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SUPERCONDUCTING MAGNETIC BOTTLE FOR PLASMA PHYSICS EXPERIMENTS*

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SUMMARY

A superconducting magnetic bottle consisting of two mirror coils, a central field coil, and a cylindrical cusp field coil was designed and constructed of seven-strand niobium - 25-percent-zirconium cable. The configuration was designed to investigate the problems involved in using superconductive materials to produce magnets useful for experiments in plasma physics. Mirror fields as intense as 5 teslas were produced in the bore of the 10-centimeter-inside-diameter coil assembly with a superimposed quadrupole cusp field of 5 to 10 percent of the center field and a mirror ratio of 2.

INTRODUCTION

Magnetic fields for plasma physics experiments have been produced in many sizes, configurations, and field strengths. In many cases the experiments have been limited in field strength or duration by insufficient power or inadequate cooling for the magnet coils. In addition, the heavy coils, support structure, and cooling passages have interfered with free access to the centerline of the field.

Now the rapidly developing techniques of manufacture of superconducting magnets offers a solution to these difficulties. Some additional problems are introduced, however, such as magnet operation limitations peculiar to superconducting materials and the requirement for a liquid-helium environment for the magnet coils. The Lewis Research Center has been studying the application of superconducting magnets to plasma physics. One such apparatus, described by Roth, Freeman, and Haid (ref. 2), has performed well in actual use during the past several months. This device consists of a split pair (mirror coils) of superconducting coils, each enclosed in its separate helium Dewar. The separation between the Dewars is adjustable by inserting support rods of different lengths.

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*Part of this material was presented at the Cryogenic Engineering Conference, Rice University, Houston, Texas, August 1965 (ref. 1).

The inner diameter of the 2.5-tesla coils is about 17.5 centimeters, and the separation can be varied from 15 to 52.5 centimeters.

The system of coils described herein was designed to study the use of superconducting coils at higher fields and in other configurations than those now in use at Lewis for plasma physics experiments. Among the configurations to be studied are those deemed most suitable for stable plasma containment (such as Ioffe cusp fields (ref. 3)).

The mirror coils were designed to produce 5.0 teslas on the central axis. A ratio of mirror to center coil field of 2 was provided, and a more uniform central field was produced by inserting a third coil between the split pair (fig. 1). In addition, a cusp field of 5 to 10 percent of the center field is produced by an array of four linear conductors, referred to as "Ioffe bars", equally spaced around the inner circumference of the coil forms. The design, fabrication, and operation of this system of superconducting coils are described herein.

SELECTION OF MATERIALS

Several high field type II superconductors are available as wires, cables, ribbons, etc. These superconductors are of two forms: the intermetallic compounds such as

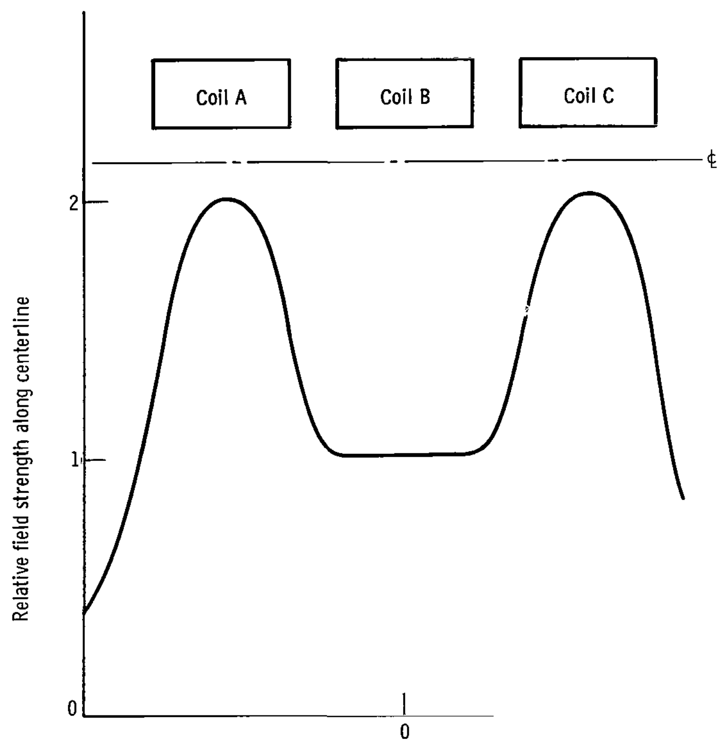


Figure 1. - Magnetic mirror configuration for plasma physics experiments.

Nb_3Sn, and the alloys, niobium-zirconium, niobium-titanium, etc. The superconductive alloys were concentrated on for the first attempt because (1) the alloys were more readily available, (2) the alloys in cable form are somewhat less difficult than ribbon materials to wind into coils, and (3) heat treatment after winding is required for some intermetallic compound materials but is not required with the alloys.

Sample amounts of niobium - 25-percent-zirconium and niobium-titanium were purchased from the known suppliers in the form of seven-conductor cable made from 0.025-centimeter-diameter superconducting wires, each with 0.0025 centimeter copper plating and overall insulation.

The quality of the copper plating and the uniformity and reliability of the insulation varied from sample to sample. These factors affected the performance of the coils wound from the materials.

In order to check the suitability of these materials for construction of superconducting coils, two coil forms were made of stainless steel (fig. 2). One of these, the cylindrical form, is 25 centimeters long with an inside diameter of 10 centimeters and a winding diameter of 10.7 centimeters. The other form consisted of two parts: a cylinder and a continuous length of half-tubing spot-welded to it. This half-tubing provided a form on which to wind the turns of the Ioffe bar coil.

Coils of the different materials were wound as nearly identically as possible. Mylar tape was used for insulation between the layers. The normal-to-superconducting contact for the current leads was the same for all the coils. This connection was formed by unwinding the strands of a copper cable (no. 10) and cutting out the center strand. The superconducting cable was soldered to this stub of the center conductor, and the strands were wound back onto the superconducting cable. The whole length of copper wires and copper-plated superconductor was then soldered with a 60-40 lead-tin solder. Superconducting-to-normal connections with a resistance of less than 0.02 microhms in the helium resulted from this method.

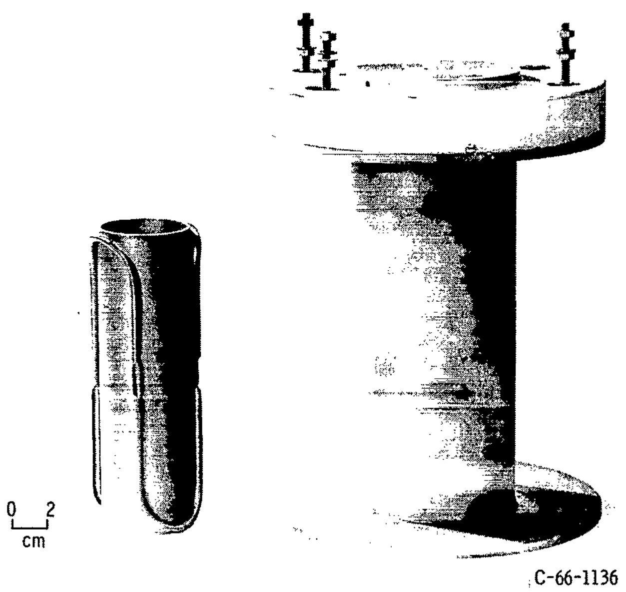
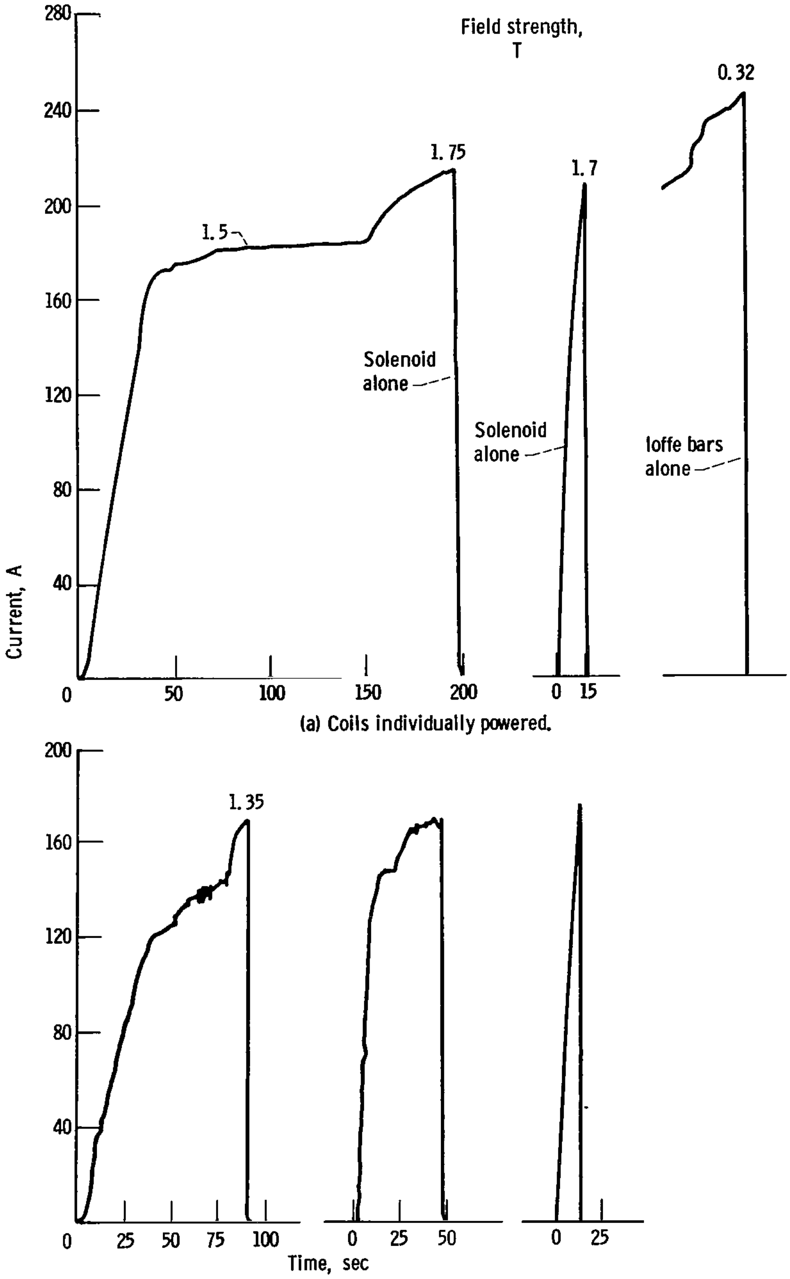


Figure 2. - Test coil forms.

The coils were tested by recording the current necessary to cause the transition to the resistive state. The rate of application of the voltage to the coil was varied from a very slow charging rate to the maximum rate the power supplies would permit. Some of the results are shown in figure 3. Figure 3(a)



(a) Coils individually powered.

(b) Coils connected in series.

Figure 3. - Solenoid and Ioffe bar characteristics for different rates.

shows the critical current for the test solenoid (at two charging rates) and Ioffe bars alone, while figure 3(b) shows the result of operating the two coils in series at three charging rates.

The significant results of these tests as seen from figure 3 are as follows:

(1) The charging rate had little effect on the critical current of the coils.

(2) Powering the coils in series (rather than individually) gave significantly lower critical currents, but because of the ease of using the series method of charging the coils, one single power supply may provide the best method of operation.

Conclusions drawn from critical observations of the materials are as follows:

(1) The use of seven-strand cable offers decided operational and fabrication advantages (while still maintaining high current densities) over coils fabricated from single-strand wire. The fewer number of turns and layers results in lower inductance, shorter time constants, and shorter fabrication time.

(2) Problems occurring in any particular section of wire can usually be associated with poor bond or other defects in the copper plating.

(3) Resoldering of joints usually degrades joint resistance characteristics.

As a result of the testing and evaluation of the superconducting materials, it was possible to select a material with decidedly superior characteristics, over the required range of the parameters of interest, from which to fabricate the magnets. The material chosen was seven-strand niobium - 25-percent-zirconium cable. Each strand of the cable had been copper-plated and the cable dip coated with high-purity indium metal. The insulation on the cable was either Teflon or Mylar. The advantage of the Mylar is that it takes less winding volume because it is thinner. Either insulation was adequate for the coils tested.

COIL DESIGN

After the materials have been selected, the physical dimensions of the bore of the assembly and the relative field strengths of the various sections are major factors in the design of the final configuration. Material selection determines the maximum field strength possible at the inner windings, and selection of the physical dimensions of the bore puts limits on the central field strength that can be obtained economically. The desired magnetic field distribution on the axis of the bottle is shown in figure 1. A mirror ratio of 2 with a center field of 2.5 teslas was to be produced by the three coils A, B, and C. Figure 4 (p. 6) indicates the field to be produced by each coil, the total field distribution, and the coil dimensions. The inside diameter of the windings is 10.6 centimeters and the lengths of the mirror coils are 12.7 centimeters and that of the center coil, 10.6 centimeters. The design parameters are given in table I.

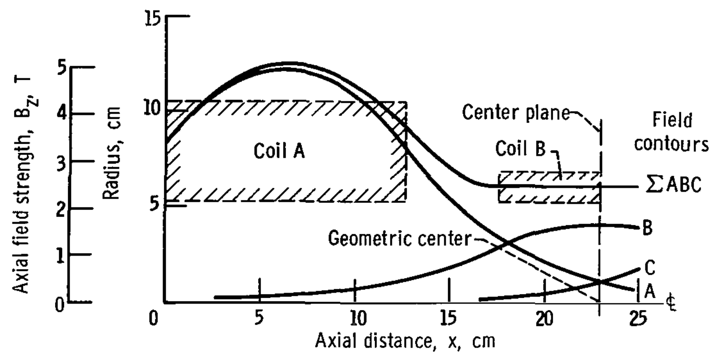


Figure 4. - Design parameters for magnetic coils. Assumed current, 25 amperes per strand or 175 amperes for seven-strand cable; overall current density, 1.2×10^{4} amperes per square centimeter.

TABLE I. - DESIGN PARAMETERS FOR SUPERCONDUCTING COILS

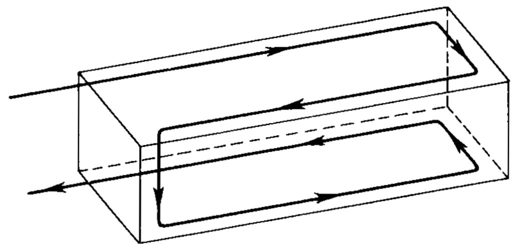
Coil	Field at center of coil, B_0, T	Length of windings, L, cm	Inside diameter, cm	Outer diameter/Inner diameter, α	Length of windings/Inner diameter, β	Length of wire, ℓ, m	Number of turns	Number of layers
A	4.85	12.7	10	2	1.2	2300	4550	44
B	1.60	10.6	10	1.3	1.0	440	1131	13
C	4.85	12.7	10	2	1.2	2300	4550	44
Ioffe bar	0.12 to 0.25	50.8	7.5	---	---	126	60	--

The coil design to produce maximum mirror fields of 5.0 teslas was straightforward. With a minimum inside bore diameter of 10.0 centimeters and with the use of the minimum wire lengths to produce the desired fields, the approximate coil dimensions and the calculated field distribution can be obtained.

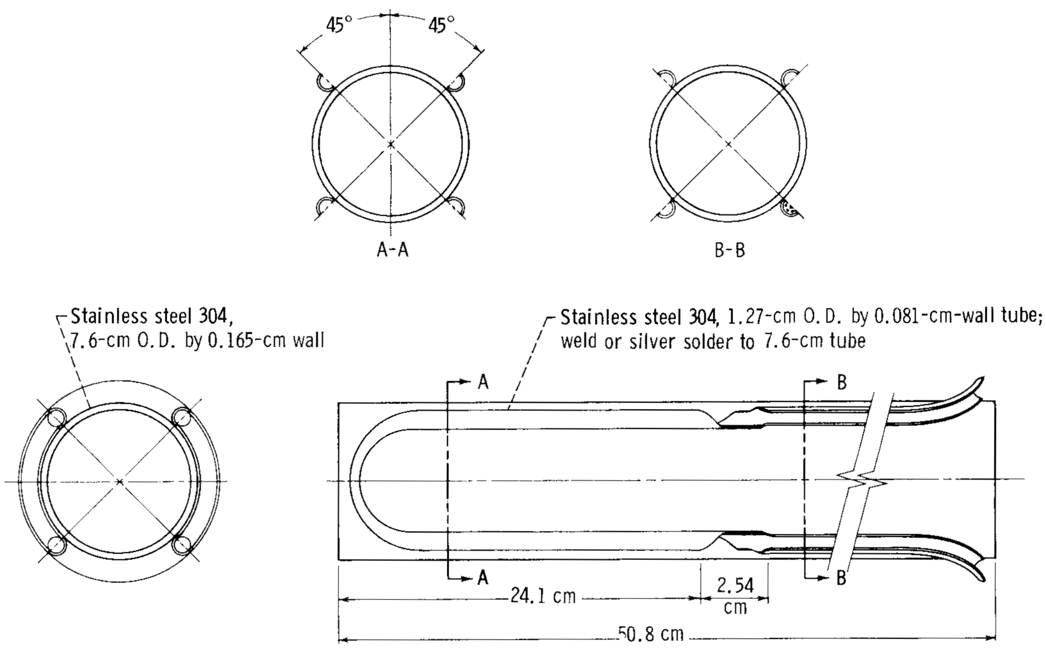
The selection of a desired uniform field length and the desired spacing between magnets coupled with the requirement for a mirror ratio of 2 allows the computation of the dimensions and field distribution of the center magnet. The contribution of each coil to the magnetic field along the axis is determined and the coil dimensions are modified to produce the desired field contour. Field calculations were based on the methods of references 4 to 6.

Figure 4 shows that the design mirror ratio and field strengths should be closely achieved. The spacing between the coils is sufficient that access to the centerline of the field could be provided if necessary. Additional windings on the center coil could shape the field into other desirable configurations.

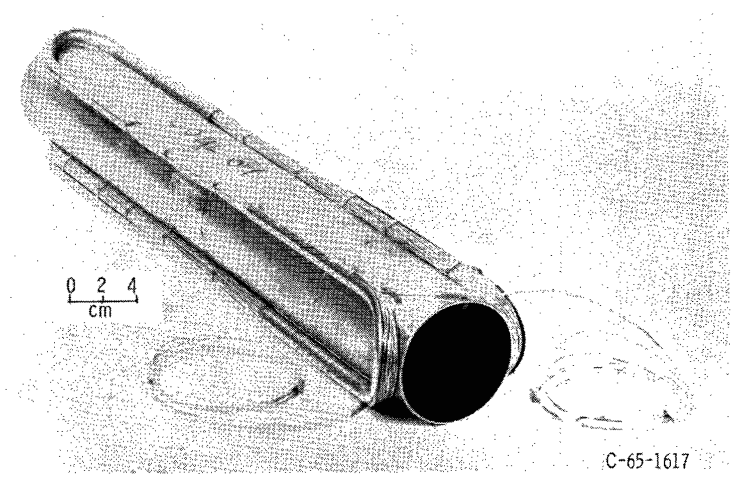
The design of the cusp field, however, presented some problems of its own. It is necessary to design a system of linear conductors (Ioffe bars, ref. 3), which will operate



(a) Current path in coil.



(b) Ioffe bar coil form.



(c) Ioffe bar with coils.

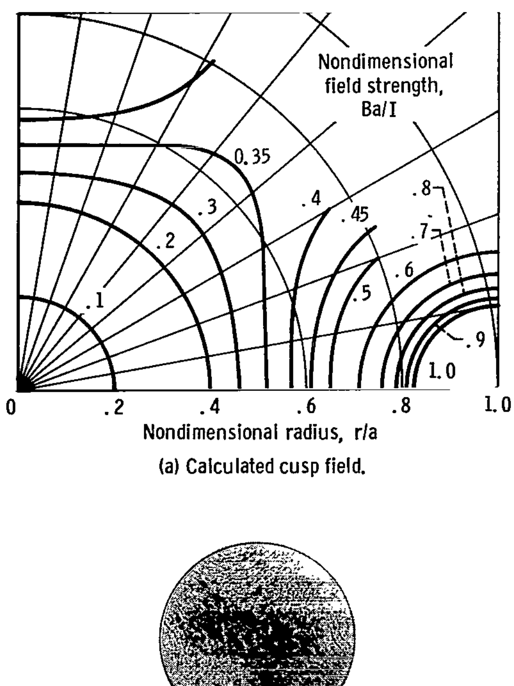
Figure 5. - Ioffe bars (quadrupole configuration).

in the high field close to the inner windings of the coils. The performance of these conductors is, of course, affected by the background field of the main coils and by the methods used to introduce the current into them. Flux jumps in the windings of any coil sufficient to drive it normal may drive an adjacent coil normal as well.

The winding of the Ioffe bars was accomplished by the scheme shown in figure 5. Figure 5(a) is a schematic diagram showing the direction of the current in the Ioffe coils, figure 5(b) is a drawing of the actual coil form, and figure 5(c) is a photograph of the completed assembly. Laying the cables carefully in the half-tubing and using an epoxy to hold them in place made it possible to obtain the coil parameter shown in table I.

Calculations for field configurations such as these Ioffe bars are available in the literature (see ref. 7). For the present design, the calculations were performed on the IBM 7094 to give tables of desired fields in terms of the geometrical dimensions of the coils.

The results of this study for a quadrupole field are shown in figure 6(a). The constant-field-strength Ba/I contours are shown as a function of nondimensional radius r/a, where B is the field strength, a is the radial position of the conductor, and I is the current. In the iron filing pictograph of figure 6(b), the actual magnetic field of the Ioffe bars is mapped with iron filings showing the direction of the field lines when a nominal current was passed through the wires on the coil form.



(a) Calculated cusp field.

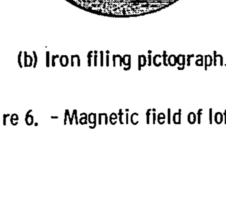

(b) Iron filing pictograph.

Figure 6. - Magnetic field of Ioffe bars.

COIL CONSTRUCTION

After the test results had indicated that the desired magnetic bottle could be constructed with a reasonable assurance of achieving the required performance, the magnetic bottle was fabricated. A multiple-coil form on which to wind coils A, B, and C was constructed according to figure 4. The coils were wound with a shorted turn interlayer of aluminum foil 0.013 centimeter thick overlapped approximately 2.5 centimeters and an insulating interlayer of 0.0025-centimeter-thick Mylar tape. The aluminum foil was used for the additional heat-transfer conduction path it could provide to the inner parts of the coil, and it was shorted upon itself for the purpose of delaying energy dissipation in the superconducting to normal transitions

TABLE II. - FINAL COIL DIMENSIONS

Coil	Field at center of coil, B_0, T	Length of windings, L, cm	Inside diameter, cm	$\frac{\text{Outer diameter}}{\text{Inner diameter}}$, α	$\frac{\text{Length of windings}}{\text{Inner diameter}}$, β	Length of wire, ℓ, m	Number of turns	Number of layers
A	4.85	12.7	10.6	2	1.2	2400	4800	43
B	1.60	10.7	10.7	1.4	1.0	439	1152	14
C	4.85	12.7	10.6	2	1.2	2400	4800	43
Ioffe bar	0.12 to 0.25	50.8	7.5	---	---	126	60	--

of the coils. Eddy currents set up in the aluminum with the collapse of the magnetic field tend to limit the voltages developed and spread the heat dissipation over a longer period of time. The final dimensions of the coils are given in table II.

The dimensions of the coils differ from the design values primarily because of the use (on the mirror coils) of Mylar insulated cable, which is somewhat thinner than the Teflon insulation considered in the design. These changes in length of wire, number of turns, and number of layers give somewhat larger fields for design current or the same field for less current.

A winding of monofilament nylon serves to restrain the windings further, to provide some abrasion protection, and to give the coils a finished appearance.

Figure 7 shows the finished magnetic bottle suspended from the Dewar flange ready to be lowered into the helium Dewar in preparation for a test. The mirror magnets are

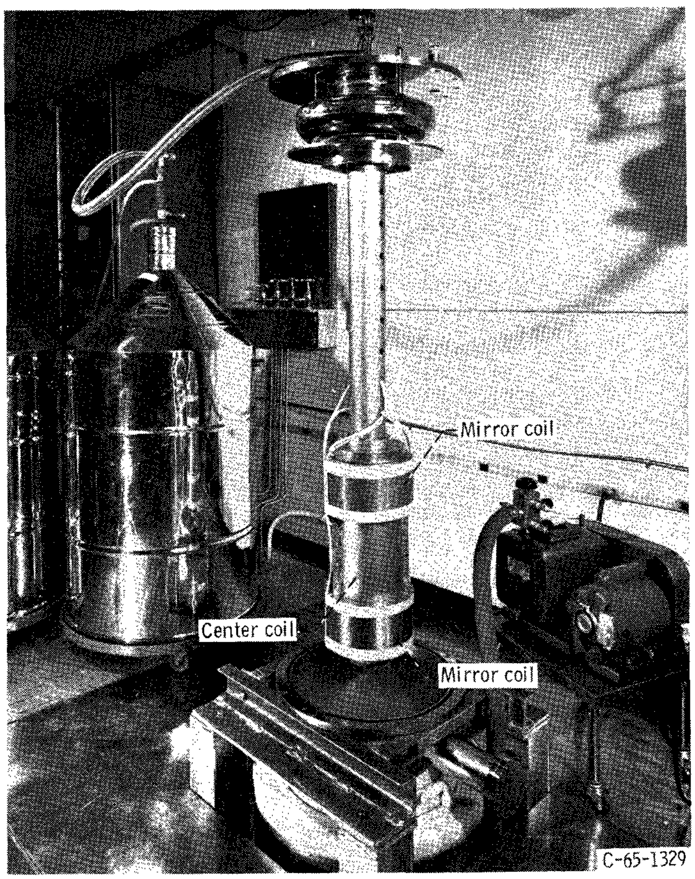


Figure 7. - Magnetic bottle.

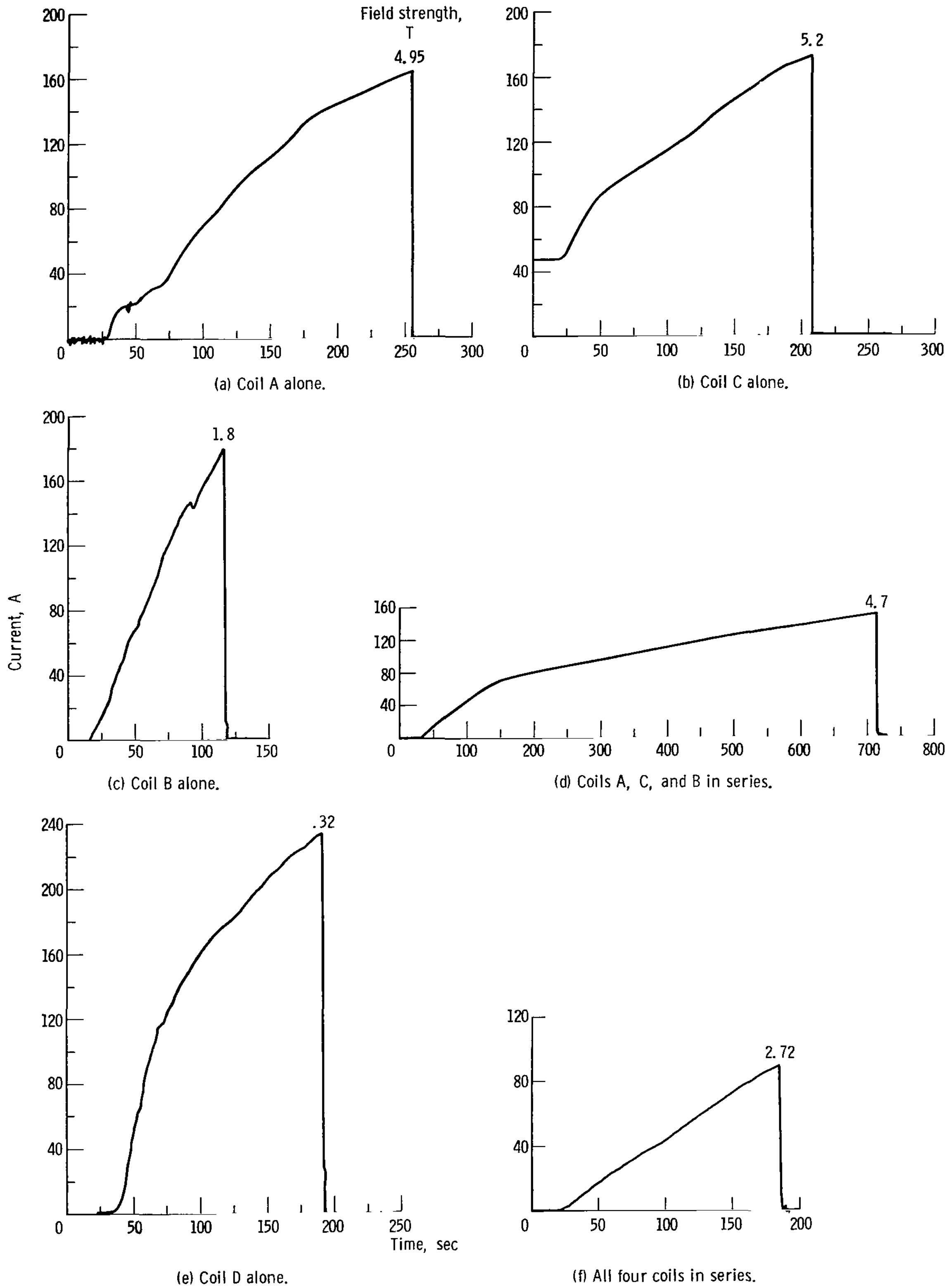


Figure 8. - Charging history.

visible in the photograph, but the center coil is inside the stainless-steel sleeve, which provides additional support for the inner mirror magnet flanges and serves as a cover and support for the leads. The Ioffe bars are inside the central tube of the other coils and, hence, hidden from view.

The superconducting-to-normal material joints were made by soldering the copper-indium-coated superconductor to a copper channel section with indium-tin solder. These channels were previously lead-tin soldered to tin-coated copper braid conductor. The channel section was used because it provided a very rigid base for the superconducting-to-normal joints and a large ratio of surface to volume for cooling. The copper braid material was selected because it could be spread out to provide better cooling of the individual braid strands in the vapor space above the liquid helium. The joints usually resulted in a resistance of 0.1 to 0.2 microhm between the copper and the superconductor.

The leads to the superconducting coils were of some concern (1) because of the number that would be required to power each coil individually and (2) because of the large size necessary to carry the high current (175 A) into the liquid-helium environment. Both of these factors increase the heat leak into the Dewar. For use in plasma physics experiments, persistent current switches combined with disconnectable current leads into the Dewar would be desirable to reduce the helium loss rate.

RESULTS AND DISCUSSION

The results of the tests on the completed magnetic bottle obtained by operating the coils both alone and in combination are shown in figure 8. This figure shows the charging history of the coils with current plotted on the ordinate. The charging rate of the coils was varied over large ranges and was of no consequence except when three or four coils were being powered. The sharp breaks in the curves are the transition point from the superconducting to normal states. The coils in the magnetic bottle were shunted by silicon diodes in all tests for protection against voltage buildup when any of the coils were driven normal.

Figure 8(a) shows the result of charging mirror coil A alone. This coil carried a maximum current of 165 amperes and produced a field of 4.95 teslas when the transition to the normal state occurred. Figure 8(b) shows the results obtained for coil C alone, which carred a maximum current of 173 amperes and produced a field of 5.2 teslas. These values indicate coil performance at almost exactly the published short-sample performance of the wire for the calculated field at the windings, that is, 24.5 amperes per strand at 5.9 teslas. The results obtained as the center coil B was charged and driven normal are shown in figure 8(c). The field requirement for this coil is 1.6 teslas, and when operated alone it produced 1.8 teslas. Critical current values and corresponding magnetic field values are shown on the figure.

Figure 8(d) shows the results of operating coils A, B, and C in series. For a slow charging rate, these coils can be operated with the desired mirror ratio at a current level of 152 amperes and a mirror field of 4.7 tesla (nearly the design field value).

The charging history of the Ioffe bars alone is shown in figure 8(e). The critical current was 234 amperes, which is more than sufficient to give the 5 to 10 percent of the center field of coil B that was sought.

Tests of all four coils in series (fig. 8(f)) was somewhat disappointing in that the coils were driven normal when the current exceeded 85 to 95 amperes. It was determined that the Ioffe bar coil was the only coil making the transition. Since this is only about half the design current, this method of operation was unsatisfactory and meant that more than one power supply was required for successful operation. When one power supply was used on the three coils in series at 148 amperes, the maximum Ioffe bar current from a second power supply was 88 amperes (0.12 tesla), which is within the range of values obtained for all coils in series.

Two additional Ioffe bar configurations were fabricated and tested in an attempt to increase the current. The first modification was simply a longer version of the original configuration, extending the end sections outside the mirror coils. The second configuration reduced the flux linkage from the magnetic bottle. This reduction was accomplished by the use of two saddle coils, which provided the desired longitudinal current paths within the magnetic bottle but which, in end-view projection, did not form a complete loop. Neither of these modifications had any appreciable effect on the Ioffe bar current capability.

Additional turns of cable on the Ioffe bars together with the use of a separate power supply to provide for lower operating currents or the use of a more stable conductor material may be a better solution than the present coils.

CONCLUDING REMARKS

The design values of current, field, and field distribution (mirror ratio) were closely achieved in a 10-centimeter-inside-diameter, 45.7-centimeter-long superconducting magnetic bottle.

Operated singly, the mirror coils wound of seven-strand niobium - 25-percent-zirconium cable generated central fields as high as 5.2 teslas at a current of 173 amperes. This value of current is almost identical to the short-sample performance capability of the wire (published by the manufacturer) for the field value at the inner winding diameter.

Operated in series, the three coils comprising the magnetic bottle carried a current of 152 amperes and generated central fields of 4.7 teslas at the mirror sections with a ratio of mirror to center coil field of 2.

The quadrupole field coil (Ioffe bar) performance was degraded from 243 amperes and 0.32 tesla when operated alone to 85 to 95 amperes and 0.12 tesla when operated in conjunction with the magnetic bottle.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 1, 1966,
129-02-05-10-22.

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