ARGONNE NATIONAL LABORATORY SUPERCONDUCTING PULSED COIL PROGRAM

by

S.-T Wang and S.-H Kim

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S.-T. Wang and S.-H. Kim
Argonne National Laboratory
Argonne, Illinois 60439

ABSTRACT

Argonne National Laboratory (ANL) has recognized the clear advantage of a superconducting ohmic heating coil and started an aggressive development program in FY 1977. The main objectives are to develop high current (~100 kA) cryostable cable configurations with reasonably low ac losses, to build a demonstration pulsed coil, and to develop a rather inexpensive large fiberglass reinforced helium cryostat.

A 1.5-MJ cryostable pulsed superconducting coil has been developed and constructed at ANL. The coil has a peak field of 4.5 T at an operating current of 11.0 kA. A large inexpensive plastic cryostat has been developed for testing the pulsed coil. The coil has been pulsed with a maximum dB/dt of 11 T/s. The coil was pulsed more than 4000 cycles. Detailed results of the ac loss measurements and the current sharing of the cryostability will be described.

Other objectives of the on-going pulsed coil program is to study the parallel operation of pulsed coils, to develop and evaluate a 50-kA and a 100-kA cryostable cable and to perform a preliminary engineering design of a 100-MJ engineering demonstration coil.

INTRODUCTION

The conceptual design studies of tokamak experimental power reactors undertaken at ANL and elsewhere over the past several years have identified the need for large-volume pulsed superconducting magnet systems to contain and drive the plasmas in these ignition devices. Because of the large stored energy of the tokamak magnet coils, they must be cryogenically stable, but they must also tolerate rapid cycling. At ANL, considerable progress has been made to identify critical elements of tokamak coil design and required technology development. The main feature of the ANL pulsed coil program is listed in Table I.

The main objectives of the pulsed-coil program are to develop high current cryostable cable with reasonably low ac losses, to design and build demonstration coils, to evaluate the performance of these coils, and to develop reliable large fiberglass-reinforced helium cryostat for these coils. Another important objective of the pulsed-coil program is to investigate the parallel-coil operation. If a pulsed coil can be divided into many parallel paths and the parallel-coil operation is feasible, then a pulsed-superconducting coil can be charged with a relatively low-voltage and a relatively high-operating current.

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TABLE I

ANL Pulsed Superconducting Coil Program

- I. HIGH CURRENT CABLE DEVELOPMENT
  - A. Cable Study
    - 1. Cryostability Studies
    - 2. AC Losses Measurement
    - 3. Mechanical Perturbation Studies
  - B. Cable Development
    - 1. 12 kA
    - 2. 50 kA
    - 3. 100 kA
  - C. High-Current Conductor Joints
  - D. High-Current Lead Development and Operation
- II. RELIABLE PLASTIC HELIUM CRYOSTAT DEVELOPMENT
  - A. 1-m Dewar
  - B. 2-m Dewar
- III. MODEL COIL DEMONSTRATION
  - A. 1.5 MJ Coil
  - B. 100 MJ Coil
- IV. PARALLEL OPERATION OF PULSED COILS
- V. FULL-SIZE-PULSED COIL DESIGN

DEVELOPMENT AND FABRICATION OF THE 12-kA CABLE

The cable configuration giving the best compromise between stability and ac losses is illustrated in Fig. 1. The six pure copper wires are soldered to the superconducting composite forming an essential current sharing subgroup. A thin coating of organic varnish is brushed on the surface of each of the three subgroups in the basic cable. The varnish coatings serve to reduce the eddy current losses among the subgroups. The coating is thin enough, however, that limited current sharing among subgroups will be allowed. The criterion chosen for cryostability is such that both minimum propagating current and recovery current are greater than critical current. The basic cable is rated at 405 A at 5 T. Each superconducting strand has a diameter of 0.051 cm containing 2041 6-μ diameter filament with a twist pitch of 1.27 cm and a copper/niobium-titanium ratio of 1.8. The basic cable is made by forming a triplex with a twist pitch of 2.2 cm. To study the ac losses and the magnet current sharing, 5-kJ model coils[1,2] were wound. The results of model coil performance tests were presented in Ref. 1.

To form the 12-kA cable, 24 basic cables are twisted around 0.8-mm thick × 31.75-mm wide stainless steel strip at a twisting pitch of 22.5 cm as shown in Fig. 1. The stainless steel strip, which has 0.25-mm thick Mylar insulation from the basic cables, will serve as the backbone in the cabling processes and as the structural member against hoop stress of the 1.5-MJ coil. The final cable is turkheaded with finished cable dimensions of 3.78-cm wide × 0.74-cm thick. The first 25-m cable was produced as a test run for cable production. The total length of the cable for the production run is 590 m. A closeup of the 12-kA cable cross section is shown in Fig. 2.

1.5-MJ COIL FABRICATION[3]

The 1.5-MJ coil has an inner diameter of 41.6 cm, and an outer diameter of 81 cm, and an axial length of 58.1 cm. At an operational current of 11 kA, the central field is 4.2 T and the peak field is 4.5 T. Main characteristics of the coil are listed in Table II. The coil bobbin , made of fiberglass G-10, has an I.D. of 40.64 cm and an O.D. of 45.72 cm. The coil consists of 18 helical layers with an average number of turns per layer equal to 14.3. Turn-to-turn insulations are provided by two layers of 0.02 cm thick glass-cloth tapes and two layers of 0.01-cm thick Mylar tapes. These tapes have a width of 2.54 cm and cover the conductor edges extending 0.9 cm over the both sides of the broad fares of the cable.

TABLE II

CHARACTERISTICS OF THE PULSED SUPERCONDUCTING COIL

Central field	4.2 T
Peak field	4.5 T
Operation current	11 kA
Inductance	24 mH
Coil I.D.	41.6 cm
Coil O.D.	81.0 cm
Axial length	58.1 cm
No. of layers	18
Total No. of turns	258
Cryostable recovery heat flux	0.35 W/cm^2
Layer-to-layer spacing	0.48 cm (1-10th layer) 0.32-cm (11-18th layer)
Average current density	2290 A/cm^2 (1-10th layer) 2685 A/cm^2 (11-18th layer)
Cable cross section	3.78 × 0.74 cm
Cable length	510 m
Total amper-meters	5.8×10^6 A-m
Maximum radial magnetic pressure	83 Mpa
Maximum axial magnetic pressure	28 Mpa
Maximum dB/dT	11 T/s
Maximum dI/dT	27 kA/s
Charging voltage	650 V
Hysteresis loss in the filaments	∿0.1 kJ/cycle
Eddy current loss in the matrix at 9 T/s	2.65 kJ/cycle
AC losses/stored energy at 9 T/s	∿0.1%
Eddy current loss in the stainless steel at 9 T/s	60 J/cycle
Heat flux due to the AC losses at 9 T/s	∿10 MW/cm^2

Coil winding with a spongeous cable is a rather interesting experience. Figure 3 shows the setup for the coil-winding operation. First, the cable was layer-wound in a spooling bobbin. The cable-spooling bobbin was then mounted to engage an electrical clutch which provides the winding tension. The initial tension used in the winding was 225 kg. It was increased to 450 kg so that approximately a constant radial pressure in the coil was maintained.

The layer-to-layer separation was maintained by many G-10 strips covering approximately 50% of the surface of a given coil layer. For Coil Layers Nos. 1 to 10, the layer-to-layer separation is 0.48 cm. For Layers Nos. 11 to 18, where both the magnetic field and the ac losses are relatively low, the layer-to-layer separation is 0.32 cm.

Although the hoop stress of the coil will be supported by the stainless steel strip within the cable, 16 wetted-wound epoxy fiberglass bands were installed on the surface of the outermost layer (Layer No. 18). The cross secction of the band is 3.2 cm × 1.9 cm thickness. These bands will hold the windings in the outermost layer. Furthermore, it will provide additional hoop stress support for the coil, as shown in Fig. 4.

DEVELOPMENT OF PLASTIC LIQUID HELIUM DEWAR

The 1.5-MJ pulsed coil requires rapid charging and discharging; consequently, it is necessary to use nonconducting dewars to minimize eddy current losses. The plastic cryostat, as shown in Fig. 5, consists of two tanks with 100 layers of superinsulation between. The inner tank will have an I.D. of 91.4 cm and a depth of 152.4 cm with internal pressure rating of 30 psig. The wall thickness is 0.95 cm. The outer tank has an I.D. of 107 cm, a depth of 156.5 cm, and a wall thickness of 1.27 cm. Two rings are provided to reinforce the tank against buckling. Both tanks are made of fiberglass-reinforced Hetron-31 polyester with 35% glass components. The superinsulation is slit at one place to reduce the eddy current heating.

It was not clear that a polyester fiberglass tank could be used as a liquid helium vessel. Therefore, as a safety measure, it was decided to reinforce the inner tank with an 0.95-cm thick layered-wound epoxy fiberglass on the outer surface of the inner tank to insure that if the polyester tank should crack all the way through, we would have another tank built around it.

The tank was mounted in a large lathe in a horizontal position. The outer surface was sanded with belt sanders, using 80-grit aluminum-oxide paper and then wiped down with ethyl alcohol to remove all dust and contaminants and insure a good bond between the polyester surface and the epoxy layers that were to be added. The epoxy used was Shell Epon 815 with General Mills Versamid 140 curing agent in a 1 to 1 ratio.

The glass cloth, 0.3 mm thick × 96.5 cm wide, was applied by brushing a layer of epoxy resin on the tank and then adding a layer of glass cloth and working the epoxy into the cloth with brushes and serrated steel rollers. The layers were added one at a time, and all seams were staggered. Patterns were cut for the bottom of the tank and these were all interleaved with the glass cloth on the sides to once again insure that there were no direct resin paths through the tank. Twenty-four layers of glass cloth were added to the tank in this manner.

The superinsulation was now wrapped on the outer surface of the inner tank. This consisted of 100 layers of 6.25×10^{-6} mm aluminized Mylar — alumimized on both sides, interleaved with 5×10^{-5} mm Dexter paper. The superinsulation was slit its entire width every revolution, and joined back together with Scotch celephane tape, leaving a 3-mm gap — to lessen the chance of eddy currents building up in the aluminized surface. The Dexter paper was also used to insulate one layer of aluminized Mylar from the next.

The tank was left in its horizontal position in the lathe and slowly rotated until the wrapping of the tank was completed with the superinsulation. Care was taken not to wrap too tightly — allowing a 2.54-cm buildup. The bottom dome portion of the tank was covered by cutting patterns consisting of a center circle, with pie-shaped wedges fanning out from it. These were stacked 25.4 cm a bundle, rotating all the seams, and then inserted in the bottom by interleaving the pie-shaped pieces with the material on the sides of the tank.

The cover plate for the helium dewar is a 5-cm thick linen-base phenolic. To reduce the heat from radiation, a 30.48-cm thick styrofoam plug with a 90-cm diameter was attached beneath the cover plate. In addition, two radiation baffle plates, made from 1.59-mm thick G-10 coated with aluminized Mylar, was also attached beneath the styrofoam plug.

It took 24 hr with a 13-cfm roughing pump and a 15.2-cm diameter diffusion pump (5.08-cm diameter pumping line) to attain a vacuum of 1×10^{-4} torr. Liquid helium was directly but slowly transferred into the dewar. Soon after (about 6 hr) the liquid helium is collected at the bottom of the dewar, a vacuum of better than 5×10^{-7} torr was attained. When the liquid helium level has a depth of 80 cm and the cryostat has reached equilibrium, the measured heat leak, without the current lead feedthroughs in the cover plate, was 1.8 W. A Veeco leak detector was hooked into the pumpout port to sample the gas in the vacuum jacket between the tanks to check for possible helium permeation through the walls of the inner dewar. No helium was detectable. This was checked against a Veeco standard helium leak sensitivity calibration Type SC-4 leak rate 4.3×10^{-8} cc/s.

PERFORMANCE TESTS OF THE 1.5-MJ COIL[4]

Testing Setup

The testing setup of the 1.5-MJ coil is shown in Figs. 4 and 5. The coil is supported by a 2.54-cm thick Micarta plate which is suspended to the Micarta cover plate of the helium dewar by eight stainless steel rods, 0.64 cm in diameter. The coil terminals were carefully brought to the top flange of the coil bobbin. After removing the organic insulation in the basic cable, the coil terminal is soldered to the bottom tips of the vapor-cooled leads.

DC Current Test

Prior to the coil energization by a 5-V, 12-kA dc power supply, the heat leak of current leads were measured. The current leads were purchased from American Magnetics, Inc., and have a dc current rating of 15 kA. During the heat-leak measurement the liquid helium level was maintained between the bottom tip of the leads and the top flange of the coil. At zero current, a heat leak of 22 W was obtained. At 12 kA and in steady-state equilibrium, the heat leak was 30 W.

During the first energization of the coil, no major conductor motion was observed. Figure 6 shows the critical current and the load line of the coil. The critical current of the cable was determined from the short sample measurements of triplex cables.

To demonstrate the current sharing and to determine the cryostability of the coil, the coil was charged beyond the critical current up to 11.75 kA (from point A to point B in Fig. 6). Beyond 11 kA, a coil unbalanced voltage was observed. The unbalanced voltage increases linearly with transport current. The process is reversible and stable indicating a stable current sharing within the cable.

Pulsed Current Tests

The coil was charged and discharged by a power supply with ±650 V output voltage and 10.9 kA output current. The coil was charged to 4.4 T peak field in 0.4 s and discharged to zero in 0.6 s, achieving a maximum dB/dt of 11 T/s. The off-time between pulses was 10 s. The ramping rate is limited by the power supply rather than by the pulsed coil. The coil was energized and de-energized for more than 3000 cycle in the single pulsing operation.

To simulate the full flux swing of a superconducting ohmic heating coil, the coil was energized to 4-T peak field (10.6 kA) in 0.64 s and de-energized immediately back to zero in the next 0.64 s. Then it was immediately energized back to 4 T in 0.64 s and de-energized to zero in the next 0.64 s. The double-pulsing charging-discharging generates ac losses fully equivalent to a full flux swing of an ohmic heating coil. The full period of the double pulsing was 9.5 s with an off-time of 6.9 s. The coil had experiences more than 500 cycles of the double-pulsing operation.

AC Losses

The ac losses of the coil were determined from helium boil-off during the pulsing and from the electronic integrator method. AC losses as a function of $(dB/dt)^2$ are shown in Fig. 7. Data points of circles and triangles are obtained from the tests with single pulses, and data points marked with dark rectangulars are obtained from the double-pulsing test. The linear variation of the ac losses as a function of $\dot{B}^2$ in Fig. 7 indicates that most of the losses are due to the eddy current in the copper.

PULSING EFFECT ON CRYOSTABILITY

After the pulsing tests of the coil, another dc current test has been conducted using a 50-kA, 5-V dc power supply. This test is to investigate the pulsing effect on the cryostability of the coil. The coil was charged with a charging voltage of 0.7 V. No significant change in the critical current was observed. The coil remained in a current sharing state up to 1 kA above the critical current, and recovered to superconducting state by reducing the current. The coil was quenched when the current was further increased. The coils were quenched three times and no degradation in coil performances were observed.

ON-GOING PROGRAM

50-kA and 100-kA Cable Development

The cable configurations for a 50-kA cable and a 100-kA cable are shown in Figs. 8 and 9, respectively. These cable designs bear many similar features to that of the 12-kA cable which was successfully developed for the 1.5-MJ coil. The main differences are that the basic cables chosen for these high current cables have a larger current capacity and that stainless steel cables were introduced as the structure members of the basic cable.

The cables are designed to be operated in a 8-T field. The copper/superconductor (NbTi) ratio is about 10. Like the 12-kA cable, cryostatic stability is accomplished within the basic strand which will be coated with 0.0125-mm thick organic insulation. The thin coating will greatly reduce eddy current losses and yet allow limited current sharing. The coating is so thin that the heat transfer characteristics will be enhanced rather than hindered.

The final cable will consist of 24 basic cables fully transposed around a stainless steel strip. As shown in Figs. 8 and 9, the stainless steel strip is insulated with Formvar and then folded into the shape as shown. This will reduce its eddy current losses. The stainless steel strip will serve as the backbone for the cabling operation as well as for the structural support for the hoop load.

Design of Pulsed-Coil Structure

Because of the spongeness of a high-current cable, it is important that a large pulsed-coil structure must allow us to isolate the electromagnetic forces in both the axial and the radial direction. Figure 10 illustrates such a coil structure using a 100-kA cable. The cable, as hown in Fig. 9, will be insulated with epoxy fiberglass bands. It will be loosely fitted into a stainless steel channel (Fig. 10). The winding bobbin will be a G-10 cylinder. The stainless steel strip which may or may not be welded to the channel, will support both the axial and the radial electromagnetic forces. Since the cable will be loosely fitted into the channel, the coil body forces could not be accumulated to the cable. The coil axial forces will be bridged through G-10 plates. Turn-to-turn insulation will be provided by a 1-mm thick G-10 or pultruded fiberglass strip.

Large Plastic Helium Dewar for Pancake Coil Performance Test

To evaluate the performance of the 50-kA/100-kA high-current cable, a large plastic dewar with 50-kA/100-kA current leads must be developed. The design of the testing dewar is shown in Fig. 11 and the photographs of these plastic tanks is shown in Fig. 12. The plastic cryostat will consist of two tanks with 100 layers of superinsulation between. The dimensions of both tanks and that of the dewar cover plate are indicated in Fig. 11. An aluminum alloy supporting stand will be incorporated into the outer tank so that the dewar could be supported in an upright position. The coil weight will be supported by an external support frame.

CONCLUSION

We have demonstrated that high-current cryostable cables and large fast-pulsed superconducting coils could be operated with good stability and relatively low ac losses. We have also demonstrated an inexpensive technology for fabricating large plastic helium dewars for fast-pulsed superconducting coils. Using these techniques, we believe one could successfully develop much larger pulsed superconducting coils for energy storage or superconducting ohmic heating coils.

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FIGURE CAPTIONS

Fig. 1. 12-kA cable.

Fig. 2. Closeup of the 12-kA cable cross section.

Fig. 3. Setup for the 1.5-MJ coil winding.

Fig. 4. Setup for the 1.5-MJ coil tests.

Fig. 5. Plastic helium cryostat for the 1.5-MJ coil.

Fig. 6. 12-kA cable short sample characteristics and the load line of the 1.5-MJ coil.

Fig. 7. AC losses versus $(dB/dt)^2$.

Fig. 8. 50-kA ac superconducting cable.

Fig. 9. 100-kA cable conductor.

Fig. 10. Pulsed-coil structure.

Fig. 11. Plastic dewar for high-current cable pancake coils.

Fig. 12. Inner and outer plastic tanks for the helium dewars.

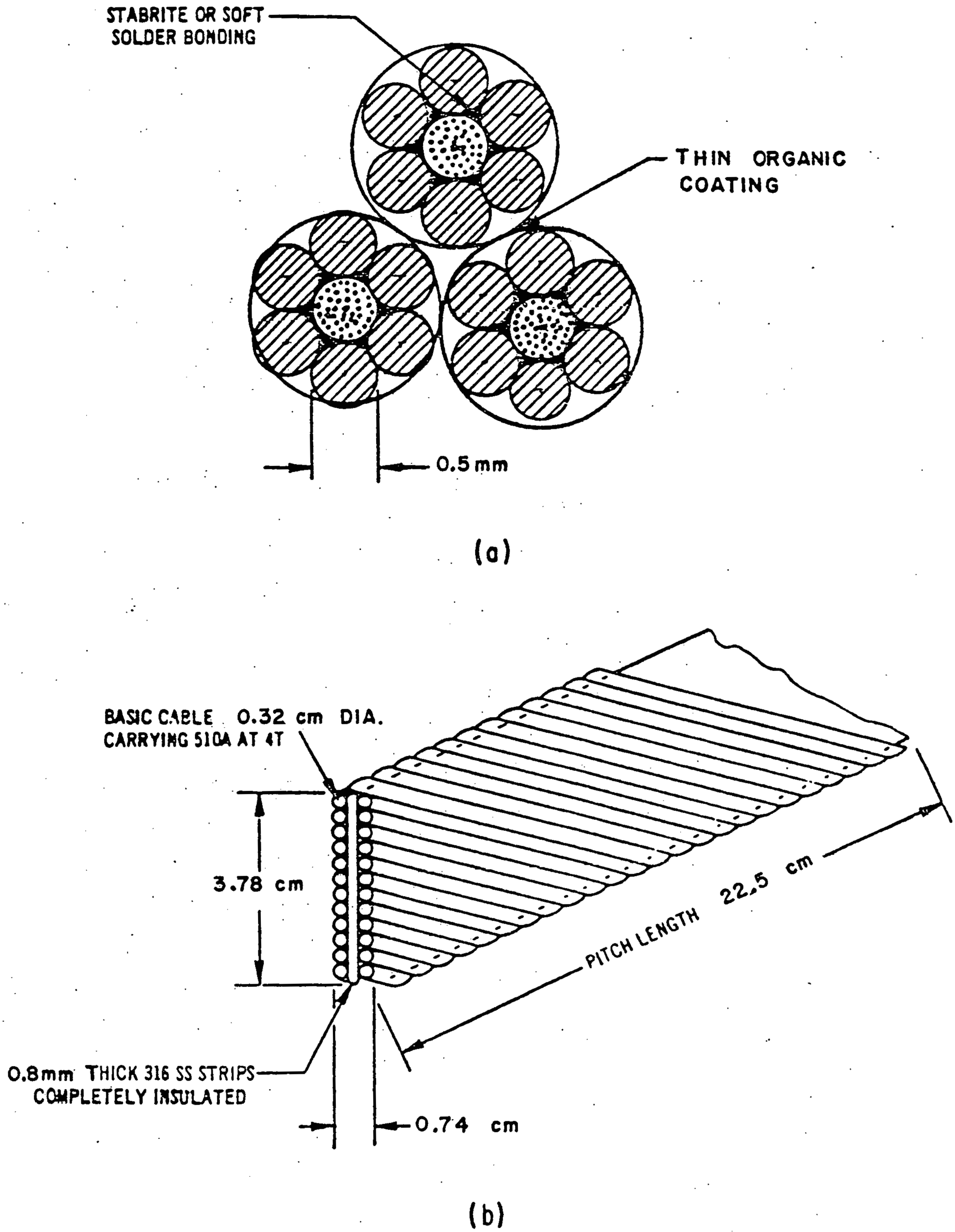

Fig. 1. 12-kA cable.

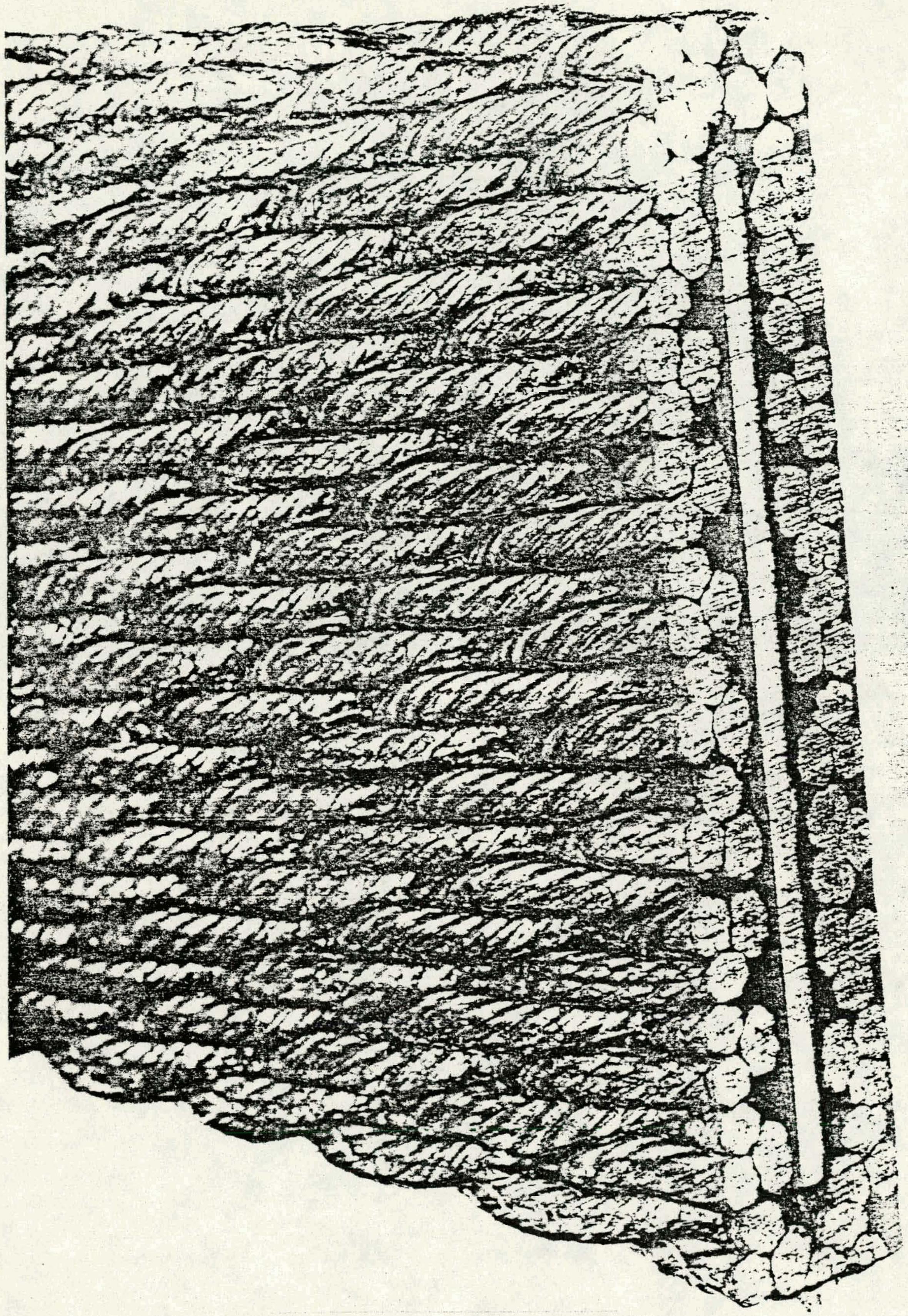

Fig. 2. Closeup of the 12-kA cable cross section.

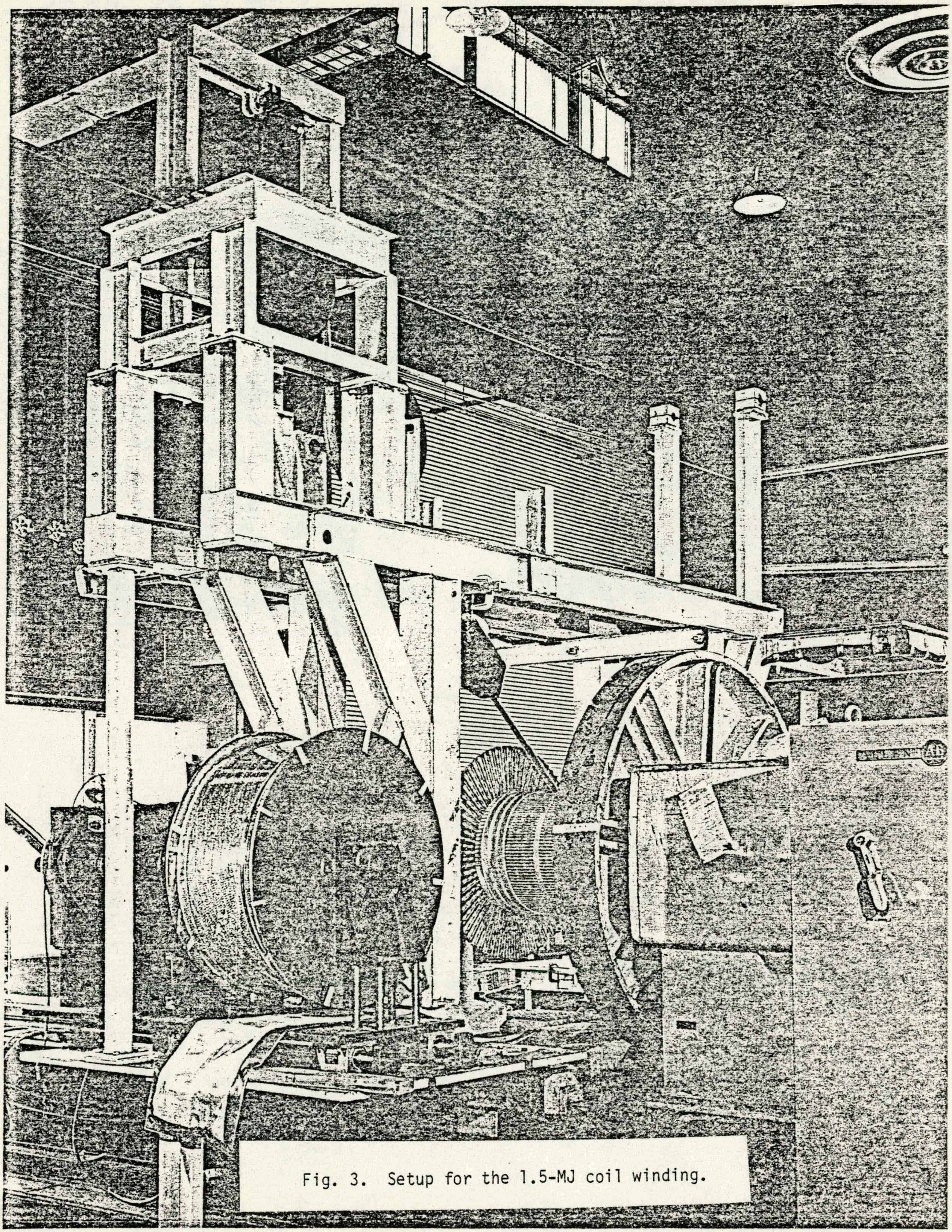

Fig. 3. Setup for the 1.5-MJ coil winding.

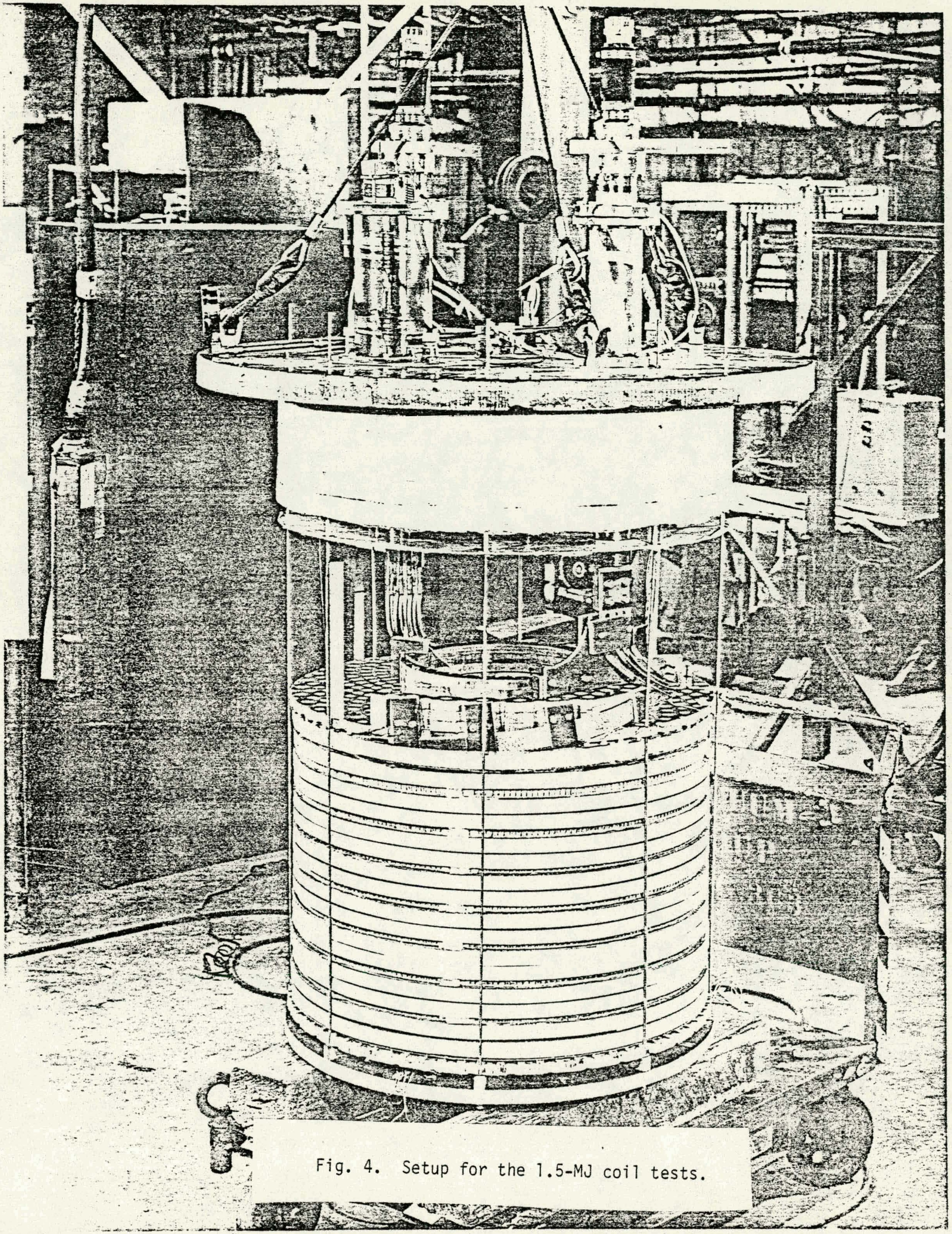

Fig. 4. Setup for the 1.5-MJ coil tests.

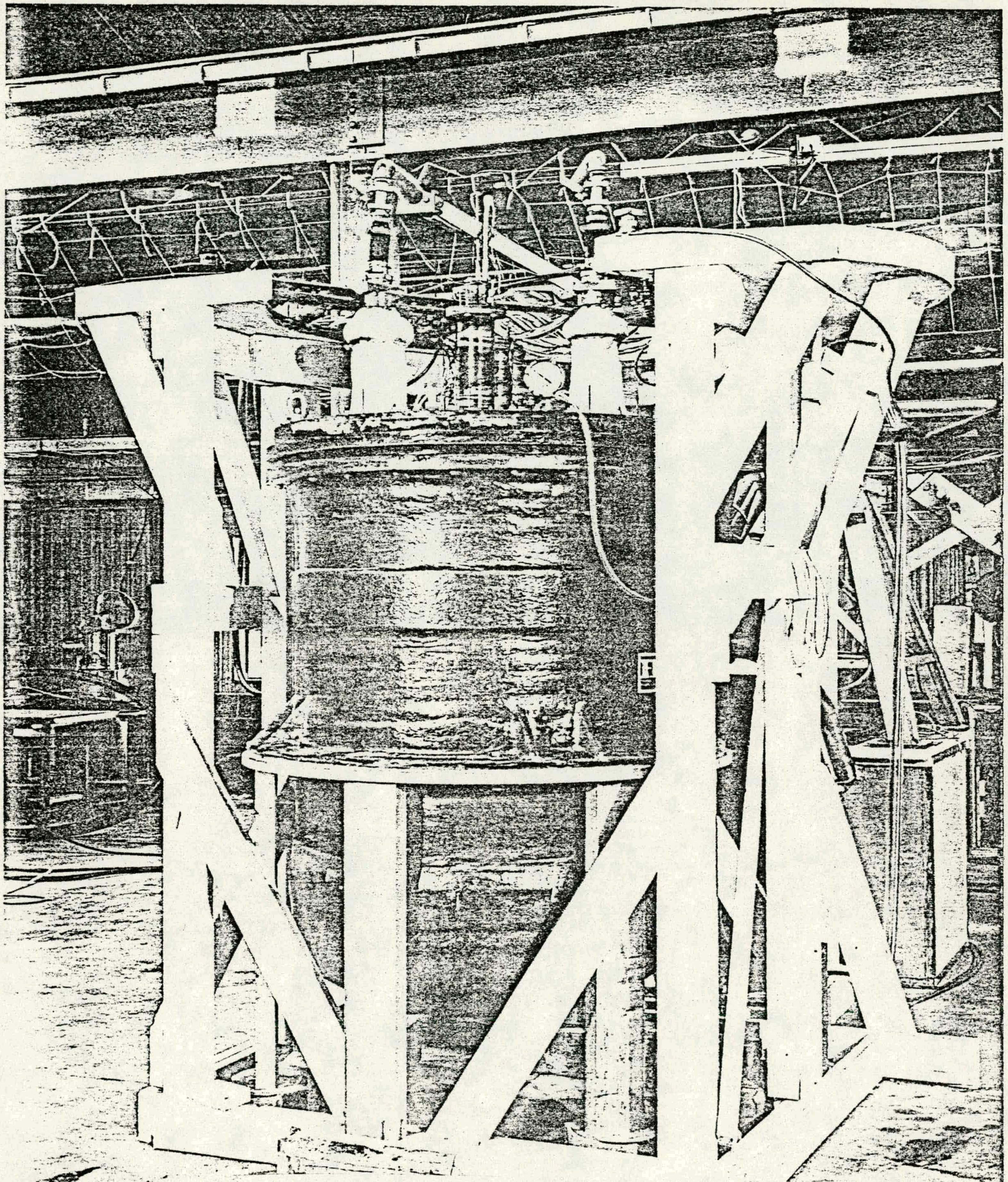

Fig. 5. Plastic helium cryostat for the 1.5-MJ coil.

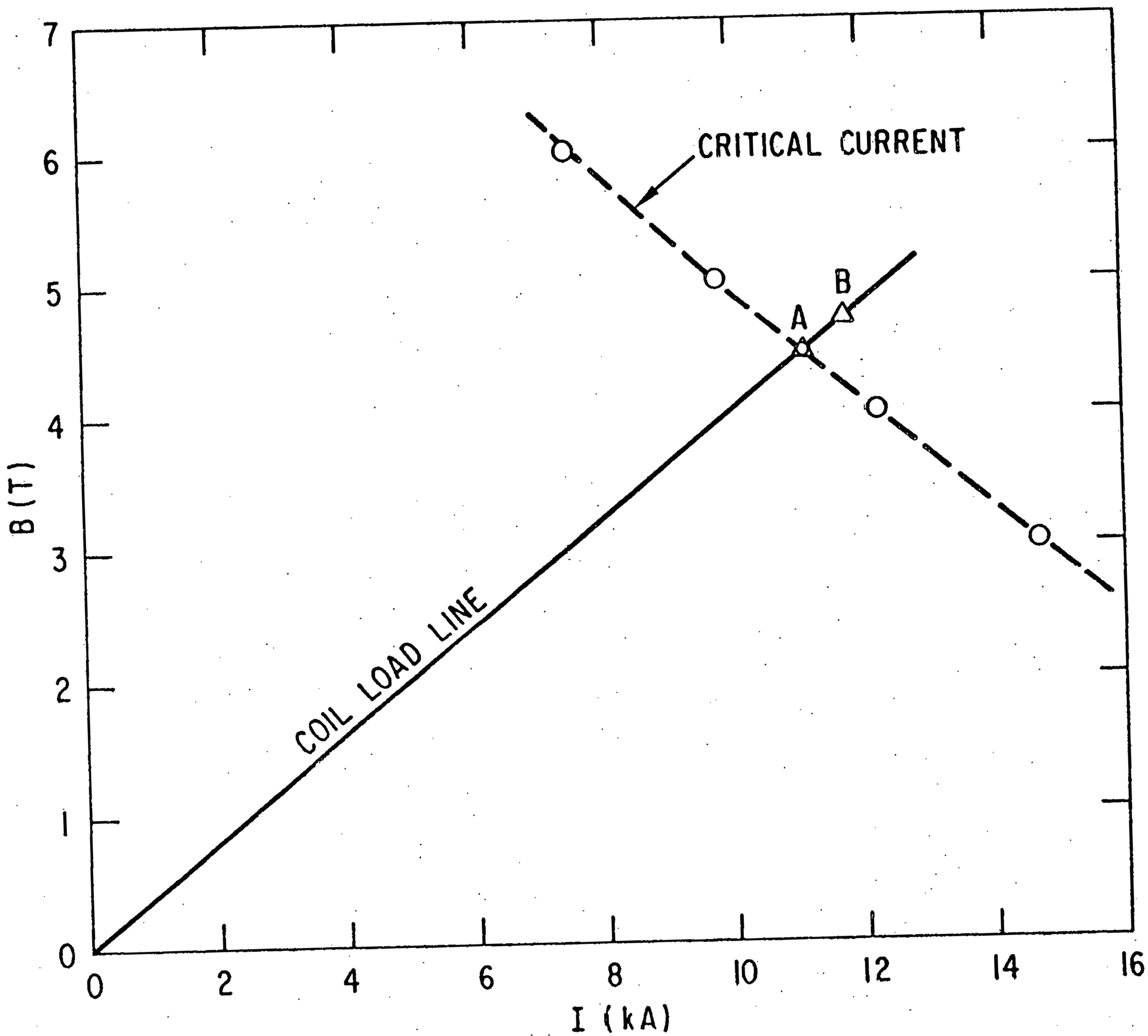

Fig. 6. 12-kA cable short sample characteristics and the load line of the 1.5-MJ coil.

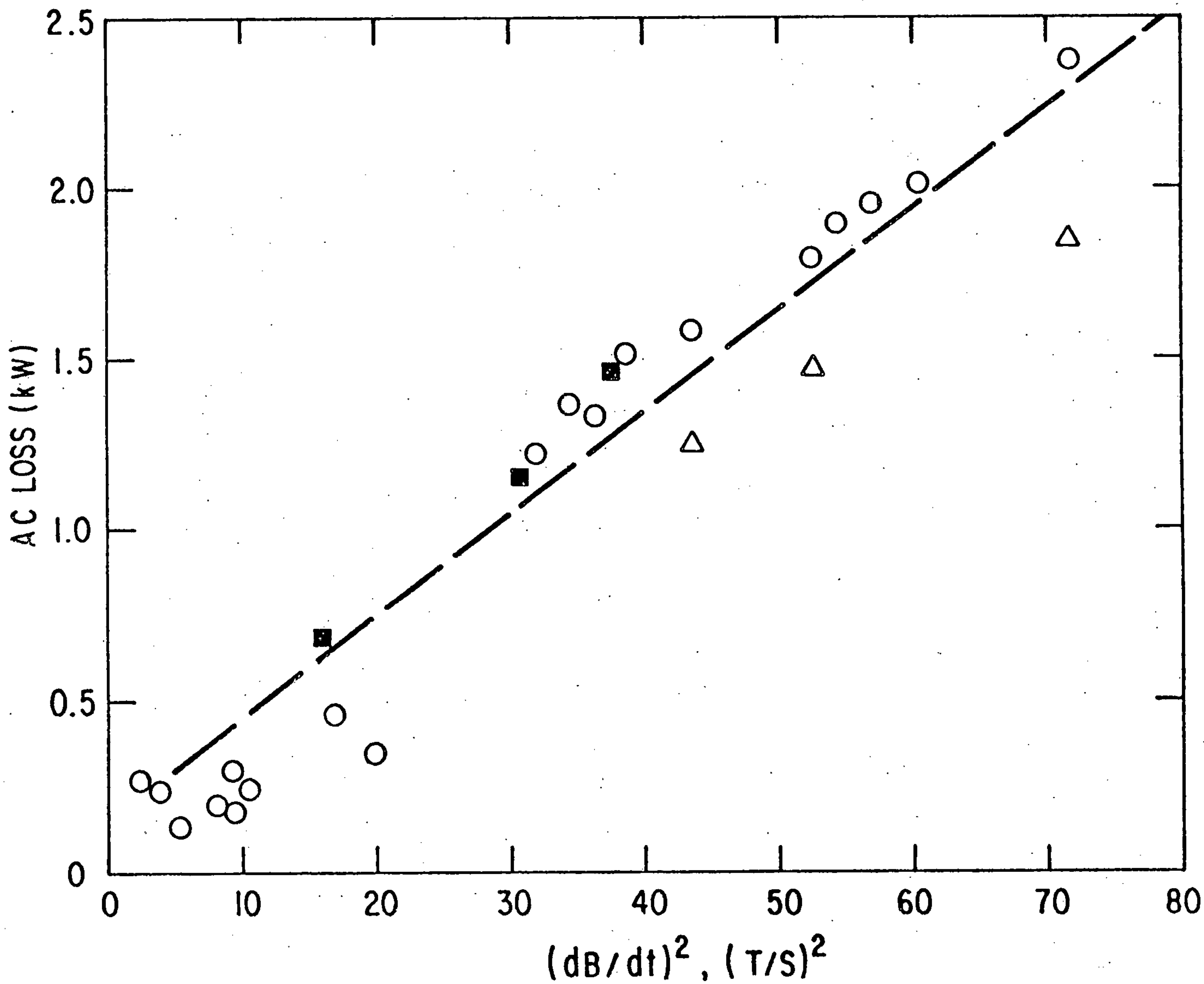

Fig. 7. AC losses versus $(dB/dt)^2$.

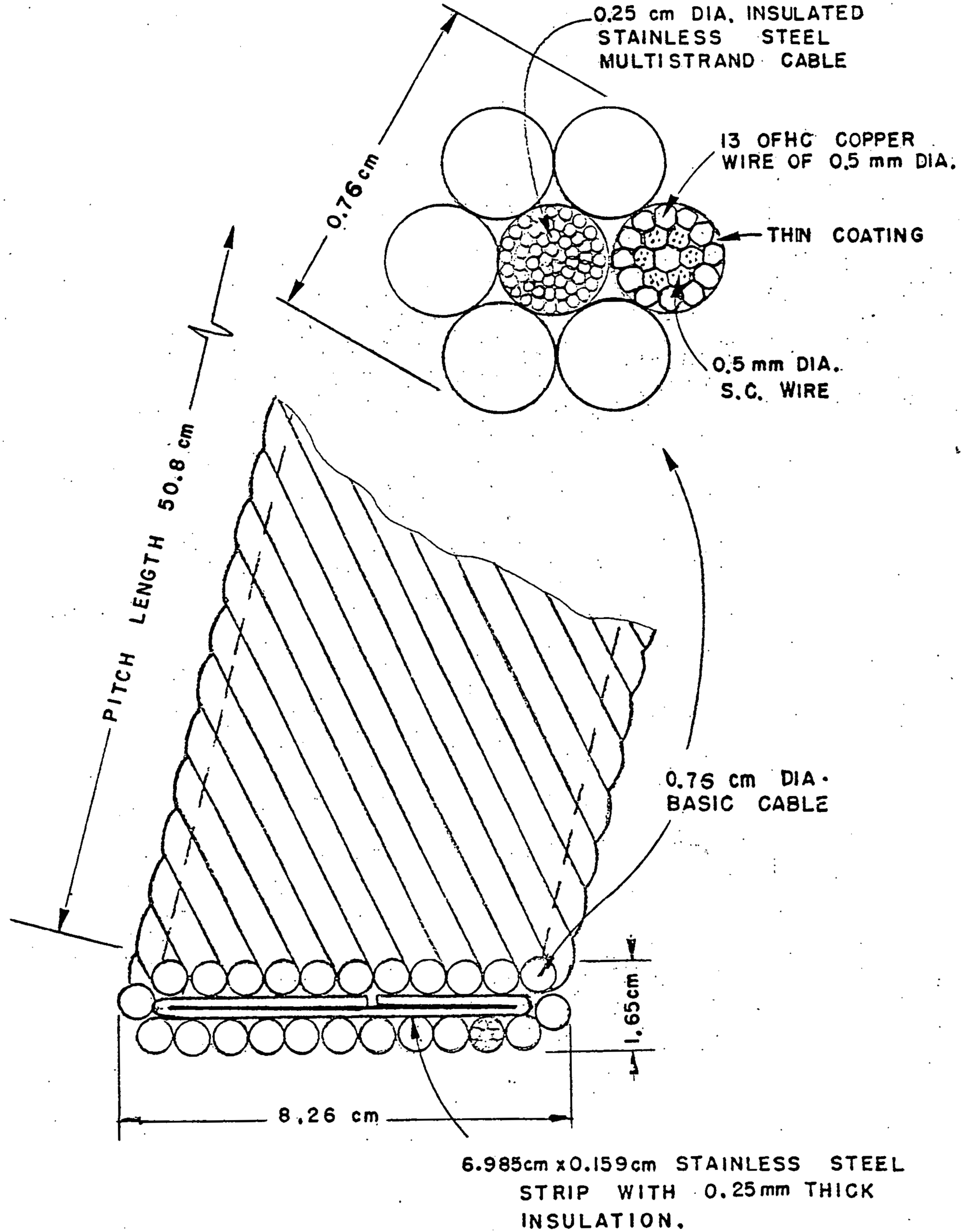

Fig. 8. 50-kA ac superconducting cable.

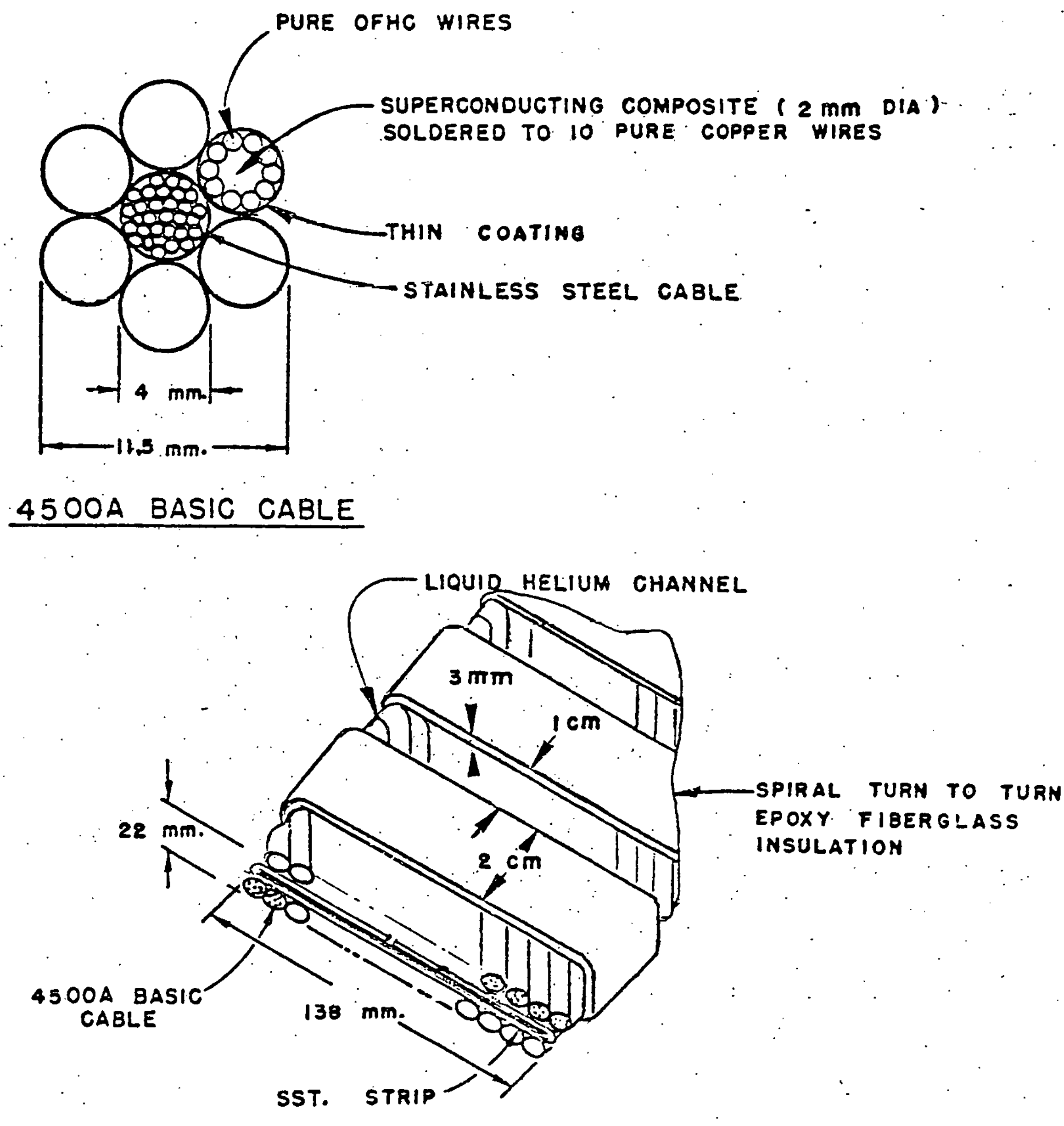

Fig. 9. 100-kA cable conductor.

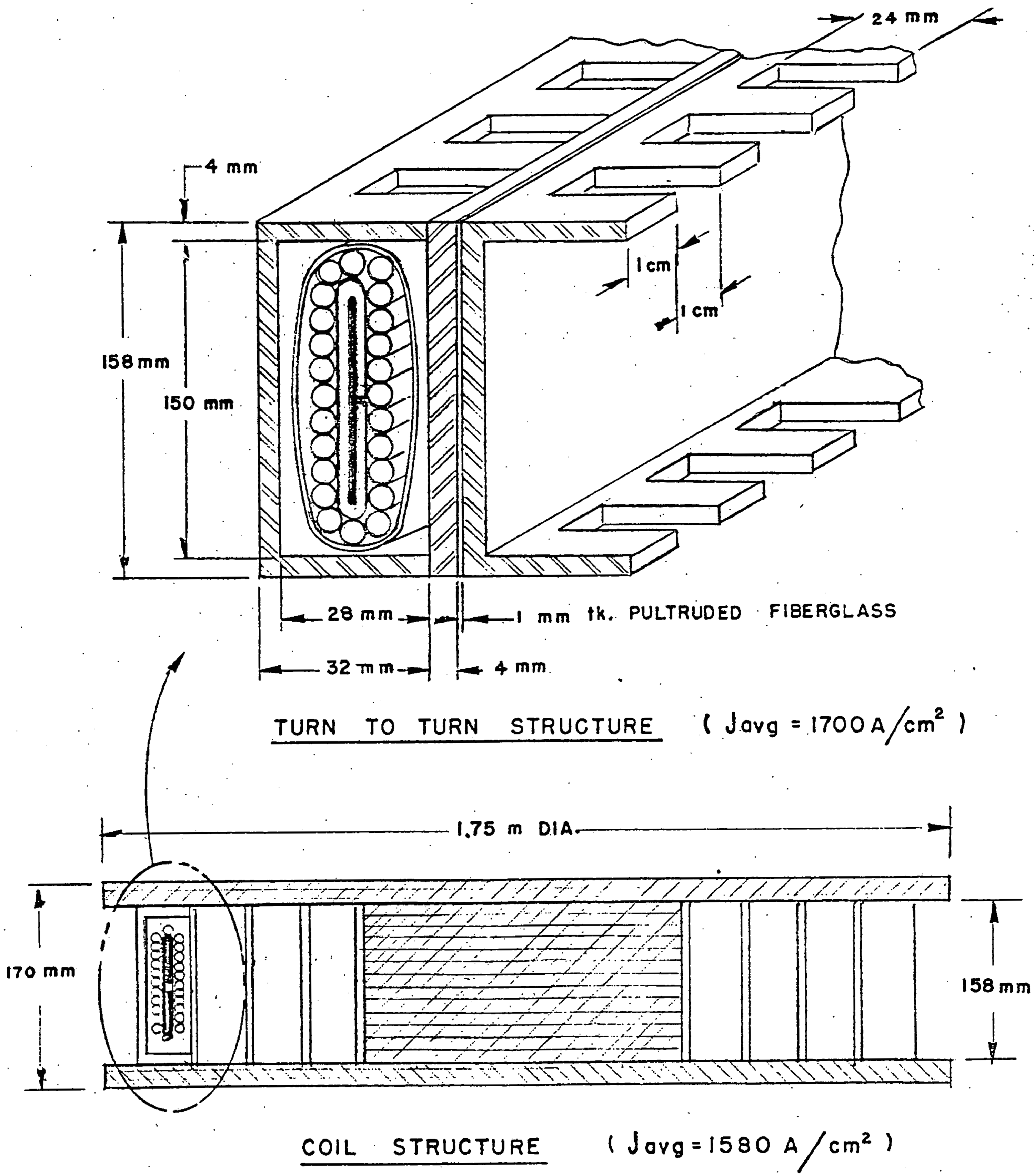

Fig. 10. Pulsed-coil structure.

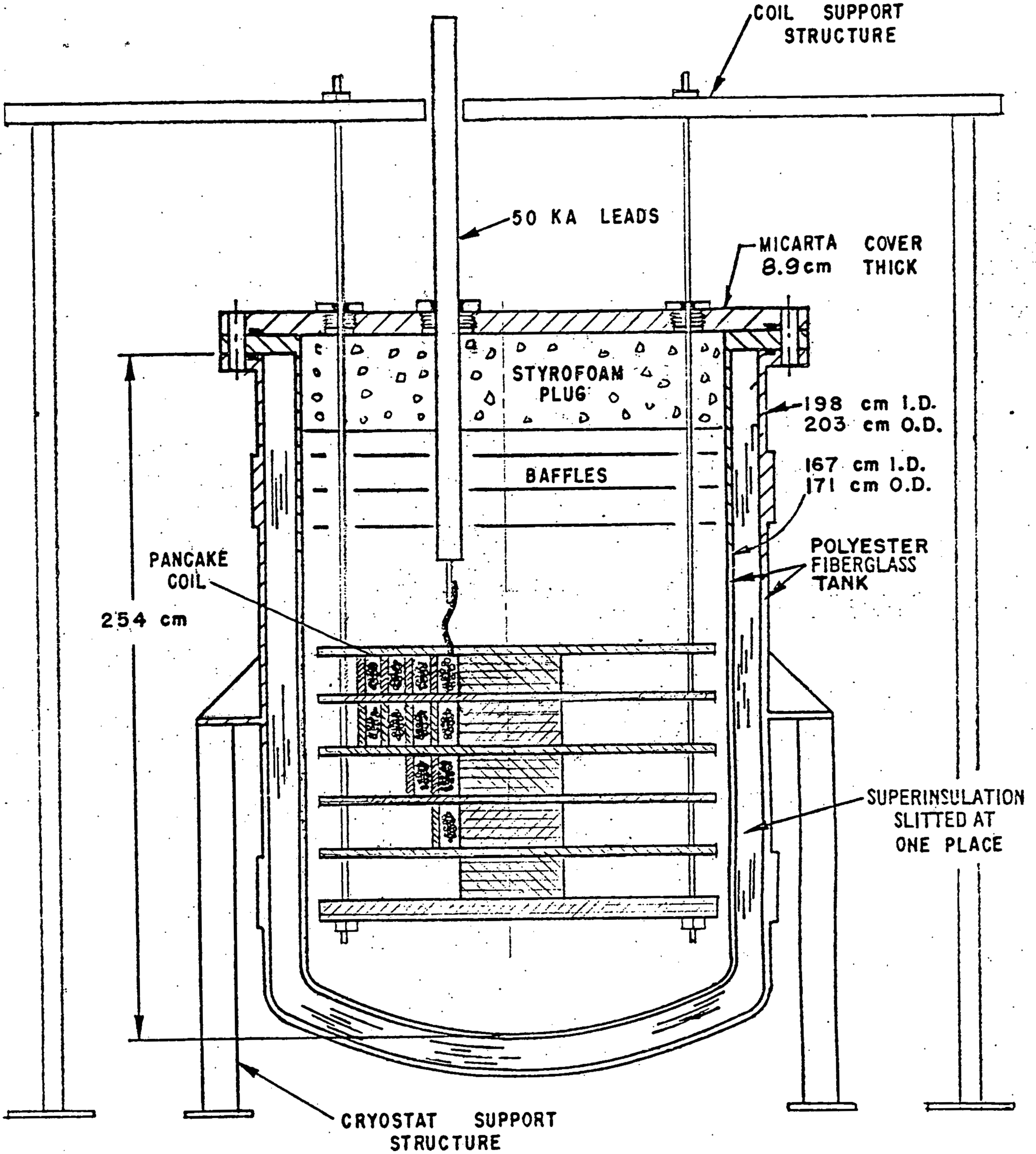

Fig. 11. Plastic dewar for high-current cable pancake coils.

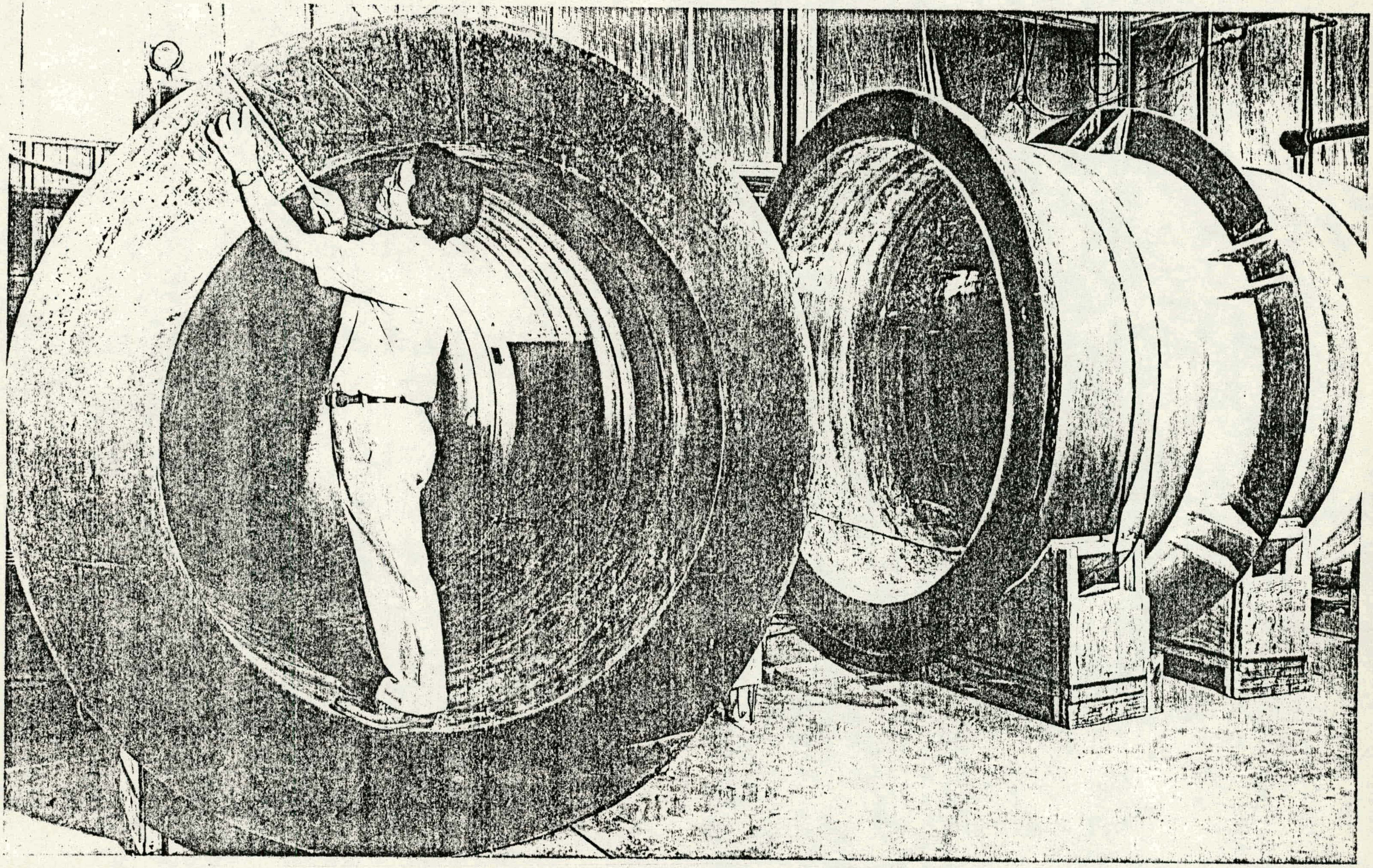

Fig. 12. Inner and outer plastic tanks for the helium dewars.