22-8485(1)
4-13

J-14108

DR-2227-6

2-20048

UCID--20048

DE84 008531

EFFECTS OF LOW-TEMPERATURE FUSION NEUTRON
IRRADIATION ON CRITICAL PROPERTIES OF A
MONOFILAMENT NIOBIUM-TIN SUPERCONDUCTOR

M. W. Guinan, R. A. Van Konynenburg
and J. B. Mitchell

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March 22, 1984

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3.1 EFFECTS OF LOW-TEMPERATURE FUSION NEUTRON IRRADIATION ON CRITICAL PROPERTIES OF A MONOFILAMENT NIOBIUM-TIN SUPERCONDUCTOR -- M. W. Guinan, R. A. Van Konyenburg, and J. B. Mitchell (Lawrence Livermore National Laboratory)

3.1.1 SPN Task

IV.G.2 Radiation Damage in Superconducting Composites

3.1.2 Objective

The objective of this work was to irradiate a Nb₃Sn superconductor with 14.8 MeV neutrons at 4 K and measure critical current in transverse fields of up to 12 T, irradiating up to a fluence sufficient to decrease the critical current to below its initial value. Critical temperatures were also to be measured. The samples were to be kept near 4 K between the irradiation and the measurement of critical properties. This work is directed toward establishing an engineering design fluence limit for Nb₃Sn when used in fusion reactor superconducting magnets.

3.1.3 Summary

Seven samples were irradiated at the same time, including one Nb₃Sn "bronze process" monofilament and two Nb₃Sn "in situ process" samples, as well as two Mo-Si amorphous superconductors and two copper wires. They were mounted side by side on the cold finger of a continuous flow cryostat. The Nb₃Sn bronze process monofilament sample was supplied by LLNL using material from Brookhaven National Laboratory. The Nb₃Sn in situ process wires were supplied by Prof. T. Okada of Osaka University, from material made by K. Tasohama of Nihon University. The Mo-Si amorphous samples were supplied by Prof. K. Suzuki of Tohoku University. The copper wires were supplied by LLNL using material from Oak Ridge National Laboratory. In this report, the details of sample geometry, mounting and measurement procedure are given for all the samples, but results are discussed only for the Nb₃Sn monofilament. Results for the other samples will be presented at the First International Conference on Fusion Reactor Materials to be held in Tokyo in December, 1984.

The samples were repeatedly irradiated in five legs at 4-5 K with 14.8 MeV neutrons, up to a total fluence of about 1.35×10^{22} n/m². After each leg, measurements of the critical current and the magnetoresistance were carried out at transverse fields up to 12 T. The critical temperatures of the superconductors were measured before and after the entire series of irradiations. Although considerable effort was directed toward keeping the samples near liquid helium temperature over the entire course of the several-week-long experiment, production of gas due to (n,α) reactions and radiolysis of the epoxy adhesive as well as entry of particles of solid air and/or ice into the liquid helium system during refilling caused temperature excursions to 50, 38, 40, 29.5, 62.5, and 61.5 K during or after the second through fifth irradiation legs. However, based upon the work of others,¹ we do not believe that significant annealing of irradiation-produced defects occurs in Nb₃Sn at these temperatures.

After five cycles of irradiation and measurement the cryostat would no longer operate at 4 K and had to be warmed to room temperature. A broken current lead on one of the in situ Nb₃Sn samples was then repaired, the ice and/or solid air were allowed to evaporate, and the cryostat was recooled to 4.2 K. A final series of measurements was then made on critical current and magnetoresistance, and the critical temperatures were also remeasured.

The results of the irradiation up to a fluence of 1.35×10^{22} n/m² at 4 K on the Nb₃Sn monofilament were a monotonic, saturating increase in the critical current as a function of fluence, in general agreement with past irradiations of "non-optimized" Nb₃Sn. At 12 T, the critical current increased to three times its original value. At 4 T, the increase was by a factor of two. After room temperature annealing, partial recovery of the critical current increase was observed. At 12 T, the recovery amounted to 16% of the irradiation-induced change. At 4 T, it was 9.8%.

The critical temperature of the monofilament Nb₃Sn was observed to drop from 17.28 K before irradiation to 16.00 K after the full fluence. The measured value after room temperature annealing was 15.99 K.

This experiment reached the highest fusion neutron fluence yet achieved on cryogenic samples, and probably represents the practical maximum for the RTNS-II output available at present and the current cryostat system. The experiment required monitoring around-the-clock for more than three months and used over 10,000 liters of liquid helium. Unfortunately we were still unable to bring about the final collapse of the critical current, and this remains as a goal for the future. With the incorporation of larger targets on RTNS-II and the increase in accelerator current, it is anticipated that a significantly higher neutron output will be available in the future.

3.1.4 Progress and Status

3.1.4.1 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 can be 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. A recent study of the reactor plant equipment costs for the Mirror Advanced Reactor Study (MARS) showed that the magnet costs comprise 41% of the total cost of the reactor plant equipment.² Under these circumstances it has become increasingly important to quantify the 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 has shown that of these, the most radiation-sensitive components for conventionally-designed superconducting magnets are the epoxy-based insulators and the copper stabilizers.³ An analysis of a MARS preliminary design for a 1.8 K magnet system showed that the aluminized polyimide thermal insulation was the limiting component for radiation sensitivity.⁴ Most recently the concept of "radiation-hardened" superconducting magnets has been introduced.⁵ This would involve use of polyimide insulators and removal of the requirement for full cryostability over the entire use cycle. In this case the insulators could withstand a higher higher dose, and greater increases in the stabilizer resistivity could be tolerated. This could make the superconductors the most radiation-sensitive components. It is therefore increasingly important to determine the fluence limits for them. Nb-Ti has been studied previously at this Laboratory⁶ and others,^{7,8} and it now appears that the degradation in critical current in this material due to neutron irradiation saturates at about 20%, at least for room temperature irradiation. On the other hand, previous studies of Nb₃Sn and other A-15 structure superconductors have shown a catastrophic decrease in critical current to negligible values at sufficiently high fluence in these materials. This behavior has been attributed to disordering of the ordered A-15 lattice.

Past studies of high energy neutron effects in Nb₃Sn have been carried out both at 4 K and at room temperature. The 4 K studies⁹ were carried to a maximum fluence of 8×10^{20} n/m² with D-T fusion neutrons, and to 7×10^{21} n/m² with D-Be neutrons. (The flux is limited in these experiments by the necessity of moving back from the source to provide a vacuum space for thermal insulation.) In these experiments the critical current continued to increase up to the maximum fluences applied. The room temperature irradiations^{10,11} were carried to 5×10^{22} n/m² of D-T fusion neutrons, and in these experiments the critical current was observed to increase at lower fluences, and then to decrease to below the initial value at a fluence between 1 and 2×10^{22} n/m².

Since it is not possible to state a priori that the limiting fluences will be equal for 4 K and room temperature irradiations, we decided to attempt to irradiate at 4 K to a fluence sufficient to decrease the critical current to below its starting value, realizing that this would require continuous cryostat operation for at least several weeks.

While the critical current in high transverse magnetic fields is the main engineering property of interest, we decided to measure the critical temperature also, because it sheds light on the damage mechanism, and is relatively easy to measure. The critical field, while also of interest, is not accessible with our existing magnet except in heavily damaged material. We intend to send the samples to C. L. Snead, Jr. of Brookhaven National Laboratory, who will measure the critical fields at the M.I.T. National Magnet Laboratory.

3.1.4.2 Sample Material and Preparation

Seven samples were irradiated at the same time in this experiment. They comprised one Nb₃Sn monofilament, two Nb₃Sn in situ samples, two Mo-Si ribbons, and two copper wires. The monofilamentary Nb₃Sn sample (NBSN1) was made by the "bronze process." The wire was obtained from M. Suenaga (Brookhaven National Laboratory, and was chosen because it is well-characterized and has been used in earlier studies at Brookhaven and Argonne National Laboratories as well as at this Laboratory.

The starting material for NBSN1 was 0.35 mm in diameter, incorporating a niobium filament 95 ± 2 micrometres in diameter, surrounded by a bronze matrix. The U-shaped sample was formed so as to conform to the copper cold finger block of the cryostat, and was then heat-treated for 4 days at 700°C in an argon atmosphere to form the Nb₃Sn layer, which turned out to be 4.4 ± 0.2 micrometres thick. The sample was then electroplated with a 10-micrometre thick layer of copper to protect it from overheating during the superconducting-to-normal transitions to be performed during critical current measurements. Photomicrographs of a cross section of the sample material after electroplating are shown in Figures 3.1.1 and 3.1.2. Based on measurements from these photographs, the cross sectional area of the Nb₃Sn layer is about 1250 micrometres.²

The "in situ process" samples (NBSN2 and NBSN3) were supplied by Prof. T. Okada of Osaka University from wire material made by K. Yasohama et al. of Nihon University. The wire was 0.167 mm in outside diameter, including a central copper core, a layer of tantalum which acted as a diffusion barrier, and an outer layer of in situ-produced Nb in a Cu matrix. The in situ material was formed by tin plating a Cu-35 wt % Nb wire (having the Ta-protected Cu core) and heat treating.

The Mo-Si samples (MOSIA and MOSIB) were supplied by Prof. K. Suzuki of Tohoku University. They were ribbon-shaped, with cross sectional dimensions 1×0.2 mm. They were amorphous, having the composition Mo₆₈Si₃₂.

The copper samples (CUUN1 and CUHP0) were made from the same wire material (supplied by C. Klabunde of ORNL) that was used in our previous experiment.¹² CUUN1 had been made from Intermagnetics General Corporation "CDA-101" stock, and had received 7.5% cold work after a recrystallizing anneal. The stock was described as OFHC copper with a minimum of 99.99% purity. CUHP0 had been made from Asarco 99.999% pure copper and had been given an internal oxidation anneal. The copper wire samples had a diameter of 0.126 mm.

Fig. 3.1.1. Photomicrograph of Etched Cross Section of Sample NBSN1 Showing Central Nb Core, Nb₃Sn Layer, Bronze Matrix, and Copper Plated Layer.

Fig. 3.1.2. Photomicrograph of Cross Section of Core Region of Sample NBSN1 Showing Central Nb Core, Nb₃Sn Layer, and Part of Bronze Matrix

3.1.4.3 Experimental Procedure

As in the past, the samples were mounted on a commercially available Helitran cryostat (Air Products and Chemicals Co.) which in this case had been modified so that seven samples could be irradiated simultaneously side-by-side. The cryostat cold finger was made from an OFHC copper block, and had small grooves spark-machined into its face for the samples. A new set of three specially-designed tapered copper current leads was helically wound and epoxied to the cryostat to supply current to the Nb₃Sn samples while minimizing heat in-leak and Joule heating. The cryostat ground was used as the current return for all the Nb₃Sn and Mo-Si samples.

The cold finger was first coated with epoxy (M-Line Type 610) to provide electrical insulation for the samples while maintaining maximum thermal conductivity. Three coats were required to eliminate bare spots. The first coat was baked in air at 90°C for 5 hours. The second was baked at 75°C for 2 hours. The third coat was baked at 75°C for 5 hours.

Voltage-measuring leads made from 0.13 × 0.025 mm copper strips were attached to the samples by spot welding in the case of the copper samples, and by indium soldering in the case of the Mo-Si superconducting samples. (One of the potential leads on sample CUUN1 broke loose before irradiating and was repaired by indium soldering.) The gauge sections thus defined were varied to stagger the locations of the voltage leads. Final gauge sections are shown in Table 3.1.1. The uncertainty in gauge section measurement is ±0.005 mm.

Table 3.1.1. Sample Descriptions

Sample	Description	Gauge Length (mm)	Initial Conditions
NBSN1	Monofilamentary Nb ₃ Sn	11.650	T _c = 17.28 K
NBSN2	"In-situ" Process Nb ₃ Sn	11.334	T _c = 15.65 K
NBSN3	"In-situ" Process Nb ₃ Sn	12.590	Sample destroyed
MOS1A	Amorphous Mo ₆₈ Si ₃₂	7.967	T _c = 6.68 K
MOS1B	Amorphous Mo ₆₈ Si ₃₂	6.220	T _c = 6.91 K
CUUN1	OFHC Copper 7.5% Cold worked	8.930	ρ ₀ = 10.23 × 10 ⁻¹¹ Ω-m
CUHPO	ASARCO 99.9999% Copper	10.062	ρ ₀ = 0.95 × 10 ⁻¹¹ Ω-m

The samples were spotted into position with epoxy, taking care not to deform them. Small pieces of Kapton tape were used to insulate intersections between leads. The samples were covered with a coat of epoxy to hold them in place and to provide good thermal contact to the copper block. This assembly was

baked in air at 500°C for 20 hours. Niobium dosimetry foils with lengths corresponding to the various gauge lengths were epoxied over the samples and baked in air at 520°C for 5 hours. Finally, the thermal radiation shield and vacuum shroud were installed, and the cryostat was placed under vacuum and baked at 500°C for 18 hours. After correcting vacuum leaks in the cryostat and electrical shorts in the wiring, the cryostat was connected to the helium supply and measuring circuitry.

Liquid helium was supplied by a cart-mounted 500-liter Cryofab liquid helium dewar using a flexible transfer line. The dewar top flange incorporated two ports so that the dewar could be refilled while the cryostat was in operation. The cryostat had been designed to be inserted into the bore of a superconducting solenoid for critical current and magnetoresistance measurements without warming the samples.

Temperature was controlled by pressurizing the dewar and pumping on the helium gas exits with metal bellows pumps. One of these pumps was mounted on the dewar cart, and two were located in the RTNS-II control room. The 500-liter dewar was refilled approximately once a week from 500-liter vendor dewars by increasing the pumping speed on the cryostat exits while releasing the pressure in the supply dewar. In this way the samples could be kept cold during insertion of the transfer line and refilling.

A vane-type mechanical vacuum pump with a liquid nitrogen cold-trap was also mounted on the dewar cart and was used periodically, particularly while moving the dewar cart, to evacuate the cryostat vacuum space. This was found to be necessary in previous experiments, because helium is produced in the cryostat by (n, α) reactions, and hydrogen results from radiolysis of the epoxy. These can give rise to loss of temperature control in this type of cryostat.

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 ± 0.05 K at low temperatures and ± 0.2 K near room temperature.

Irradiation was performed using the Rotating Target Neutron Source (RTNS-II) with 0.23-m diameter targets. Centering of the cryostat on the neutron source spot was done using a laser centering device, and was checked after each irradiation leg by Polaroid autoradiography of the cryostat end window. The average centering error for the entire experiment was about 4 mm. The machine produced an average flux of 8.5×10^{11} n/m²-sec. on the samples for a total irradiation time of 440 hours, giving a total fluence of 1.35×10^{22} n/m². The neutrons were nearly monoenergetic at 14.8 MeV. 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 niobium foils which were located over the sample wires and on the outside center of the cryostat end window. 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 magnetoresistance probe built into the magnet. As described before,¹² this probe has been calibrated against the permanent magnet "Big Bertha" at Lawrence Berkeley Laboratory, and the uncertainty in the field is less than ± 0.01 T for this experiment.

On the Nb₃Sn samples, the measurements included critical current and critical temperature. On the Mo-Si samples, voltage-current characteristic curves were plotted, and critical temperatures and currents were measured. Magnetoresistance measurements were performed on the copper samples, as well as resistance measurements during irradiation.

The critical current measurements on the Nb₃Sn samples were carried out by inserting the cryostat nose into the bore of the magnet, ramping the field to the appropriate value, and ramping the sample current up until a 1 microvolt signal was observed across the gauge section, using an Astrodata model TDA-121 nanovoltmeter. Then the current was automatically switched off by a trip circuit to prevent overheating the sample. The sample currents were measured by monitoring the voltage drop across a 0.01 ohm standard resistor wired in series with a 50 A current supply and the sample, using a Hewlett-Packard model 3460B digital voltmeter and a strip chart. The critical current measurements were repeated each time and were found to be reproducible to within ± 0.1 A. Measurements were made at field values in the following order: 12, 10, 8, 6, 4, 2, and 0 T. It was not possible in all cases to measure the critical current at the lower field values, because it exceeded 35 A, which was the approximate limit for the current leads, before heating became significant.

The critical temperatures of the Nb₃Sn samples were measured by passing a current of about 10 mA through the samples and monitoring the voltage drops across them using the nanovoltmeter and strip chart, as the temperature was slowly raised and lowered through the transition. The resistance of the carbon resistor was simultaneously plotted on the same chart. The critical temperature was defined as the average of the 50% voltage drop points for the temperature raising and lowering, and the width of the transition was also noted.

The voltage-current characteristics of the Mo-Si samples were plotted by ramping a 200 mA current supply and monitoring the voltage drop across a 1-ohm standard series resistor and the sample, using the instruments described above. Critical current values were taken from these plots. Critical temperatures were determined as with the Nb₃Sn samples, except that the current used was 1 mA.

During irradiation and during magnetoresistance measurements the potential drops across all seven

samples 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 0.05×10^{-11} ohm-metre. The largest contributors to this uncertainty were the voltage measurements.

The resistance measurements were made primarily to study the behavior of the copper samples, but they were also helpful in interpreting the Nb₃Sn results, since the copper measurements provided information about neutron flux as a function of time and helped in determining the extent of temperature excursions. They also provided a way of detecting possible open circuits due to gross damage of the samples in case of failure of the epoxy mounting.

The sequence of events during the experiment was as follows: First, resistance measurements were made on the copper samples at 297 to 309 K to determine the starting values and to make comparisons with the previous experiment. Then the samples were cooled in stages, and resistance measurements were made at 250, 200, 150, 100, 50, and 4.2 K. Attempts to measure the critical current of sample NBSN3 resulted in its destruction because of an error in wiring. The problem was remedied, and the critical currents of the other superconducting samples were measured. Critical temperatures were also measured, and characteristic curves were plotted for the Mo-Si samples. All these measurements were made in the hot work room.

After these initial measurements, the dewar cart, incorporating the equipment described above, was moved to the left target room. The cryostat was mounted in a support clamp 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 5×10^7 counts, which was equivalent to a fluence of about 6×10^{19} n/m², and temperature was monitored and controlled by adjusting helium flow. 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 cart back to the hot work room. The control and monitoring equipment was likewise moved to the hot work room and reconnected to the cryostat. During the move, we monitored the temperature of the samples and attempted (by pressurizing the dewar and pumping on the exit line) to keep it at a sufficiently low value that annealing of defects would not take place. The two vacuum pumps were kept in operation by means of long extension cords.

In spite of these efforts, we still experienced brief temperature excursions to 50, 38, 40, 29.5, 62.5, and 61.5 K during or after the second through fifth irradiation legs. These presumably resulted from production of helium and hydrogen by (n, alpha) reactions and radiolysis of epoxy, respectively, build-up of ice and/or solid air particles in the helium flow tubes and expansion valve, and disturbances in cryostat flow during moving because of sloshing of liquid helium in the dewar. Aside from these excursions, the temperature was maintained between 4 and 4.5 K.

Once equipment was in place and reconnected in the hot work room, we repeated the measurements mentioned above, with the exception of critical temperatures, which were measured only at the completion of all the irradiation legs. The dewar was then refilled with liquid helium and moved back to the left target room. This was repeated for five irradiation legs.

After the fifth leg and the measurements which followed, the cryostat would no longer operate at 4 K, presumably because of the buildup of particles of ice or solid air in the flow channels and expansion valve. We therefore made critical temperature measurements on the superconductors, and then performed an isochronal anneal up to room temperature. During this warm-up, one of the current leads on sample NBSN2 opened up. After allowing the cryostat to remain at room temperature for 100 days, we repaired the current lead by indium soldering. The cryostat was then evacuated and re-cooled to 4.2 K. A final series of critical current and magnetoresistance measurements was then made, followed by measurements of critical temperatures.

3.1.4.4 Results and Discussion

The results reported here are only for the BNL monofilamentary Nb₃Sn superconductor, NBSN1. Changes in critical temperature, T_c , and critical current and current density, I_c , and J_c , will be compared to the results of previous experiments at both ambient and cryogenic temperatures.

Critical temperature

Changes in T_c observed as a result of irradiation with 14.8 MeV neutrons to a fluence of 1.35×10^{22} n/m² can be seen in Table 3.1.2. Measured temperatures at which the resistance of the sample reached 10%, 50%, and 90% of the normal state resistance, R_N , while the temperature was swept through the transition are listed for these conditions: before irradiation, after irradiation, and after a 300 K anneal.

The change in T_c due to irradiation varies from -1.28 K to -1.44 K for the three resistance levels. This change is compared on a damage energy basis to results from room temperature irradiations at RINS-I and the UC Davis cyclotron (30 MeV d-Be neutrons) and to 60 C irradiations in the Brookhaven High Flux Beam Reactor (HFBR) in Fig. 3.1.3. All of the samples in these studies are nominally identical to the present sample. The range of variation in initial T_c was 0.25 K and initial critical currents were all within 20% of our sample. Damage energy cross sections for all three facilities were taken from Snead, Parkin and Guinan.¹¹

Table 3.1.2. Measurements of Critical Temperature for BNL Monofilamentary Nb₃Sn (Sample NBSN1)

Resistance (% of R_N)	T_c (K)		
	Before Irradiation	After $1.35 \times 10^{22} n/m^2$	After 300 K Anneal
10	17.14	15.70	15.64
50	17.28	16.00	15.99
90	17.53	16.22	16.24

Experimentally observed T_c changes in irradiated A-15 superconductors are dominated by changes in long-range order.¹³ More subtle effects, due to point defects, radiation induced strain and suppression of the martensitic phase transformation are not yet completely understood.¹⁴ In the primary recoil energy range appropriate to fission and fusion neutrons, we expect disordering in different neutron spectra to scale with damage energy, from studies of Cu₃Au¹⁵ and neutron and heavy ion studies^{10,11,16,17} of Nb₃Sn.

As expected, Fig. 3.1.3 shows that ΔT_c in the present 4.2 K study scales with damage energy compared to ambient temperature reactor and high energy neutron irradiations. The error bars on ΔT_c represent the range of ΔT_c observed at 10%, 50% and 90% of R_N . The error bars in damage energy represent both fluence and damage energy cross section uncertainties. No error bars are shown for the HFBR irradiations, because of lack of detailed data. The present result demonstrates that T_c changes during neutron irradiation are not sensitive to spectrum (over the range expected in fusion magnets) or to irradiation temperature or annealing up to 300 K, when compared on a damage energy basis.

Fig. 3.1.3. Changes in temperature, ΔT_c , in monofilamentary Nb₃Sn as a function of damage energy for irradiations at HFBR (60°C), Δ , RTNS-1 (20°C), $\square$, and UCD (30 MeV d-Be) (20°C), $\circ$, are compared to the present result, $\blacksquare$, obtained at 4.2 K at the RTNS-11.

Critical current

The critical current, I_c , at 4.2 K as a function of field is shown in Fig. 3.1.4 before irradiation and after each leg of the irradiation. The 14.8 MeV neutron fluence is indicated for each curve. The same data are presented numerically in Table 3.1.3. As the figure shows, I_c is still increasing as a function of fluence at all fields. However, it does appear that we were close to reaching the maximum I_c enhancement. At 12 T, I_c has increased by a factor of 3.05 to a value of 6.4 A, corresponding to a critical current

density (J_c) of 5.1×10^9 A/m². Table 3.1.3 also includes values measured after a 300 K anneal.

Table 3.1.3. Critical Currents (A) of BNL Monofilamentary Nb₃Sn (Sample NBSN1)

RTNS-11 Fluence (10^{22} n/m ²)	Field (T)						
	12	10	8	6	4	2	0
0	2.1	4.1	6.9	10.7	17.4	31.2	(a)
0.35	4.3	8.2	13.5	19.8	26.6	(a)	(a)
0.59	4.9	9.3	15.2	22.4	32.5	(a)	(a)
0.87	5.7	10.3	16.5	24.2	34.7	(a)	(a)
1.09	6.0	10.8	17.1	24.9	35.5	(a)	(a)
1.35	6.4	11.2	17.5	25.3	35.8	(a)	(a)
After 300K Anneal	5.7	10.2	16.2	24.0	34.0	(a)	(a)

(a) $I_c > 36$ A

In Fig. 3.1.5 the present results for I_c at 10 T and 4.2 K are compared to previous results on nearly identical samples. In addition to the ambient temperature data for which the corresponding ΔT_c values are given in Fig. 3.1.3, I_c data from the 4 K irradiations of Scanlan and Raymond⁹ at both RTNS-1 and the U.C. Davis cyclotron (30 MeV d-Be spectrum) are included. One additional data point¹⁸ from a 4 K irradiation in a fission spectrum (the Argonne CP6, VT53, facility) is also included. For all the data, the ratios of critical current to the initial value, I_c/I_{c0} , are plotted versus accumulated damage energy in eV/atom.

Fig. 3.1.4. Critical current, I_c , as a function of field, H , after each irradiation leg. Fluences are given in units of 10^{22} n/m² for each curve.

Fig. 3.1.5. Fractional changes in critical current I_c/I_{c0} as a function of damage energy for 4.2 K irradiations. $\blacksquare, \blacktriangle, \bullet, \blacktriangledown$ are compared to those obtained in ambient temperature irradiations. $\square, \triangle$.

Two aspects of the present results were unexpected. First, the magnitude of the I_c enhancement is nearly twice that observed in the ambient temperature irradiations. We had expected some increase, since both the change in normal state resistivity, $\Delta\rho_n$, and ΔI_c are observed to recover 10 - 25% at 300 K.

following low temperature irradiation.^{1,19,20} Second, the enhancement persists to a damage energy greater than 0.33 eV. In all previous work¹⁶ the maximum enhancement occurred at damage energies less than 0.30 eV.

The increase in I_c observed here is much too large^{17,21} to result only from increase in the upper critical field, H_{c2} , which occurs at low damage exposures as a result of increase in the normal state resistivity. (At higher exposures the decreases in T_c and the electronic specific heat coefficient, γ , overwhelm the increase in ρ .) The increase must result primarily from flux pinning by the irradiation produced disordered zones. This is better illustrated by a plot of the volume pinning force, $F_p = J_c H$, as a function of reduced field $h = H/H_{c2}$.

The value of H_{c2} at each measured fluence was estimated by extrapolating J_c to zero. For this purpose we assumed¹⁹ F_p is proportional to $h^n(1-h)^2$ and fitted n and H_{c2} to the data. The resulting initial value is close to that measured²² for similar samples, and the increase inferred at a fluence of 8×10^{21} n/m² is just slightly larger than that measured²² for the sample irradiated at room temperature to the same fluence. The value obtained after annealing to 300 K will be checked by actual measurements. The results are shown in Fig. 3.1.6. The maximum value of F_p is increased by a factor of two to 1.2×10^{11} N/m³ and the reduced field at which the maximum occurs shifts from $h = 0.23$ to $h = 0.30$.

Fig. 3.1.6. Volume pinning force, F_p , as a function of reduced field, H/H_{c2} , before irradiation, after 1.35×10^{22} n/m² and after a 300 K anneal.

3.1.5 Conclusions

1. Critical temperature changes in Nb₃Sn due to neutron irradiation are not sensitive to the spectrum (over the energy range expected in fusion reactor magnets) or to irradiation temperature or to annealing up to 300 K, when compared on a damage energy basis.
2. The critical current of monofilamentary Nb₃Sn continues to increase under 14.8 MeV neutron irradiation at 4 K up to a fluence of at least 1.35×10^{22} n/m² (or a damage energy of 0.33 eV/atom).
3. The increase in critical current density observed under these conditions is at least twice as

large as the maximum increase observed in HFBR irradiations at 60°C, and also appears to be larger than that from room temperature 14.8-MeV neutron irradiation. More room temperature 14.8 MeV neutron data are needed to clarify this difference.

4. The magnitude of the increase in critical current density is too large for it to result only from the observed increase in H_{c2} . Flux pinning therefore must play an important role.

3.1.6 Acknowledgments

We are grateful to a number of people who helped us to carry out this experiment. F. Dishong performed heat treating on the Nb_3Sn sample. Metallography was carried out by P. Ambalal, T. Dkade and P. Hahn helped in wiring the cryostat. B. Borman provided mechanical support and assisted in operating the experiment. R. Nuckolls provided dosimetry support and assisted in operation. C. Ichihara, T. Lavietes, and M. Traifal served as operators. W. Shaw typed the manuscript. The RTNS-II staff provided neutrons, and willingly adjusted personal schedules to meet the needs of the experiment.

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