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ABSTRACT

Performance data are presented for tests of 51-cm bore solenoids operated at temperatures below 2 K. The magnet coils are wound of vapor-deposited Nb_3Sn ribbon which was copper-clad for one of the magnets and silver-plated for the others. Coil protection was provided by cross-layer shorting strips which also provide very limited stabilization. Each coil was designed to produce a 4.0-T center field. Results obtained at the low temperature are compared with those obtained at 4.2 K. System description and charging characteristics are included in the discussion.

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SUMMARY

Performance data obtained with large bore superconducting solenoids operated in superfluid helium are presented and compared with results obtained at 4.2 K. The magnet coils are wound of vapor-deposited Nb_3Sn ribbon, which was copper-clad for one of the magnets and silver-plated for the others. Coil protection and very limited additional stabilization was provided by cross-layer shorting strips. The copper-clad superconductor was superior in stability and maximum current density. Performance enhancement achieved by operation at the low temperature (<2 K) was as much as a factor of 1.6 for the silver-plated conductor and 1.3 for the copper-clad conductor. Current densities of 14 000 and 17 000 amperes per square centimeter including internal structure were obtained for the silver-plated and copper-clad conductors, respectively.

INTRODUCTION

Some of the work of the NASA Lewis Research Center is aimed at future power and propulsion needs for space flight. As a result, the attainment of high current densities and light weight is one of the goals of Lewis magnetics research. In mid-1965 a contract (NAS3-7928) was entered into with RCA to supply superconducting magnets for a plasma physics facility. Although these magnets are not intended for flight use, many of the requirements were nearly as stringent as for flight hardware. Design philosophy for these magnets was to obtain the highest possible field strengths consistent with providing the required bore diameter and the requirements for access between coils for plasma excitation and diagnostic apparatus. The access requirement made high current densities mandatory. The additional requirements of providing adequate strength and protection for the coils reduces the current densities attainable. The results of the tests on these magnets are the subject of this paper.

Significant advances in superconductor technology have been made in the past few years, particularly in the area of stabilized conductors. However, the current densities

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attainable with the fully stabilized conductors are as yet not sufficiently high to satisfy the design requirements for these magnets. Because of the obvious advantages offered by partial conductor stabilization, the contract was amended for one of the magnets to allow the use of a conductor that provided more stabilization than was obtained with the conductor material used in the other three magnets.

The winding bore of the magnets is 51 centimeters, each coil is 10 centimeters long, and in an array of four, spaced 15 centimeters apart, the design field is 7.2 tesla. Maximum field at the windings for the design current is calculated to be about 9.5 tesla.

Coil design was based on extrapolation of test results from a feasibility study and experience gained in the construction of another large, but nearly concurrent magnet (refs. 1 and 2). It became evident early in the test program that the design goal of 7.2 tesla was optimistic.

Performance enhancement of Nb_3Sn magnets when operated in superfluid helium was demonstrated several years ago (refs. 3 to 5) and at the Lewis Research Center. Figure 1 shows magnet characteristics obtained at Lewis using a 15-centimeter bore, 16-kilojoule test coil. These results are very similar to those obtained by Sampson, et al., (ref. 5) for a 3-centimeter bore solenoid. A region of reduced performance exists at temperatures between 4.2 K and the lambda point (2.17 K), with improved performance obtained below the lambda point. Increases of 10 to 15 percent in quench current were obtained in the latter region. The increased energy released in the flux jumps at the lower temperatures causes the reduction in quench current below 4.2 K, but this reduction is not of sufficient magnitude to offset the increased cooling effectiveness in the superfluid region at temperatures below 2 K.

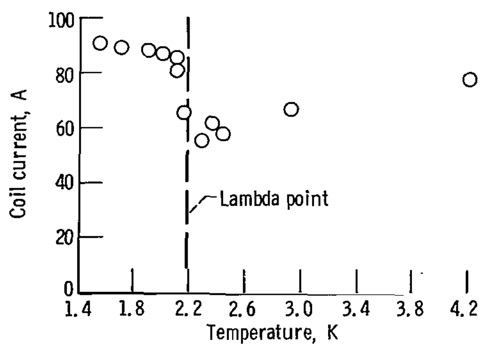

Figure 1. - Quench current as function of temperature for 15-centimeter bore test coil.

Therefore, in order to maximize the performance of the 51-centimeter bore magnets, it was decided to take advantage of the unique characteristics of superfluid helium.

MAGNETS AND APPARATUS

The superconducting material used in the magnets is Nb_3Sn vapor-deposited on a Hastelloy substrate with silver plating for three of the magnets and copper cladding for the fourth magnet. The overall cross section of the copper-clad material is approximately 20 percent greater than for the silver-plated material. Conductor dimensions are approximately 5 by 90 mils (0.127 by 2.29 mm) with some differences in thickness for the different parts of the magnets and, of course, for the copper-clad material. As a result of the rather small size of the conductor and large number of turns in magnets of this size, inductances are very high and charging times are long.

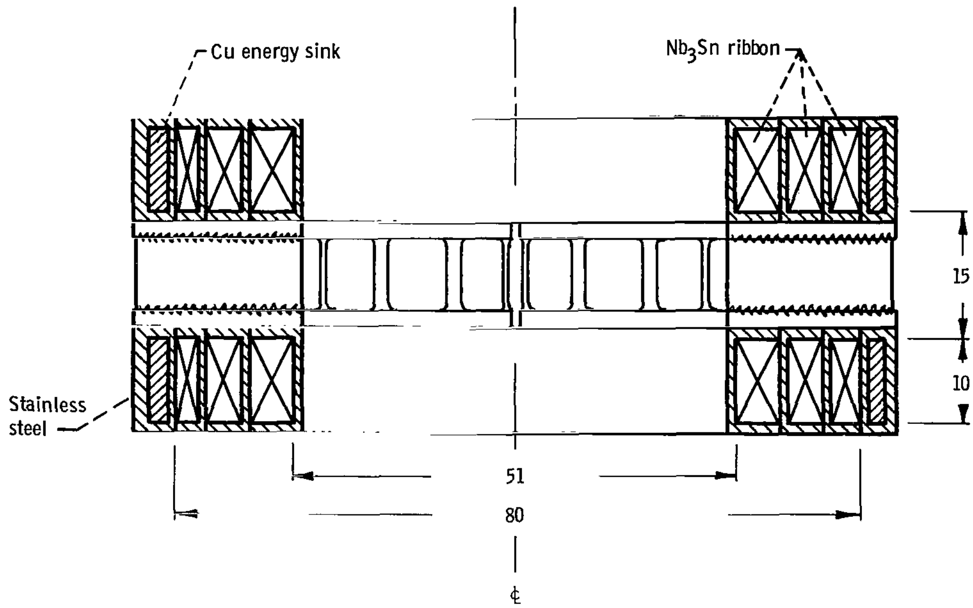

Figure 2. - 51-Centimeter magnet pair. Dimensions are in centimeters.

A three-module magnet design was used, as shown in figure 2. Modules are concentric with an outer winding diameter of 80 centimeters. Current leads were so arranged that the modules could be powered singly or in any other practical fashion. Design current was the same for all modules to allow series operation, although, in Lewis experience, series operation has never produced the highest field values.

The winding technique used was the one that was developed in the feasibility study and was essentially the same as was used on the Lewis 15-centimeter bore 14-tesla magnet. The superconducting ribbon, matched to the field and strength requirements at the various sections of the magnet by changes in thickness of the substrate and superconducting layers, is layer wound on Teflon-coated stainless-steel coil forms. To contribute toward stability and to limit induced voltages and thus protect the magnets during quench, thin, narrow shorting strips of phospher-bronze are laid across each winding layer at 4 to 6 inch (10.2 to 15.2 cm) circumferential intervals. These are held in place by the superconductive ribbon, and winding tension provides the contact pressure. Light, intermittent applications of a silicone vacuum grease were applied to the windings to aid in securing the ribbons. Some axial slippage of the conductor has been observed in outer windings due to the large forces tending to compress the windings. Mylar-copper-mylar interlayer insulation is used with the copper foil shorted on itself to provide energy dissipation damping. An outer ring of stainless steel has a massive copper core to act as an energy sink during magnet quench. No other external protection is provided except for the power supply diodes. The magnets are tightly wound and liquid helium penetration is minimal.

A magnet separating member is also indicated in figure 2. It consists of an open-grid welded assembly and simulates the separators to be used to provide radial access in the plasma physics facility. Compressive forces on the separators for the four-magnet array would be of the order of 600 tons at design conditions. The coil pair suspended under the Dewar lid is shown in figure 3.

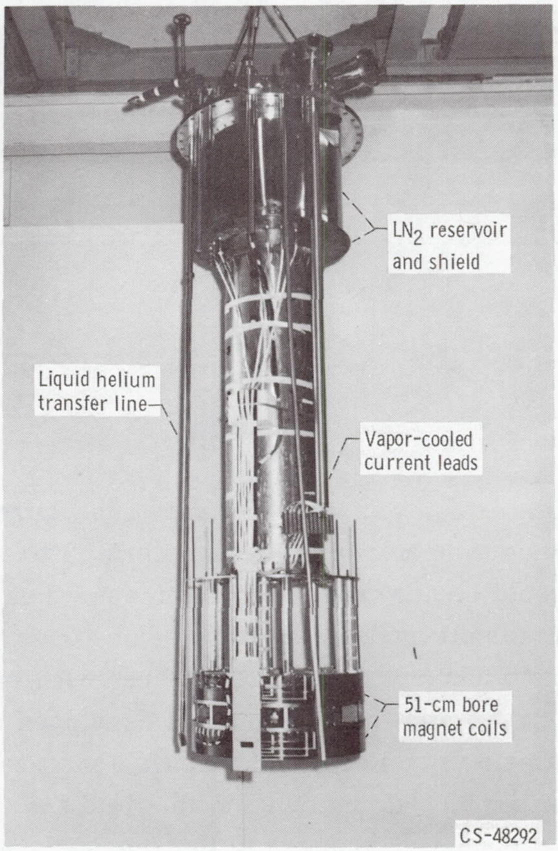

Figure 3. - Magnet coil pair and Dewar lid assembly.

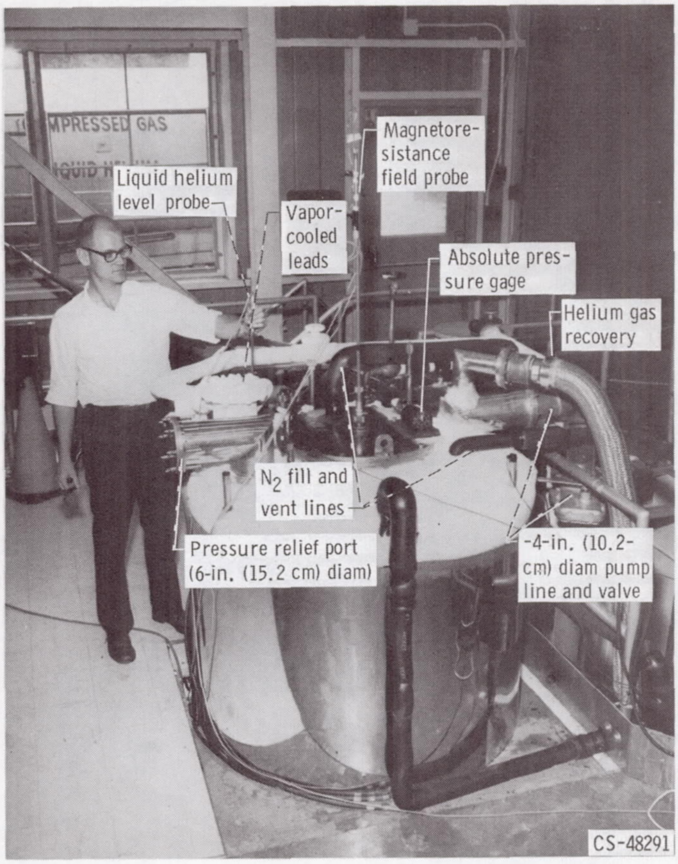

Figure 4. - Upper section of 96.5-cm inside diameter, 4.5-meter tall Dewar.

The upper section of the 96.5-centimeter inside diameter Dewar, which is approximately 4.5 meters tall, is shown in figure 4. Liquid helium is supplied from a trailer located outside the building. The Dewar is vented to the existing laboratory helium recovery system consisting of two 27.5-meter diameter hemispherical balloons and two 100-liter-per-hour liquifiers with their associated purification and storage facilities. A copper magnetoresistance probe is used for the center field measurement. Other magnetoresistance and Hall effect magnetometers are attached to various coil forms.

Pumping facilities to provide the reduced temperature environment consist of 4-inch- (10.2-cm-) diameter piping and valves, and a large vacuum pump with a capacity of 870 cubic feet (24.6 m^3) per minute.

PROCEDURE

Individual modules of each magnet were tested at 4.2 K, and each of the individual magnet assemblies were tested both at 4.2 K and under pumped helium conditions at ap-

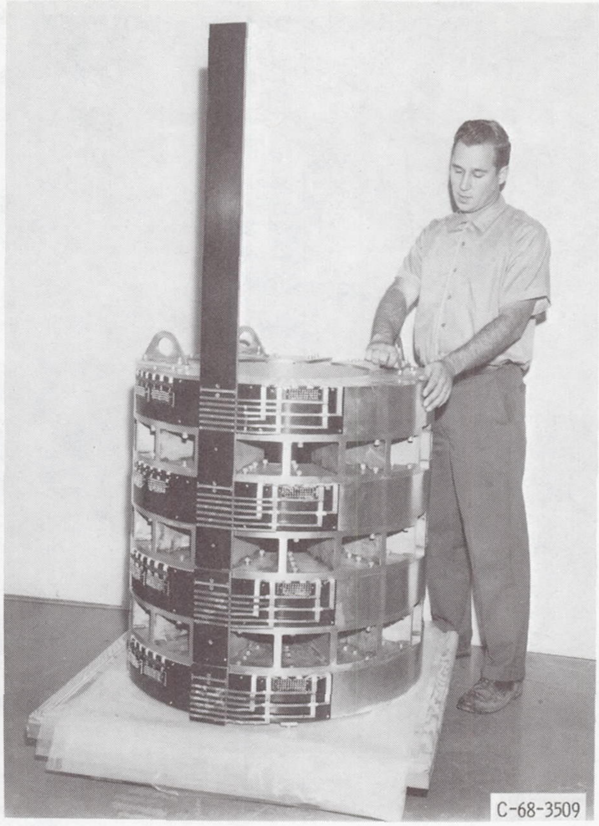

Figure 5. - Four-magnet assembly.

proximately 1.8 to 1.9 K. Two-, three-, and four-magnet assemblies have been tested at the low temperature. The four-magnet assembly is shown in figure 5.

In the individual magnet tests, each module was powered to quench with the other two modules held at approximately one-third design current, primarily to reduce shielding effects. The purpose of this procedure was to determine a maximum current capability for each module from which a powering schedule for the assembly could be determined. It was realized that significant changes in field direction and intensity would occur in the assembly tests and would alter the module performances, but it did provide some basis for succeeding tests.

Because of the high inductance of the magnets and the presence of the protective shorting strips across each winding layer, not all of the current from the power supplies circulates around the windings to produce magnetic field during the charging operation (i.e., some of the current is shunted through the shorting strips due to the inductive voltages developed). To determine the circulating currents in the windings, it is necessary to periodically reduce the charging voltage to a value sufficient only to match the resistive drop across joints in the superconducting material and then to measure the current. Some time must be allowed for readjustments of currents within modules.

DISCUSSION AND RESULTS

The improvement in magnet performance when operated in superfluid helium is limited to the difference between short sample critical current at the reduced temperature and the 4.2 K magnet quench current. Thus greater improvement potential exists for the less stable magnets although the full value may not be attainable. Fully stabilized materials operating at their critical current values can be improved only by the amount the critical current changes with temperature. The resistive, or current sharing, region may be extended. Partially stabilized materials have characteristics between the two extremes.

The superfluid helium properties which contribute to the improved performance are the very high thermal conductivity and very low viscosity. Complete penetration of the liquid into the winding spaces and elimination of vapor pockets is the expected result. If the heat flux is below a critical value, the transition from liquid to vapor occurs only at the liquid surface and not at the heat source. Moderate heat dissipation within the windings, therefore, does not result in bubble formation and vapor binding of the magnet passages. The very rapid distribution of heat pulses to surrounding magnet areas and to the bath tends to damp the effects of such perturbations.

Achievement of 7.2-tesla center field will require a contribution from each magnet of just under 3.4 tesla. Only one of the magnets has exceeded this value in single magnet tests at 4.2 K. This was the magnet wound with the copper-clad material.

Test results obtained with the various magnets and assemblies are presented in table I. Shown are the fields obtained at both temperatures (as measured by the vapor

TABLE I. - 51-CENTIMETER BORE MAGNET TEST RESULTS

Magnet	Center field, B_0, tesla		Performance improvement factor, $\frac{B \text{ at } 1.8 \text{ K}}{B \text{ at } 4.2 \text{ K}}$	Circuit[a]
	At 4.2 K	At 1.8 K		
I	2.0	3.2	1.61	A, B, C
II(Cu clad)	3.4	4.4	1.3	A, B, C
III	2.3	3.6	1.60	A, B, C
IV	2.0	3.2	1.60	A, B, C
I, IV	3.3	5.2	1.58	A → B → C, A → B → C
I, IV	---	5.8	----	A → B → A → B, C → C
I, IV	4.8 at 1.8 K to 5.0 at 4.2 K		----	A → B → A → B, C → C

[a]A, inner module; B, middle; C, outer; →, series.

pressure above the surface of the liquid helium), the ratio of the fields (or performance improvement factor), and the powering circuit used.

Maximum module current density in the windings alone for the silver-plated ribbon was 18 000 amperes per square centimeter, and the maximum overall current density achieved for a complete magnet including internal structure was 14 000 amperes per square centimeter. For the copper-clad magnet, maximum module winding current density was 23 000 amperes per square centimeter, and maximum current density for the magnet including internal structure was 17 000 amperes per square centimeter. The values given for the windings alone include the structure provided by the substrate material and interlayer insulation, foils, and voids.

The ratio of the center fields produced at the two temperatures for most of the silver-plated conductor configurations was almost exactly 1.6. For the copper-clad conductor magnet, the improvement factor was 1.3.

With series powering of the magnets in each pair, 5.2-tesla center field was obtained with two magnets at the low temperature. This value is very nearly the contribution required from a coil pair to meet the design goal for the array. With the inner two modules of each magnet (four modules) in series with one power supply and with the two outer modules of the pair in series with a second power supply, the central field obtained was 5.8 tesla. Corresponding maximum field at the windings is 8.7 tesla. Power supply currents were 80 and 84 amperes, and actual winding current was estimated to be 77 amperes in all coils at quench.

One test was made in which a magnet pair was powered to 4.8 tesla at 1.8 K and then additional helium was added to bring the temperature back up to 4.2 K with the field held nearly constant. Powering was resumed at 4.2 K, and quench occurred in about 20 minutes at 5.0 tesla. During this test, approximately 40 liters of liquid was added to the vessel at pressures below the lambda point.

In succeeding tests with the four-magnet array, liquid helium addition at pressures below the lambda point was attempted. Helium could be transferred at pressures below the lambda point at low rates, but, when the temperature was allowed to rise above the lambda point, quench occurred even with constant field operation. In order to provide sufficient helium for the tests without transferring liquid at high field, the magnets were powered to 2.0 to 3.0 tesla at 4.2 K, and then additional helium was added before and during the pump-down to the superfluid region.

Four-magnet test results were disappointing in that only 0.13 tesla higher field was obtained than had been achieved with a magnet pair (i.e., 5.93 tesla as compared to 5.8 tesla). One of the magnets showed considerably more instability than the others, as evidenced by periodic flux jump type excursions in power supply current or voltage depending upon the power supply mode of operation. Quench occurred during the recovery period following one of these excursions for several tests. Figure 6 shows power supply current as a function of time for constant voltage operation for a typical record at quench.

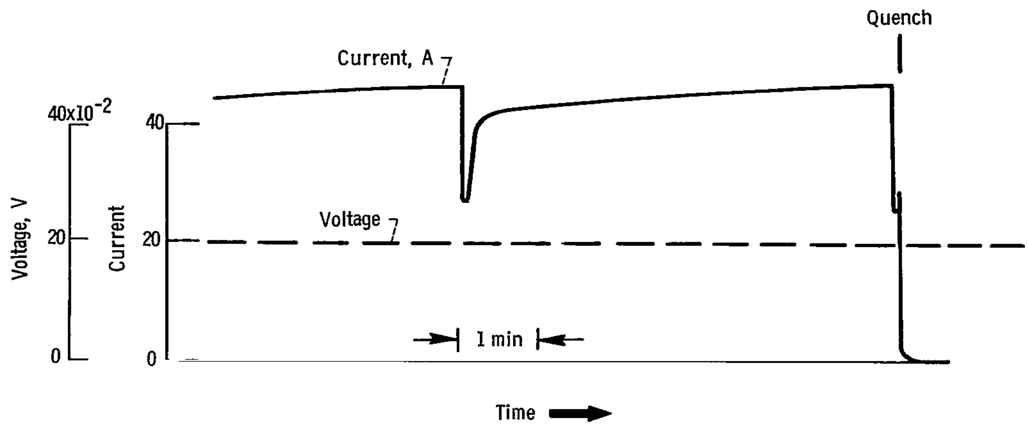

Figure 6. - Charging history preceding quench for single magnet in individual dewar.

This type of behavior occurred at about the same central field value whether the unstable module was at high or low current.

The unstable magnet was removed from the assembly and the remaining three magnets tested. Here again it was not possible to obtain the performance values previously reached with the magnets in the two coil tests. Periodic disturbances in power supply current or voltage were again experienced throughout the test, and quench occurred at 5.2 tesla. The degraded performance of the magnets in all of the later tests probably results from damage sustained during the high field quenches in earlier tests. Evidence of conductor shifting had been observed and corrected after one series of tests, but was of such a nature as to give little confidence that similar bunching of the conductor would not occur again.

CONCLUDING REMARKS

Operation of the large magnets under superfluid helium enhanced their performance by a factor of as much as 1.6 for the minimally stabilized conductor and 1.3 for the copper-clad conductor. Current densities obtained were quite high (14 000 and 17 000 A/cm^2 for the silver-plated and copper-clad conductors, respectively, including internal structure). The degradation of coil performance which occurred was not attributed solely to the usual coil interaction effects but more to progressive movement of the windings sustained in the numerous quenches.

The copper-clad superconductor was superior in stability and maximum current density attainable and in addition gave no indication of conductor movement.

Charge-up time of all of the magnets was long. Higher current, lower inductance design is recommended for large magnets.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, January 30, 1969,
120-26-09-15-22.

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