Paper F-2

SHIELDING OF SPACE VEHICLES BY MAGNETIC FIELDS

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Abstract

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Protons emitted by solar flares represent a significant radiation hazard to crew members of an interplanetary space vehicle. Shielding the vehicle from charged particles by the use of magnetic fields is an obvious possibility. Reduction of secondary radiation otherwise produced in bulk shielding is an added incentive to study magnetic shielding. The feasibility of this type of shielding was reported by R. H. Levy, who utilized the properties of new superconducting materials. A program has been initiated at General Dynamics/Fort Worth to study various aspects of magnetic shielding of space vehicles. In one phase of the program, a procedure has been formulated and coded for the IBM-7090 computer for rapidly computing the field of an optimized superconducting solenoid.

In another phase, samples of NbZr wire have been irradiated with neutral particles from two sources. Preliminary results are now available. Irradiation with 10^{11} neutrons per cm^2 from the D-T reaction showed no change in the critical current versus magnetic field curve. Irradiation with 10^{16} neutrons ($>$2.9 Mev) per cm^2 showed a slight downward shift in the critical current. It is difficult to say whether this shift was due to the irradiation or due to the environment during the irradiation.

Introduction

A program for studying the magnetic shielding of space vehicles against charged space radiations was initiated approximately a year ago at the NARF facility of General Dynamics/Fort Worth. Two assumptions are basic in this program:

1. Magnetic shielding against charged space radiations is feasible for space vehicles;
2. Superconductors even more effective than existing superconductors will be developed.

The first assumption was based on a study by R. H. Levy[1]. The second assumption was made after a survey of the literature[2,3] and after conferences with many active research workers in the field of superconductivity.

This program was broken down into the subdivisions:

1. Design of optimized superconducting magnets;
2. Shielding effects of magnetic fields against charged particles;
3. Optimized solenoid configurations for shielding prescribed volumes;
4. Structural support design, refrigeration, and power sources for a superconducting electromagnet system;
5. Protection of the superconducting magnet system against quenches;
6. Experimental investigation of the effects of different kinds of radiations, particularly neutrons and protons on the properties of superconducting materials.

Work is being actively carried out on phases 1, 2, and 6. In this paper, a discussion is given of the analytical and experimental activities at GD/FW.

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[1] R. H. Levy, Radiation Shielding of Space Vehicles by Means of Superconducting Coils. Avco-Everett Research Laboratory (April 1961, Contract AF04(647)-278.

[2] J. E. Kunzler, "Superconductivity in High Fields." Rev. of Mod. Phys., 33, 4 (October 1961).

[3] J. J. Haak, G. D. Cody, P. R. Aron, and H. E. Hitchcock, (RCA Labs, Princeton, N. J.), "Some Physical Properties of Deposited Nb_3Sn." High Magnetic Fields, MIT Press (Cambridge) and John Wiley and Sons, Inc., (New York), 1962.

Problems and Computational Techniques for Superconducting Magnets

For a given temperature in the temperature range for which a given material is superconducting, there is for any transverse magnetic-field strength within a definite range of magnetic-field strengths a current I_c, the critical current, so that for currents less than I_c the superconductor behaves as a superconductor and for currents greater than I_c the superconductor behaves as a conventional or normal conductor. The superconductor goes normal or quenches at $I = I_c$. This experimental fact is added to the classical methods for computing the magnetic fields arising from current-carrying circuits to develop methods for computing the fields due to superconducting electromagnets. For example, at a given location within the windings of a superconducting solenoid, the transverse magnetic field would be the vector sum of the transverse external magnetic field and the field generated by the solenoid. The current carries by the superconducting winding at this point would be fixed from above by this total transverse magnetic-field strength. Methods for computing the magnetic-field intensities generated by superconducting solenoids have been developed by a number of workers[4,5]. These methods are discussed in Reference 6.

To apply these methods, it is necessary to have procedures for rapidly computing the field due to a superconducting solenoid both within and without the solenoid structure.

A IBM-7090 computer FORTRAN code, MAGFI, based on classical formulae for solenoids having a rectangular cross section, has been prepared. This code, furnishes a very fast means for mapping the field of a solenoid.

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4. R. W. Boom, and R. S. Livingston, "Superconducting Solenoids." 1961 Western Electronics Show and Convention, San Francisco, August 22-25, 1961.

5. W. F. Gauster and C. E. Parker, "Some Concepts for the Design of Superconducting Solenoids." High Magnetic Fields. pp. 3-13. MIT Press (Cambridge) and John Wiley and Sons, Inc. (New York), 1962.

6. N. Edmonson, Magnetic Field Shielding Against Charged Space Radiations. GD/FW Report FZK-9-181 (to be published).

If the magnetic field of a solenoid is mapped by MAGFI, the solenoid requirements for superconducting material and structural support for the superconductors can be reduced in the following way. In general, the maximum field of a rectangular solenoid occurs at the longitudinal midpoint of the inner surface of the solenoid. The field decreases in all directions from this point. Thus, if the solenoid were wound in ring-shaped segments, the number of turns in each segment could be reduced and the current raised in accordance with the critical current-magnetic field relation of the superconducting material, so as to keep the ampere-turn constant. This technique would lead to a reduction in material and size for the solenoid for the same magnetic field strength. An optimization procedure is currently being developed for the IBM-7090.

Shielding Effects of a Magnetic Field

The shielding effect of a magnetic field is investigated by use of Störmer's concept of "forbidden regions" and by computations of the orbits of individual charged particles in a magnetic field.

The basic concepts of Störmer's theory are given in References 7 and 8. Both of these references are concerned with geomagnetic effects on charged particles. The geomagnetic field is approximated by a dipole. For the much smaller space vehicle, the dipole approximation is not sufficiently accurate. A more realistic approach is to compute the vector potential of a loop current. The equivalent solenoid may then be computed. Perhaps a more realistic procedure is to compute a solenoid optimized as described earlier and then to compute the vector potential of each one of the ring-shaped segments of the solenoid. Then the total vector potential of the solenoid is the result of a summation of the elementary vector potentials. The computations of the vector potential of a ring-shaped current is a classical procedure to be found in any advanced treatise on electromagnetism[9]. Its application to the determination of regions open to charged particles and closed (or forbidden) to charged particles is discussed in References 1 and 6.

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7. M. S. Vallarta, "Theory of Geomagnetic Effects," Handbuch der Physik, Band XLVI/1, 88, Springer, Gottingen, 1961.

8. C. Störmer, Polar Aurora, Clarendon Press, Oxford, 1955.

9. W. R. Smythe, "Static and Dynamic Electricity," 2nd Ed., New York; McGraw-Hill Book Co., (1950).

In applying the Störmer procedure to shielding problems, a shut-off energy is selected, so that the total dose for all charged particles having energies above this shut-off energy is tolerable. For more exact information about the effects of charged particles in the neighborhood of this pre-selected shut-off energy orbit, computations may be necessary. Such computations are classical[7-10].

The Experimental Program

A major goal of the present experimental program at GD/FW is to investigate the effects of neutral particle irradiation on a superconducting material. At present, the principal interest in superconductors at GD/FW is for use in producing a large volume magnetic field for shielding a space vehicle. Clearly, magnetic shielding is not effective against neutral particles; however, in the event that the space vehicle is nuclear-powered, it is essential to determine whether neutral radiation will affect the superconducting properties of the material. The techniques developed during the phase of neutral irradiation can be used during the later phase of charged-particle irradiation.

The maximum current density of a superconducting material or alloy is not only a function of the environmental conditions during its use, but also its purity, crystal structure, and the manufacturing process used to produce the material. Work-hardening during the manufacturing process makes some materials better superconductors. For example, the maximum current density of extruded NbZr wire increases by 50% between 20- and 10-mil wire. Since it is known that irradiating a material can change the structural strength and crystal structure, one may expect a change in maximum current density after irradiation. Changes are particularly expected at low temperatures, where lattice defects may remain frozen in the material.

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7. *Ibid.*
8. *Ibid.*
9. *Ibid.*

10. L. Paige, *Electrodynamics*, New York, Van Nostrand.

Measurement of the critical current (I_c) as a function of an applied external magnetic field is the method selected to observe changes due to irradiation. The critical current is described as the current necessary to cause a small resistive voltage to appear across the sample. All measurements are made in liquid helium at ambient pressure (approx. 4.2°K) and in a magnetic field of 10 to 15 Kgauss.

NbZr wire being used in the experiment is 0.014 inch in diameter, hard drawn (>99% reduction), and of a Nb 25 at. % Zr alloy.

The Dewar used is a conventional liquid-nitrogen-jacketed, glass, helium Dewar with a liquid helium capacity of approximately one and one-half liters. Current leads are brought into the dewar through liquid nitrogen to decrease liquid-helium boiloff. This setup allowed about 45 minutes working time. (See Fig. 1.)

The circuit used to measure the critical current is shown in Fig. 2. A Keithly Model 149 millimicrovoltmeter is used to measure the voltage across the sample. Its output is attached to the y axis of a Sylvania Type B-281 x-y recorder with the x axis attached to a precision resistor through a D-C amplifier to record the current. The current is supplied by two large storage batteries and controlled through a transistorized series amplifier.

The sample holder (see Fig. 3) is cut so that it will fit into the 5/8-in.-diam Dewar tip and hold the sample in the center of the Dewar. The sample is mounted parallel and coincident to the center plane midway between the poles of the magnet. All samples are copper-plated, except for three lengths between the four contact points. The contact between the superconductor and current lead is made by winding 12 inches of wire around the current lead and then soft-soldering with 60/40 lead-tin or indium. The contact resistance with these junctions was on the order of 5×10^{-6} ohms.

Two pieces of NbZr wire were irradiated at ambient temperature in the Ground Test Reactor and compared with control samples. The total neutron flux was 10^{17} neutrons (>2.9 Mev) per cm^2. X-ray diffraction and optical magnifications to x 1000 showed no observable change in the crystal structure. The micro-hardness test, using a Knoop micro-hardness tester and converting the readings to the Rockwell "c" hardness scale, showed a change of from 30.5 to 28.6 on the hardness scale after irradiation. Another sample that was completely annealed by heating changed from 30.8 to 25.1. Due to the dependence of the current density on work-hardening these measurements indicate a plausible explanation for any possible change in the critical current due to irradiation.

Three different samples have been irradiated in the Ground Test Reactor at ambient temperature, with a total flux of $>10^{16}$ neutrons (>2.9 Mev) per cm^2. Preliminary results of several measurements of the critical current before and after irradiation are shown on the bottom curve of Fig. 4.

Effects of neutron irradiation are being studied by irradiating samples with 14.2-Mev neutrons from the D-T reaction using a Cockcroft-Walton type accelerator. The critical current as a function of the magnetic field is measured before, during, and after irradiation with the sample temperature kept at $4.2^{\circ}K$ during the experiment. Preliminary results of this irradiation are shown by the top curve of Fig. 4.

Summary of Experimental Results

The upper curve of the accelerator irradiation shows no significant change, but the lower curve with reactor irradiation is suggestive of a downward shift in the critical current curve. One other sample was irradiated at the accelerator and two other samples were irradiated with the reactor. Those data show similar trends. However, the reproducibility from one run to the next and between samples leaves something to be desired. The spread in the points is comparable to the apparent effects observed with the reactor irradiation. Note that the accelerator exposure was only 10^{11} neutrons compared to more than 10^{16} from the reactor.

The data then seem to suggest that there may be an effect at the higher exposures, but our experimental techniques must be improved to reach a firm conclusion. This will be the next step in this current phase in the experimental program at GD/FW. Beyond that, the next phase in the overall program will include the construction and testing of optimized magnets.

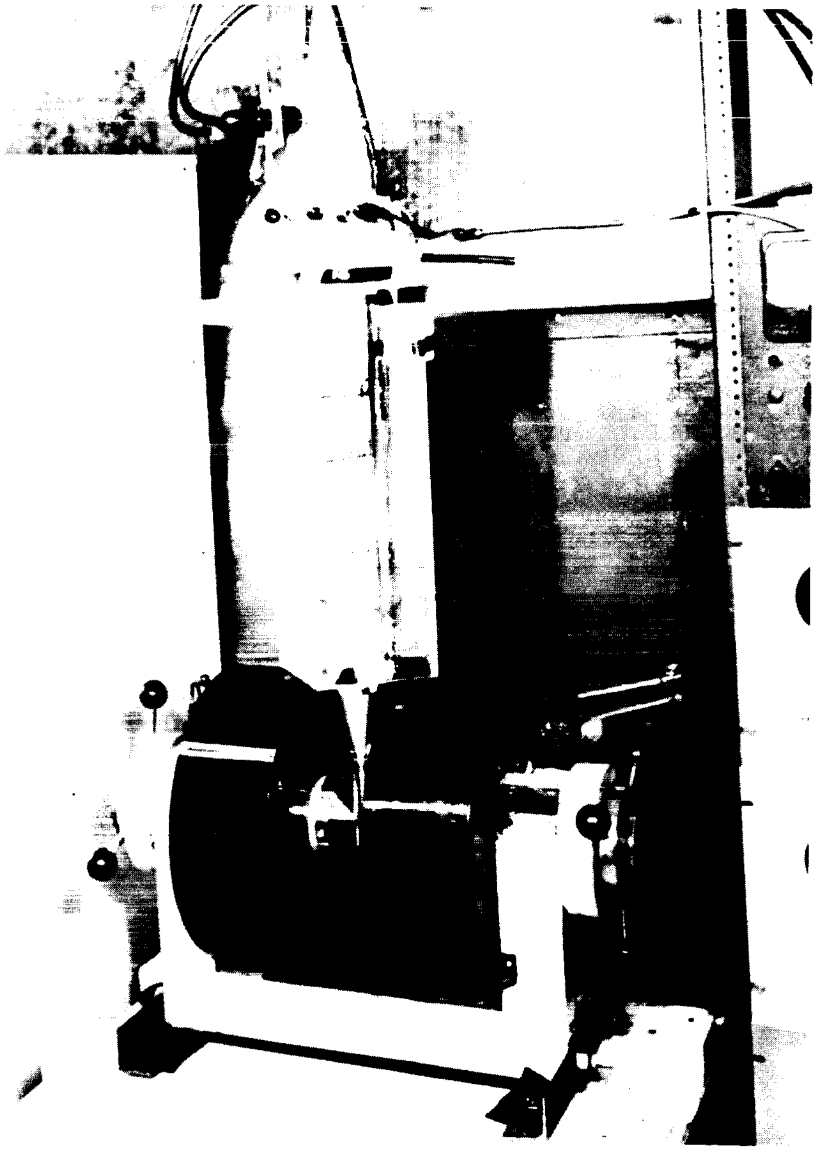

FIGURE I. DEWAR AND MAGNET

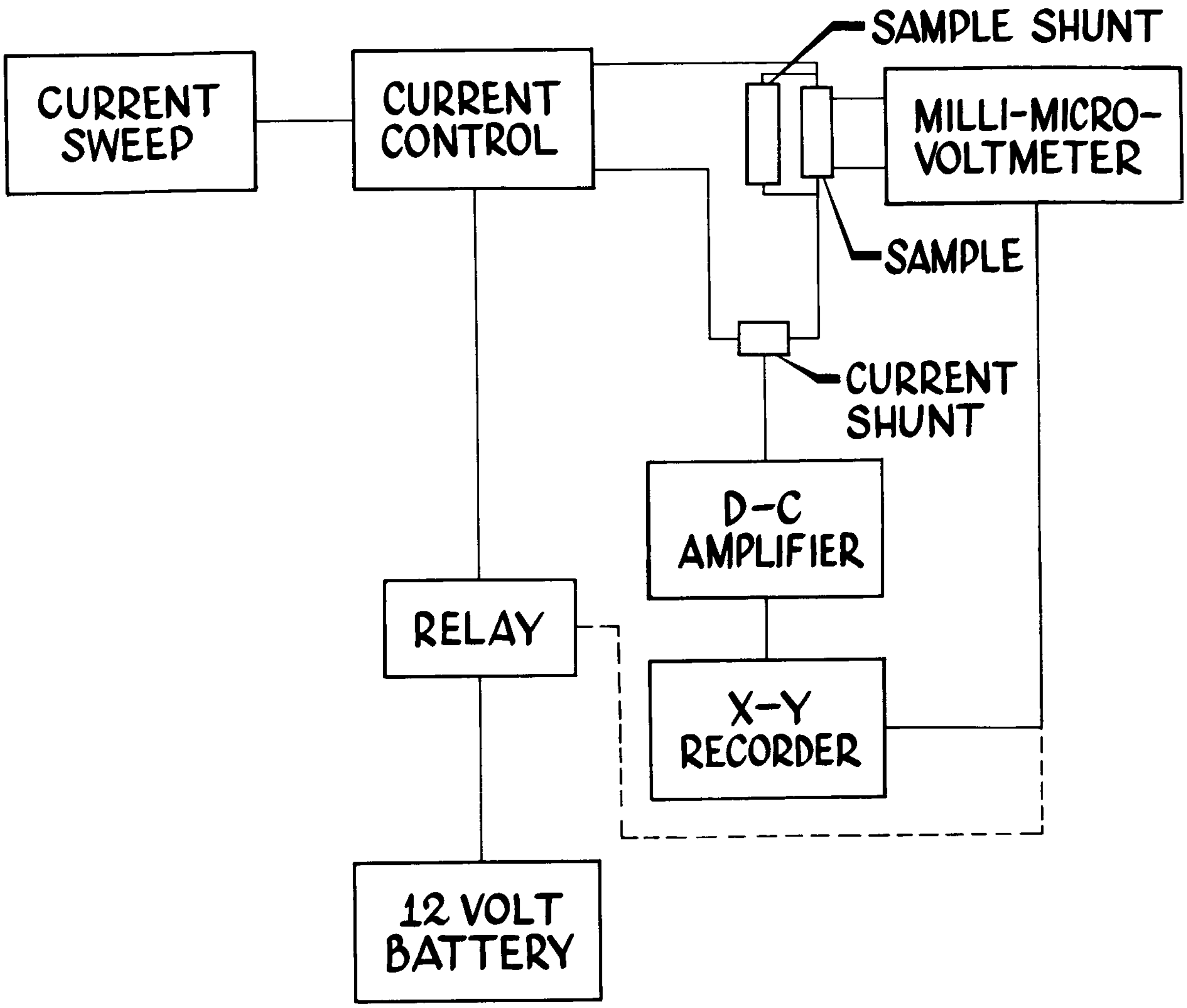

FIGURE 2. BLOCK DIAGRAM OF ELECTRICAL CIRCUIT

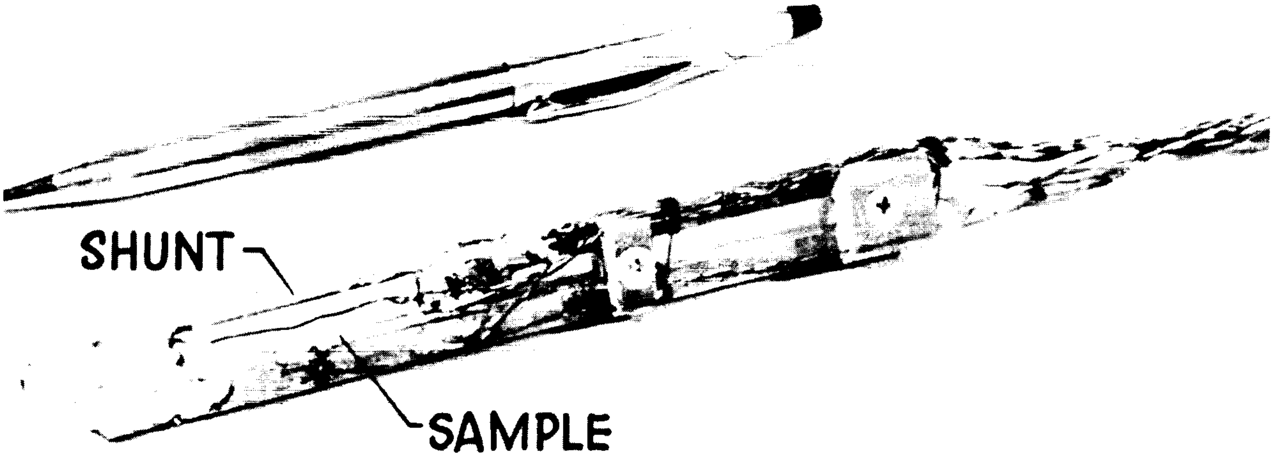

FIGURE 3. SAMPLE HOLDER WITH NbZr SAMPLE

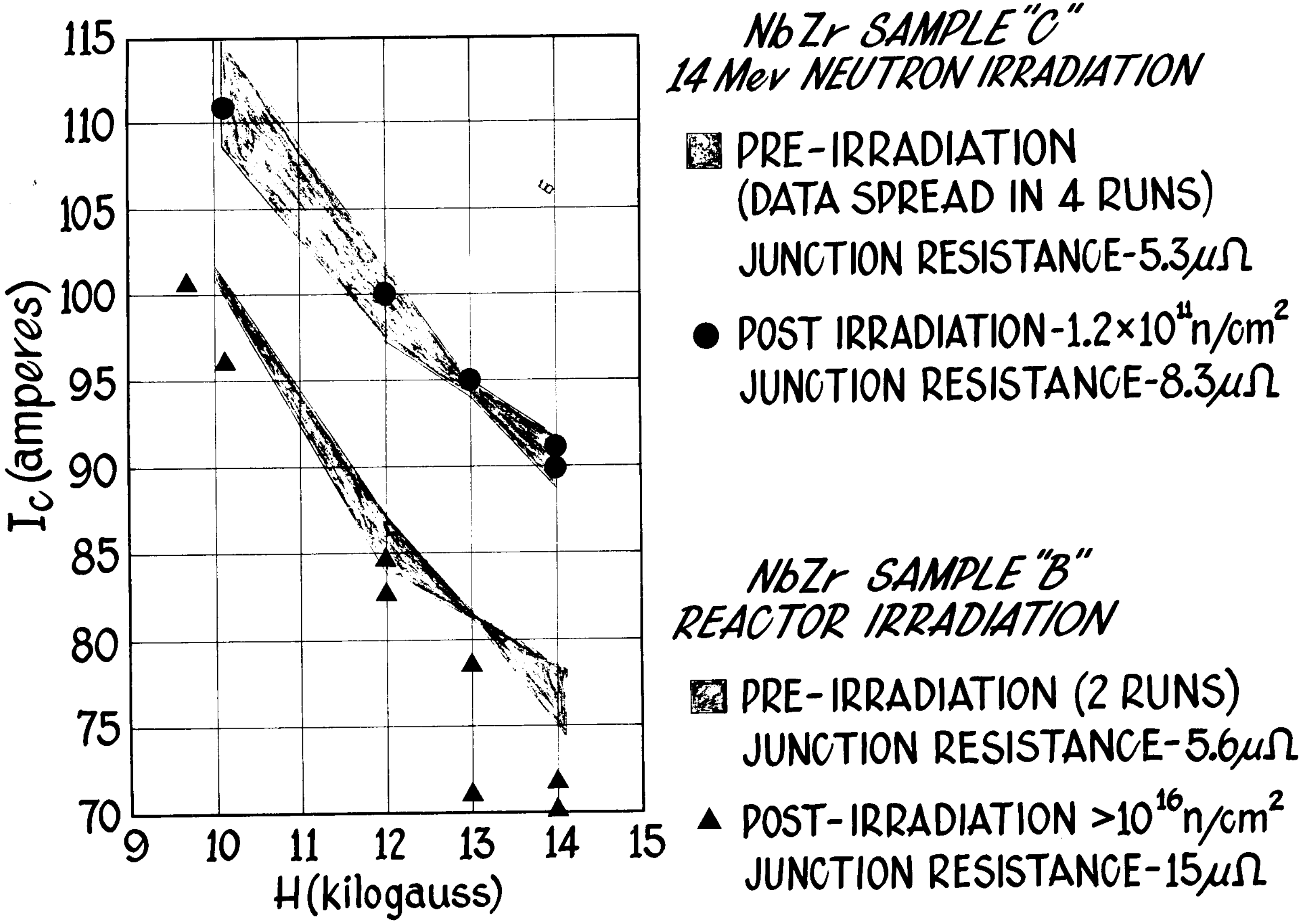

FIGURE 4. PRELIMINARY RESULTS