystallized	.1259	11.0	4.74	363
CUUN1 ^a	7.5% cold-worked	.1261	11.1	11.27	153
CUUN2 ^a	14.3% cold-worked	.1261	10.1	19.10	91
CUOX0 ^b	Recrystallized	.1260	7.9	2.77	621
CUOX1 ^b	7.5% cold-worked	.1263	9.1	9.35	185
CUOX2 ^b	14.3% cold-worked	.1261	10.0	16.15	107
CUHP0 ^c	Recrystallized	.1262	9.3	0.37	4621
CUHP2 ^c	14.3% cold-worked	.1260	8.1	9.59	180

^aOFHC copper Intermagnetics General Corp. CDA-i01.

^bSame as ^a with an oxidizing anneal.

^c99.999% Asarco copper with an oxidizing anneal.

^dCorrected for size effect. Resistivity in $10^{-11} \Omega\text{-m}$.

^eRatio of resistance at 293 K to that at 4.2 K.

3.4.4.3 Experimental Procedure

As in the past^{4,5} the samples were cooled using a commercially available Helitran cryostat (Air Products and Chemicals Co.) which in this case had been modified so that eight samples could be irradiated simultaneously. The cryostat was supplied by a 500-liter Cryofab liquid helium dewar. The cryostat had been designed to be transferred to the bore of a superconducting solenoid for magnetoresistance measurements without warming the samples. The cryostat cold finger was made from an OFHC copper block, and had small grooves spark-machined into its face for the sample wires. The cold finger was first coated with a layer of epoxy (M-Line Type 610) and baked in air at 170°C for 4 hours to provide electrical insulation for the samples. Ni⁶⁰ dosimetry foils with lengths corresponding to the various sample gauge lengths

were attached between the grooves with epoxy. The samples were then spotted into position with General Electric Type 7031 varnish, taking care not to deform them. Small pieces of Kapton tape were used to insulate intersections between leads. The samples were then covered with a coat of epoxy to hold them in place and to provide good thermal contact to the copper block. The ends of the eight samples were spot-welded and indium-soldered together so that all eight samples could be connected in series to the current supply. The voltage leads were spot-welded and indium-soldered to sixteen 0.076 mm diameter copper wires leading to the voltage measuring apparatus. After mounting, the cold finger, samples, and epoxy were baked in air for 8 hours at 44°C to cure the epoxy and preanneal the samples well above the planned annealing temperature of 34°C.

The temperature of the samples was monitored by two carbon glass resistors (Lake Shore Cryotronics) from 4 to 50 K and by two copper-constantan thermocouples from 50 K to above room temperature. The thermocouples were connected to Omega reference junction compensators. The carbon glass resistors were mounted in the base of the copper cold finger block, 65 mm back from the samples, in order to minimize radiation effects on them. The thermocouples were located about 1 mm back from the samples. The temperature of the block was maintained at 4.2-4.4 K during the irradiation and measurements. A temperature rise of 0.2 K occurred whenever the neutron flux was introduced onto the samples. A small heater was mounted on the base of the cold finger for annealing. The uncertainty in temperature measurement is estimated to be $\pm .05$ K at low temperatures and $\pm .2$ K near room temperature.

Irradiation was performed using the Rotating Target Neutron Source (RTNS-II) with 0.23-m diameter targets. The machine produced an average flux of 1.2×10^{16} n/m²-sec. on the samples. The neutrons were nearly monoenergetic at 14.8 MeV, as mentioned above. The fluxes and fluences have been estimated from previous measurements of resistance changes in copper at RTNS-II, since the dosimetry foils have not yet been counted at the time of writing due to the high level of radioactivity of the cryostat. Later on, we intend to measure the activation of the nine

niobium foils which were located between the sample wires, using the technique described by Van Konynenburg.⁶ Total neutron output from the RTNS-II was recorded during the experiment using a counter attached to a proton recoil detector.

The magnetic field was produced by an IGC superconducting solenoid magnet built into a specially-designed Janis dewar with a room-temperature horizontal bore. The field was measured using a copper wire magneto-resistance probe built into the magnet. Since the sample positions were about 25 mm from the probe position, we decided to calibrate the field as a function of position to more accurately define the fields used in this work. For this purpose, we used a flux standard, search coil and integrator supplied by Don Nelson of the Magnetic Measurements Division at Lawrence Berkeley Laboratory (LBL). The portable flux standard, calibrated at LBL in a large (0.65 T) permanent magnet (Big Bertha) provided field accuracy of $\pm .005$ T. The uncertainty in the field is less than .01 T during sample measurements.

The potential drops across the samples and r series current measuring resistor were measured by a computerized data acquisition system which incorporated a Vidar Model 520 digital voltmeter and a Digital Equipment Corp. LSI-11 computer. This system was programmed to compute the resistance of each sample by measuring voltages twenty times in both current directions over a period of 2-1/2 minutes and then averaging the results. The system also measured voltages from an internal standard cell, one of the carbon glass resistors, one of the thermocouples, and an internal short. In addition, it recorded data from the proton recoil counter. The overall uncertainty in resistivity determination was $\pm .05 \times 10^{-11}$ Ω m. The largest contributors to this uncertainty were the voltage measurements, since the samples were necessarily short (less than 11 mm long).

The experimental procedure used before each leg of the irradiation was first to cool the samples to 4.2 K and measure their initial electrical resistances over the transverse field range from zero to 12 T in the RTNS-II hot work room. Then the cryostat and dewar were moved to the left target room of the RTNS-II, and the cryostat was mounted and

aligned behind the accelerator target. Electrical and helium gas lines to the control room were connected, and the control and monitoring equipment was moved from the hot work room to the control room and reconnected. (Two metal bellows pumps were used to overcome flow resistance in the helium gas lines from the target room to the control room.) After verifying that the resistance values had not changed, we began the neutron irradiation. During each irradiation leg, resistance measurements were made every 2×10^7 counts, which was equivalent to a fluence of about $3 \times 10^{19} \text{ n/m}^2$. After each leg of the irradiation was completed, we waited for a few hours to allow the shorter-lived radionuclides to decay, and then moved the dewar and cryostat (which was clamped to the dewar during the transfer) back to the hot work room. The control and monitoring equipment was likewise transferred to the hot work room and reconnected to the cryostat. During the transfer, we monitored the temperature of the samples and attempted (by pressurizing the dewar) to keep it at a sufficiently low value that annealing of defects would not take place. We were successful in doing so after the first and fourth legs, when the temperature rose to maxima of about 5 and 7 K respectively. However, during the transfers after the second, third, and fifth legs, the temperature rose to 55, 36, and 32 K respectively. These warmups appear to have occurred when sloshing of the helium in the dewar resulted in a small temperature excursion which apparently was sufficient to cause release of helium produced earlier from (n, alpha) reactions in the epoxy. The resulting gas in the vacuum space surrounding the cold finger gave rise to increased heat transfer and more warming, which in turn probably vaporized hydrogen, the principal radiolysis product of the epoxy, leading to more heat transfer. We found it necessary to evacuate the gas using a mechanical pump during the transfer, and to proceed slowly and carefully in moving the dewar. This gave better results, but the problem appeared to become more severe at higher fluence, presumably because of deterioration of the epoxy.

Once the equipment had been reconnected in the hot work room, we were able to perform post-irradiation measurements of magnetoresistance as well as isochronal annealing. Immediately after the first irradiation

leg, we measured magnetoresistance up to 12 T without annealing, and then proceeded to do 10-minute isochronal anneals at 10 K intervals up to 90 K, measuring the resistances in zero field after each anneal. These were followed by 10-minute anneals at 25 K intervals up to 290 K, again with zero-field resistance measurements. Finally, we performed a 30-minute anneal at 307 K (34°C), followed by magnetoresistance measurements at 4.2 K from zero to 12 T.

After the second, third, and fourth irradiation legs, we measured the magnetoresistances after the transfer to the hot work room, and then conducted isochronal anneals to 60, 115, 190, 265, and 307 K, each followed by a zero-field resistance measurement. The 307 K anneal lasted 30 minutes, while the others lasted 10 minutes. In addition, after the 60 K anneal following the fourth leg we measured the magnetoresistances up to 12 T.

After the fifth irradiation leg, we measured the magnetoresistances up to 12 T and then did 10-minute isochronal anneals at 40, 50, 60, 115, 165, 190, 215, 240, 265, and 290 K, each followed by a zero-field measurement. Then we performed a 30-minute anneal at 307 K, followed by zero-field measurement. Next we performed a 30-minute anneal at 307 K, followed by zero-field measurements. Then the cryostat was allowed to warm to ambient temperature (about 295 K maximum) for a few days (Christmas vacation). We estimate that the equivalent annealing time at 307 K was 6-8 hours. This was followed by zero-field measurements. Finally, we did 307 K anneals for 1/2 hour, 5 hours, and 45 hours, each followed by zero-field magnetoresistance measurements.

Shortly after the beginning of the first irradiation, a potential lead on one sample developed some current leakage to ground. Fortunately it was possible to remedy this problem by electrically floating the rest of the measurement circuit, and even though the leakage resistance varied widely over the course of the experiment, the data were not affected.

During one decay period while the samples were being held at 4 K, we experienced a laboratory-wide power outage. Fortunately, emergency power kept the bellows pumps operating and maintained the temperature below 7.5 K.

3.4.4.4 Results

Pre-irradiation values of the resistivity as a function of field for all eight samples are given below in Table 3.4.2. The field and resistivity values shown are averages of measurements made in stepping the field up to and down from 11.783 T.

Table 3.4.2. Pre-Irradiation Resistivities^a

Field ^b	0	1.816	3.827	5.791	7.694	9.767	11.783
Sample							
CUUN0	4.99	12.39	22.43	31.96	40.50	49.39	57.60
CUUN1	11.14	17.54	26.84	36.51	45.98	56.12	65.83
CUUN2	17.04	23.31	31.86	40.93	50.08	60.13	69.83
CUOX0	3.09	10.93	20.40	28.39	35.88	43.42	50.49
CUOX1	8.46	15.05	24.58	33.97	42.92	52.39	61.32
CUOX2	14.72	21.26	29.96	38.96	47.85	57.46	66.60
CUHFO	0.82	8.29	16.25	23.64	30.83	38.78	47.01
CUHP2	9.25	17.34	26.18	34.67	43.01	51.80	60.22

^aSize effect corrected. Values in units (± 0.05) of $10^{-11} \Omega m$

^bValues in tesla (± 0.005)

In order to make comparisons with the work of Coltman and Klabunde on these materials as precise as possible, the values of A/l for conversion of resistance measurements to resistivities were inferred from resistance measurements near room temperature, rather than from measured values of area (A) and gauge length (l). The standard thermal resistivity (ρ_{th}) adopted⁷ for this purpose was $1.7860 \times 10^{-6} \Omega m$ at a temperature of 36.1°C. Because of the small diameter of the wires and the high purity of some of the samples, corrections for size effects are important. These were made from the tables published by Dworschak et al.⁸ using a value⁹ for the product of the bulk resistivity and electron mean free path in copper ($\rho_b l$) of $7 \times 10^{-16} \Omega m^2$.

In comparing the values at zero field obtained here to those determined by Klabunde (Table 3.4.1) we note that all the recrystallized samples have somewhat higher resistivities ($+0.25$ to $+0.45 \times 10^{-11} \Omega m$)

while the cold-worked samples all have lower values (-1.3 to $-2.06 \times 10^{-11} \Omega m$). This is the result of two separate effects. For the annealed samples the increase is due to unavoidable cold work at the spot-welded potential leads. This would be a negligible effect for sample lengths ordinarily employed in resistivity measurements, but arises here due to the short gauge section required for RTNS-II irradiations. The lower values obtained for the cold-worked samples are the result of our pre-irradiation anneal at $44^\circ C$. The experimental schedule precluded a several-week pre-irradiation soak at the maximum annealing temperature of $34^\circ C$ as employed by Coltman and Klabunde.

During the remainder of this report we will consider only the results for unoxidized OFHC copper, since these three samples are most typical of stabilizers in present use in large magnets. A complete set of results will be reported at a later date.

Sample CUUN1 was used as a monitor during the irradiation-anneal cycles with the objective of reaching the same resistivity at 12 T at the conclusion of each irradiation. A raw data plot of sample resistance at zero field vs. proton recoil counts is shown in Fig. 3.4.1. The number of recoil counts is approximately proportional to the neutron fluence on the sample. This relationship is not exact because of small variations in the deuteron beam size and position. However, combining the five irradiation legs, this assumption is sufficiently accurate to derive a value for the saturation resistivity, ρ_{∞} , of $165 \pm 15 \times 10^{-11} \Omega m$ for this sample.

It is evident from Fig. 3.4.1 that a higher percentage of damage recovers in later cycles compared to that recovered in the first cycle. This is illustrated in Fig. 3.4.2 for all three OFHC samples. Here we have plotted the percentage of the accumulated resistivity change retained after 30 minute anneals at 307 K as a function of the total damage resistivity change produced at 4.2 K. For all three samples the percentage of retained damage decreases with increasing damage. As cold work is increased the damage retained decreases significantly. For example, at an accumulated damage resistivity of $100 \times 10^{-11} \Omega m$, the recrystallized sample retains $14.5 \times 10^{-11} \Omega m$, while the 7.5% and 14.3% cold-worked samples retain 13.2 and $11.7 \times 10^{-11} \Omega m$, respectively.

Fig. 3.4.1 Resistance of sample CUUN1 as a function of fluence (proton recoil counts) during 14.8 MeV neutron irradiation at 4.2K. The sample was annealed at 307K between each irradiation leg.

Fig. 3.4.2 The percentage of the total accumulated resistivity change at 4.2K retained after annealing at 307K as a function of the total resistivity change accumulated at 4.2K during neutron irradiation.

For comparison, we have also plotted the results of six other annealing studies following low temperature neutron irradiation. The three data points at low damage resistivities are from Takamura et al.,¹⁰ and they also illustrate the effects of increasing amounts of cold work. The three points at the damage resistivities comparable to the maximum accumulated values attained here, in order of increasing damage, are from Burger et al.,¹¹ Horak and Blewitt,¹² and Brown et al.¹³ Table 3.4.3 shows the initial sample resistivities, damage resistivities, and retained damage.

Table 3.4.3. Results of Isochronal Annealing Studies to 307 K

Neutron Source	Ref.	Neutron Spectrum	Initial ρ^a at 4.2 K	Damage ρ^a at 4.2 K	Annealing time (min)	Damage ρ^a retained after 307 K anneal	% Retained
JRR-3 (LHTL) ^b	10	Fast	1.5	2.9	6	0.75	25.8
"	10	"	5.8 ^e	3.2	6	0.63	19.7
"	10	"	9.2 ^f	3.2	6	0.55	17.2
FRM (LTIF) ^c	11	Reactor	-	94.3	3	15.8	16.8
CP-5 (VT53) ^d	12	Fast	0.82	116.2	5	14.5	12.5
CP-5 (VT53) ^d	13	Fast	3.80	127.0	5	18.5	14.6
RTNS-II	-	14.8 MeV	5.01	30.32	30	6.00	19.8
"	-	"	11.14 ^g	31.35	30	5.41	17.3
"	-	"	17.03 ^h	31.02	30	4.56	14.7

^aResistivities in units of $10^{-11} \Omega \text{m}$

^bLiquid Helium Temperature Loop at the JRR-3 Reactor at Jaeri (Tokai-Mura)

^cLow Temperature Irradiation Facility at the FRM Reactor at Munich

^dVT53 facility in CP-5 Reactor at Argonne National Laboratory

^eSample cold-worked by twisting 53%

^fSample cold-worked by twisting 106%

^gSample drawn to 7.5% reduction of area

^hSample drawn to 14.3% reduction of area

In plotting our data in Fig. 3.4.2, we have made small corrections to account for the fact that a portion of the recovery observed in each of the second through the fifth anneals resulted from annealing of damage which had been put into the samples during earlier irradiation legs. In order to be able to apply the present data, which resulted from half-hour anneals, to fusion reactor magnets, which will be annealed for much longer times, it was convenient to first make these corrections which put all the legs on the same basis. As it turned out, the corrections were quite small, since by far most of the annealing for each leg's damage occurred during the first half-hour. The maximum correction occurred for the fifth anneal. After this anneal, the measured total retained resistivity was $14.21 \times 10^{-11} \Omega\text{m}$, and the corrected value was $14.52 \times 10^{-11} \Omega\text{m}$.

The approximate agreement seen in Fig. 3.4.2 between our present results and those of earlier studies at damage resistivities comparable to our total accumulated damage resistivity is encouraging because it indicates that the percent retained is relatively insensitive to the detailed annealing schedule actually employed after one or two of our cycles. However, care should be taken in extrapolating these results to cases in which the damage is introduced in a significantly smaller amount before the anneal. In copper, for low damage resistivities, uncorrelated vacancy recovery occurs at or above room temperature.¹⁴ As one increases the amount of damage introduced before annealing, one finds that this recovery peak shifts to lower temperatures and is eventually incorporated into the correlated vacancy recovery peak of stage III. This is a consequence of the fact that the uncorrelated vacancies have to diffuse over smaller distances to be annihilated when there is a higher density of damage. For high purity copper subjected to 14.8 MeV neutron irradiation, preliminary evidence¹⁵ indicates that this shift occurs at damage levels corresponding to $\Delta\rho_{4.5\text{K}}$ of about $20 \times 10^{-11} \Omega\text{m}$, and results in a rapid decrease of the retained damage resistivity (after annealing at 307 K) from about 24% to about 18%.

As noted earlier, the magnetoresistivities measured as a function of field before irradiation have been tabulated in Table 3.4.2. We have

interpolated the measurements on the three unoxidized OFHC samples to produce magnetoresistivity values for them at $10.00 \pm .01$ T in the following states: before irradiation, after the first irradiation, after the first irradiation-anneal cycle, and after the fifth irradiation-anneal cycle. These values are tabulated in Table 3.4.4, and they span the full range of values of zero-field resistivity encountered with these samples.

Table 3.4.4. Resistivities at 0 and $10.00 \pm .01$ tesla
(expressed in $10^{-11} \Omega m$)

Sample	Before Irradiation		After Cycle 1 Irradiation		After Cycle 1 Anneal		After Cycle 5 Anneal	
	$\rho(0)$	$\rho(10)$	$\rho(0)$	$\rho(10)$	$\rho(0)$	$\rho(10)$	$\rho(0)$	$\rho(10)$
CUUNO	5.01	50.34	35.33	76.43	11.01	58.24	20.20	65.49
CUUN1	11.14	57.23	42.49	81.26	16.55	61.67	25.35	69.08
CUUN2	17.03	61.25	48.05	85.51	21.59	65.23	29.55	72.41

The results above involving the variation of zero field resistivity by cold work, irradiation, and repeated irradiation and anneal cycles, all fall on a single Kohler line¹⁶ to within $\pm 2\%$. This plot is compared to that obtained from the pre-irradiation variation with field in Figs 3.4.3 & 4. Here the points are again all within $\pm 2\%$ of a single line covering 1-1/2 orders of magnitude. For comparison, the Kohler plot obtained by Fickett¹⁷ on pure copper samples when purity, temperature, and field were varied is also shown. At high values of $H/\rho(0)$ the magnetoresistances are comparable, but at low values, corresponding to increasing $\rho(0)$ at constant field, the curves diverge.

3.4.4.5 Discussion

From the point of view of stabilizer materials for superconducting magnets, the results given above are significant in two respects: 1) A Kohler plot determined on a conductor solely by varying the field can also be used to describe the variation of the magnetoresistance as a

Fig. 3.4.3 Kohler plot for unoxidized OFHC copper. Data points were taken from Tables 3.4.2 (filled symbols) and 3.4.4 (open symbols). Dashed line is from Fickett.¹⁷

Fig. 3.4.4 Resistivity at 10 tesla as a function of resistivity at zero field for unoxidized OFHC copper. The open symbols are measurements taken at 10 tesla. The closed symbols are values deduced from the Kohler plot of Fig. 3.4.3. The dashed lines correspond to Fickert's Kohler plot $\pm 5\%$.

result of cold work, high energy neutron irradiation and subsequent annealing. This greatly simplifies the task of predicting the response of the magnetoresistance of actual conductors to changes resulting from fabrication of magnets and use in fusion reactors. 2) The fraction of accumulated damage remaining at 4.2 K after several irradiation-anneal cycles is nearly a factor of two lower than that previously estimated from studies of the annealing of lower-dose neutron damage.¹⁸ The consequences of these facts are explored in the following two examples.

1) The present results significantly increase estimated lifetimes for copper stabilizers. Table 3.4.5 presents past and present estimates of lifetimes for the stabilizer of the inboard leg of the toroidal field coil in the Engineering Test Facility (ETF) design. (This example is used because a detailed neutron spectrum was available for this design.) Also shown is an estimate based only on data available in 1978. For each entry, the year of the estimate, the allowed change in resistivity at zero field to increase the resistance at 8 and 12 T by 25%, the lifetime and the estimated accuracy are shown.

Table 3.4.5. Lifetime of the copper stabilizer in ETF

Year	$\Delta\rho^a(0)$ to increase $\rho(8T)$ by 25%	$\Delta\rho^a(0)$ to increase $\rho(12T)$ by 25%	Lifetime ^b MWy/m ²		Uncertainty (%)
			8T	12T	
1978	5.2	7.1	10	13	+100 - 50
1980	9.8	13.3	18	24	+100 - 50
1981	14.5	21.6	23	33	± 40
1983	16.3	18.9	38	44	+ 30 - 10

^a Resistivities in units of $10^{-11} \Omega\text{m}$

^b Assuming 10 annealing cycles

In early 1978, there were no studies available of magnetoresistance following neutron irradiation. There were, however, the extensive magnetoresistance measurements of Fickett¹⁷ and a large body of data¹⁸⁻¹⁹ from reactor irradiations at 4-15 K. The various data available from reactor irradiations gave values of the change of resistivity at zero field per displacement per atom (dpa) which differed from each other by as much as a factor of 2. Although codes for calculating neutron-induced displacements were highly developed and the dpa calculations were probably accurate to within $\pm 25\%$, the neutron spectra in most facilities were seriously in error as a result of flux and spectrum determinations based on much older neutron cross-section data. By 1979, in part because of the growing interest in neutron spectral effects in the fusion program many facilities had been recharacterized and discrepancies in $dp/d(dpa)$ were reduced to $\pm 25\%$.²⁰ At present we believe the uncertainty in this parameter is within $\pm 10\%$ as a result of improved neutronics calculations and careful experiments^{9,21} involving neutrons, ions and electrons.

Over the same time period magnetoresistance measurements after neutron irradiation at 4.2 K^{21,5} were refining our ability to predict changes in resistivity at field from changes at zero field. Most recently cyclic annealing experiments have been carried out in both a very soft spectrum² and here (at RTNS-II) in a very hard spectrum. Planned cyclic irradiations by Coltman et al. in a spectrum closer to that expected in fusion reactor magnets will complete these refinements. From the results which they have already in hand we expect that our results from the hard spectrum over-estimate the fraction which will be retained after annealing with a fusion reactor spectrum. Hence, we expect that the lifetime estimates in Table 3.4.5 will increase further.

2) Application of the present results to an advanced superconductor design shows that the stabilizer is not the determining factor for the lifetime of LHe-II-cooled (1.8 K) magnets. G. Carlson has prepared a preliminary design of the conductor pack to be used in the anchor and plug yin-yang coils for the Mirror Advanced Reactor Study (MARS).²² These coils present the most critical shielding problems in MARS because of local peaks in neutron source strength and limited space for shielding.

Fig. 3.4.5 Resistivity at 10 tesla of the copper stabilizer in the anchor and plug yin-yang coils of a MARS design as a function of time at full power.

In this design the determining factor for shield thickness was an assumed dose limit of 100 Mrad to the aluminized polyimide thermal insulation separating the cryocooled magnet case from the shield.

The conductor used for the MARS design is similar to that already in use in the MFTF-B yin-yang coils, but in MARS it would operate at 1.8 K and 10 T. Under these conditions the conductor would have a cryostability limit on stabilizer resistivity of $120 \times 10^{-11} \Omega m$, assuming a heat transfer limit of $1 W/cm^2$ of area wetted by the LHe-II. A design safety limit of 80% of this value would most likely be employed. (We note that the design operating limit for the MFTF-B yin-yang coils was 70% of the cryostability limit, and for the final MFTF-B choke coil it was 80% of the cryostability limit.) To estimate the response of the copper resistivity to irradiation it would receive with the MARS shield design, the calculated values of copper dpa per full power year (FPY) (cited by Carlson from the work of Maynard and El-Guebaly) were converted to $\Delta\rho(0)$ by the following equation: $\Delta\rho(0) = 300 \times 10^{-11} \Omega m (1 - e^{-360 dpa})$. This equation takes into account the high damage efficiency of the low energy neutrons in this spectrum.⁹ Using the annealing results and the observed field dependence for sample CUUN1 we calculated the time history of the resistivity at field. The results are shown in Fig. 3.4.5. As can be seen, only two annealing cycles are required to reach the design lifetime of 24 FPY.

3.4.5 Conclusions

1. A Kohler plot determined by varying only the magnetic field on a sample was adequate to describe the effects on the magnetoresistivity of subsequent variations in $\rho(0)$ due to cold work, irradiation, and annealing.

2. The fraction of irradiation-produced zero-field resistivity which remained after successive irradiation-anneal cycles decreased as the total amount of damage resistivity produced at 4.2 K was increased. This held true up to the maximum accumulated 4.2 K damage resistivity studied, which was $120 \times 10^{-11} \Omega m$.

3. From consideration of these data and a preliminary design of a LHeII-cooled magnet system (1.8 K), it appears that the magnetoresistivity of the stabilizer will not be the determining factor for shielding requirements in systems of this type which utilize polyimide thermal insulation.

4. Upon the completion of planned experiments at the Intense Pulsed Neutron Source by Coltman and Klabunde of ORNL using the same sample materials as used here, it will be possible, from all the data, to make accurate predictions of the magnetoresistive behavior of copper stabilizers under expected fusion reactor conditions.

3.4.6 Acknowledgments

We would like to express our appreciation to Charles Klabunde and Ralph Coltman, Jr. of ORNL for supplying the sample material and for helpful discussions and to Don Nelson of IRL for providing equipment for the magnet calibrations. We would also like to thank John Kinney, Ruth Nuckolls, Bruce Borman and Ruth Anderson for help in conducting the experiment and the dosimetry. Our gratitude also goes to the staff of RTNS-II, who willingly subjected themselves to our inconvenient operating schedule. Work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

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