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OPERATING CHARACTERISTICS OF THE 1.5 MJ PULSED SUPERCONDUCTING COIL

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by

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OPERATING CHARACTERISTICS OF THE 1.5 MJ PULSED SUPERCONDUCTING COIL*

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INTRODUCTION

The ohmic heating coils of Tokamak Fusion Reactors require a stored energy on the order of 1 GJ, a ramping rate of ∿ 9 T/s, and a peak operation current of 50 ∿ 100 kA. Due to power balance requirements of the reactors at these sizes, only superconducting coils are expected to be economical. For the development of the ohmic heating coils, a cryostable pulsed superconducting coil has been constructed and tested at Argonne National Laboratory. The coil has a stored energy of 1.5 MJ and a peak field of 4.5 T at the peak operation current of 11.2 kA. The coil was tested with boch DC and pulsed currents.

FABRICATION OF THE CABLE

The design of the cable for the 1.5 MJ coil is based on detailed cryostability studies of basic cables and 5 kJ model coils [1]. The cable was fabricated by Supercon, Inc., to Argonne National Laboratory specifications by twisting 24 basic cables around an insulated stainless steel strip with a twist pitch of 22.5 cm. A close-up of the cable cross section is shown in Fig. 1. The basic cable is made by twisting three seven-strand conductors (triplex cable) with a twist pitch of 2.2 cm. The seven-strand conductors are made of six OFHC copper wires twisted around a superconducting center conductor and soldered with staybrite. Since the

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requirements of low ac losses and cryostability conflict with each other, the basic principle chosen is to achieve cryostability within the basic cable. To restrict ac coupling among the 24 triplex cables in the final cable, only limited current sharing among the triplex is allowed by coating a thin insulating film around the seven-strand conductors. The critical current of a short sample of the basic cable is 405 A at 5 T. Each superconducting strand has a diameter of 0.051 cm containing 2041 6-μ filaments with twist pitch of 1.27 cm and a copper superconducting ratio of 1.8.

The final cable is compressed during the cabling with heavy rolls from four sides. This is required to minimize mechanical perturbations of the basic conductors during pulsing of the 1.5 MJ coil. The compression did not damage the insulation between the stainless steel strip and the 24 triplex cables. However, due to the deformation of the soft soldering in the seven-strand conductor, about 5% degradation of the recovery current in the triplex has been observed. The dimensions of the finished cable are 3.78 cm wide and 0.74 cm thick. The first 25-m long cable was produced as a test of the cabling technique. The total cable length fabricated for the coil was about 590-m long.

1.5 MJ COIL FABRICATION

Coil winding with a spongeous cable is a rather interesting experience. The coil is composed of 18 helical layers with an average of 14.3 turns in each layer. Turn-to-turn insulations are provided by two layers of 0.02 cm thick glass-cloth tape and two layers of 0.01 cm thick Mylar tape. The winding layers for the first to tenth layers are separated by 0.48 cm thick and 0.64 cm wide G-10 strips. In the low field region of the 11th to 18th layer, the thickness of the strips is reduced to 0.32 cm. Characteristics of the coil are listed in Table I.

Figure 2 is a close-up of the coil winding in the thirteenth layer. Spaces between the strips provide 0.64 cm wide cooling channels in the vertical direction. The G-10 bobbin has cooling channels in the radial direction. During the winding, the tension in the cable was increased gradually from 225 kg to 450 kg to provide a constant radial pressure in the coil. Total length of the cable used for the coil is about 510 cm. Nine potential taps have been installed in the coil to study possible conductor motion and six thermocouples to monitor temperature variation during the test of the coil. When the coil is charged, the average hoop stress in the cable is about 310 MN/m^2. Part of the stress can be sustained by the stainless steel strip in the cable itself. To support the excess stress, 16 bands are placed outside the coil. Each band is made of 30 layers of 0.025 cm thick by 3.2 cm wide fiberglass cloth.

SET-UP OF THE COIL TESTS

The 1.5 MJ coil is assembled for tests as shown in Fig. 3. Most of the materials used for the set-up are non-metallic to avoid eddy current losses during the pulsing of the coil. The top flange is made of 5.7 cm thick micarta plate. The coil is suspended to the top flange using eight 0.64 cm dia. stainless steel rods. Bottom of the coil is further supported by a 2.54 cm thick micarta plate. As thermal radiation shields, a 10 cm thick piece of styrofoam and 8 layers of aluminum foil are attached to the bottom of the top flange. The two coil terminals are brought to the top of the coil by gradually changing the winding angles. After removing the thin insulation in the basic cable, each terminal is soft soldered to eight copper stabilized monolithic superconductor of 1 cm wide and 0.2 cm thick. This is to change the directions of the terminals easily and to make the terminals mechanically solid. Then the terminals are connected to the bottom tips of the vapor cooled current leads.

The leads purchased from American Magnetics Inc., have a current capacity of up to 15 kA DC. Heat leaks of the leads are about 22 W without current and 30 W with 12 kA DC current. During the test of the coil the liquid helium level should be maintained between the bottom tips of the leads and top of the coil. The distance between them is about 23 cm, which corresponds to the helium boil-off energy of about 380 kJ. It turned out that with this energy the coil could be pulsed about 140 times with a pulsing rate of 9 T/s.

DC CURRENT SHARING

The 1.5 MJ coil was first charged up to the critical current of 11.2 kA of the short sample cable by a 5 V, 12 kA dc power supply. During the first charge of the coil no major conductor motion or mechanical perturbation was observed. Figure 4 shows the critical current and the load line of the coil. The critical current of the cable is determined from measurements of the critical current of short sample triplex cable.

To demonstrate the cryostability of the coil, it was charged beyond the critical current up to 11.75 kA (from point A to point B in Fig. 4). A bridge circuit was used to detect when parts of the coil in the high field region go normal. Beyond the critical current, unbalanced voltage of the bridge increased gradually, indicating a stable current sharing between the superconducting filaments and the copper stabilizer. The current sharing section, with a resistive voltage of 2 mV, is estimated to be about 1.5 m long in the cable. Charging the coil up to point A without developing a resistive voltage is a significant result. This means that the cable is fully transposed and the current carrying capacity of each of the 24 basic cables is equal without any degradation.

PULSED CURRENT TESTS

Single Pulsing. After the current sharing test, the coil was pulsed with a 7 MW (650 V at 10.9 kA) power supply. A summary of the pulsed current characteristics is shown in Table I. The coil was charged to 4.4 T peak field in 0.4 sec and discharged to zero in 0.6 sec with a maximum ramping rate of 11 T/s. The off-time between pulses was 10 sec. The terminal voltage of the coil, V_{coil}, can be written as

$$V_{coil} = L\frac{dI}{dt} + V_{loss}, \qquad (1)$$

where L is the inductance of the coil and V_{loss} is the voltage associated with the energy losses in the coil during pulsing. Figure 5 is a set of recordings for a typical pulsing test. In this figure the peak current is 10 kA with a pulsing time of 1 sec. Left side of the figure is an expansion of the recording, and right side shows a continuous pulsing between off-time of 10 sec. The current variation dI/dt is close to a triangular waveform (Fig. 5a) with a maximum rate of 27 kA/s. This rate is not limited by the coil performance but by the power supply used. The terminal voltage of the coil, V_{coil}, (Fig. 5b) is balanced with an inductive voltage taken from a mutual inductor placed outside of the coil. The resulting loss voltage V_{coil}, is shown in Fig. 5c.

Double Pulsing. After more than 3000 single pulses the coil was tested with double triangular waveform pulses as shown in Fig. 6. The double pulsing mode was used to simulate the full flux swing of ohmic heating coils. The peak current during the pulsing was 10.6 kA with a central field of 4.0 T. The current waveform is shown in Fig. 6a. The full period of the double pulsing was 9.5 sec. with an off-time of 6.9 sec. The charging and discharging times were about 0.64 sec., respectively, in each pulse. The double pulse at the left side of the figure is an expansion of the pulses at the right side of the figure. Potential leads are tapped to several layers of the coil. The potentials between layers number 2 and 4, and between layers number 12 and 14 are shown in Fig. 6b and 6d, respectively. After 570 double pulsing cycles no visible differences between the two voltage waveforms have been observed.

AC LOSSES

The AC losses of the coil were determined from helium boil-off during the pulsing and from the electronic integrator method [2,3]. 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. Eddy current losses in the copper stabilizer can be expressed as [4]

$$P_{ed} = V_{cu}\left[\left(\frac{\ell_p}{2\pi}\right)^2 + \left(\frac{R}{2}\right)^2\right]\left(\frac{R}{R_t}\right)^2 \frac{\dot{B}^2}{\rho_\perp} \qquad (2)$$

where V_{cu} is the volume of copper, ℓ_p is the twist pitch length, R is the radius of superconducting wire, $\rho_\perp$ is the effective transverse resistivity, and R_t is the conductor radius including copper stabilizer. 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.

The insulation on the surface of the six-strand wire is thin enough to have limited current sharing among the triplex cable [2]. This will allow certain degree of ac coupling among the 24 triplex cable of the 15 MJ coil. If the coupling is assumed to be limited within the six-strand wire, from the experimental data of Fig. 7 and Eq. (2) the effective resistivity is found to be about 2×10^{-10} Ω-m, which is somewhat lower than expected. This is an indication that some portion of the ac losses come from the ac coupling among the triplex cables and the six-strand wires. From the above results one can conclude that the thin insulation of the 1.5 MJ coil cable has a right thickness to compromise the current sharing and low ac losses.

PULSING EFFECT ON THE CRYOSTABILITY

After the pulsing tests of the coil, another DC current test has been conductor using a 50 kA, 5V 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 0.7V. No significant change in the critical current has been 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 amount of the energy released in the quench estimated from the blow out of the helium is approximately 0.5 MJ. In the subsequent charging, discharging, and quench, no significant changes in the characteristics of the coil have been observed.

SUMMARY

It is demonstrated for the first time that a relatively large cryostable superconducting coil can be pulsed with relatively low ac losses at high ramping rates. The low ac losses with limited current sharing have been achieved by insulating the surface of the basic cable with thin organic film. The ac losses at 9 T/s are about 0.1% of the stored energy in the coil. After more than 4000 pulsing cycles, no changes in the pulsing characteristics and cryostability of the coil have been observed. The quench current of the coil is approximately 1 kA higher than the critical current of the coil.

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TABLE I

CHARACTERISTICS OF THE

PULSED SUPERCONDUCTING COIL

Central Field	4.2 T
Peak Field	4.5 T
Operation Current	11 kA
Inductance	24 mH
Coil ID	41.6 cm
Coil OD	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 cm x 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

FIGURE CAPTIONS

Fig. 1 Cross Section of the AC Cable.

Fig. 2 Thirteenth Layer of the 1.5 MJ Coil Winding.

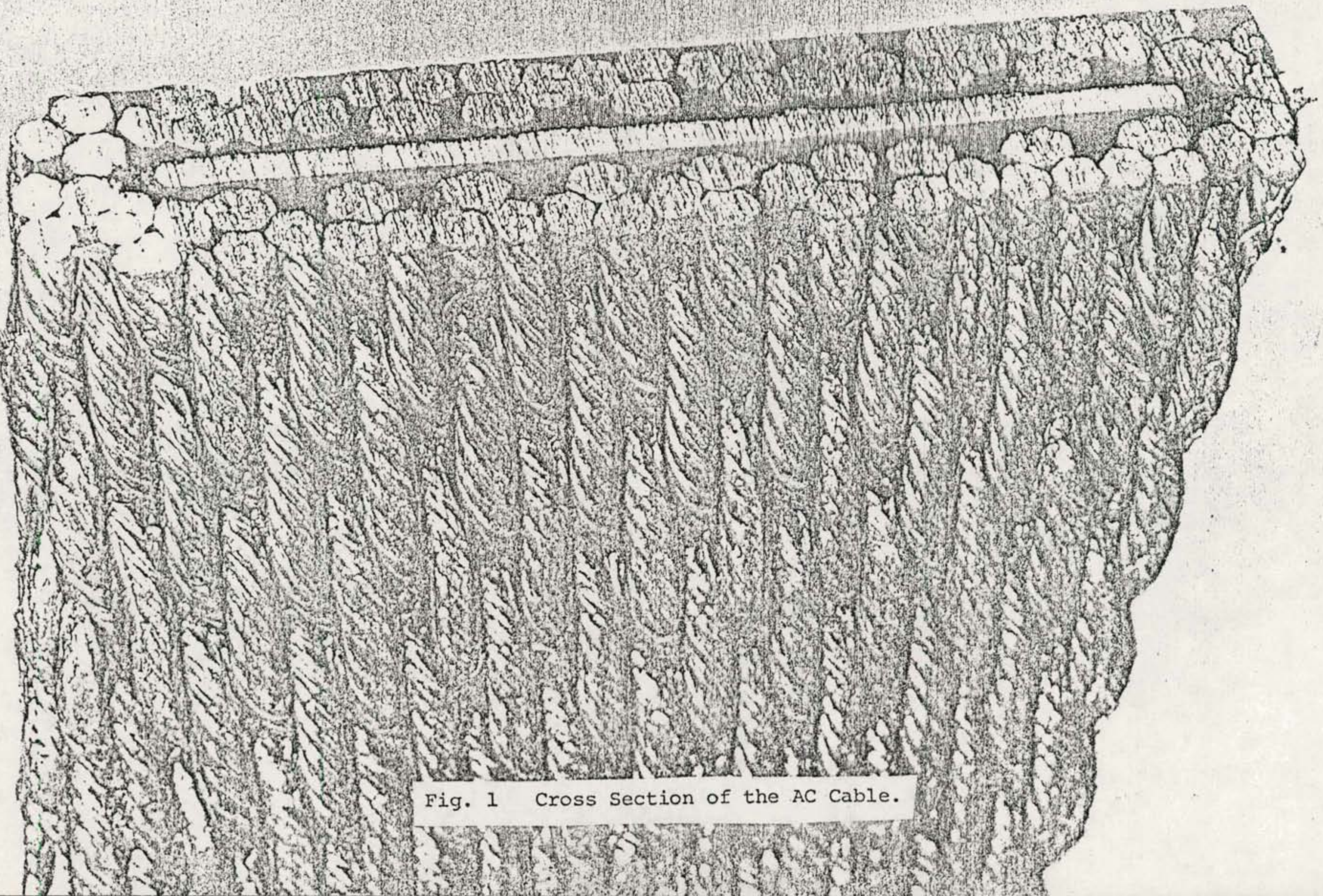
Fig. 3 Set-up of the 1.5 MJ Coil for Tests.

Fig. 4 Critical Current of the Short Sample Cable and the Load Line of the 1.5 MJ Coil.

Fig. 5 Recording of a Single Pulsing Test. (a) Current Waveform, (b) Coil Terminal Voltage, (c) Loss Voltage, (d) Integrated Loss Voltage.

Fig. 6 Recording of a Double Pulsing Test. (a) Current Waveform, (b) Voltage of 2-4th Layer of the Coil (2V/div.), (c) Loss Voltage of the Coil (0.2V/div.), (d) Voltage of 12-14th Layer (5V/div.).

Fig. 7 AC Losses vs. $(dB/dt)^2$. Data Points of Circles and Triangles are Obtained from Single Pulsing Tests and Rectangulars are from Double Pulsing Tests.



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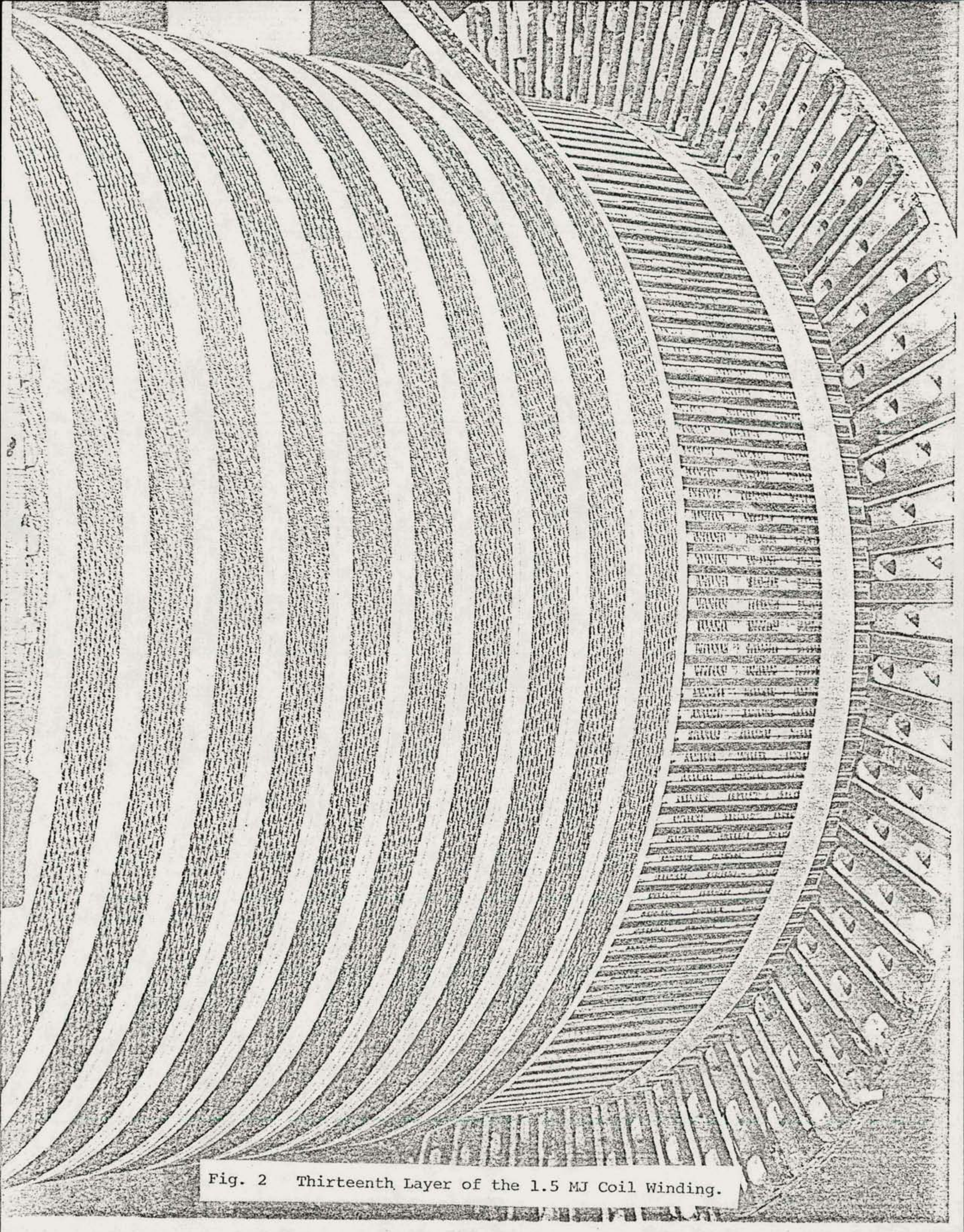
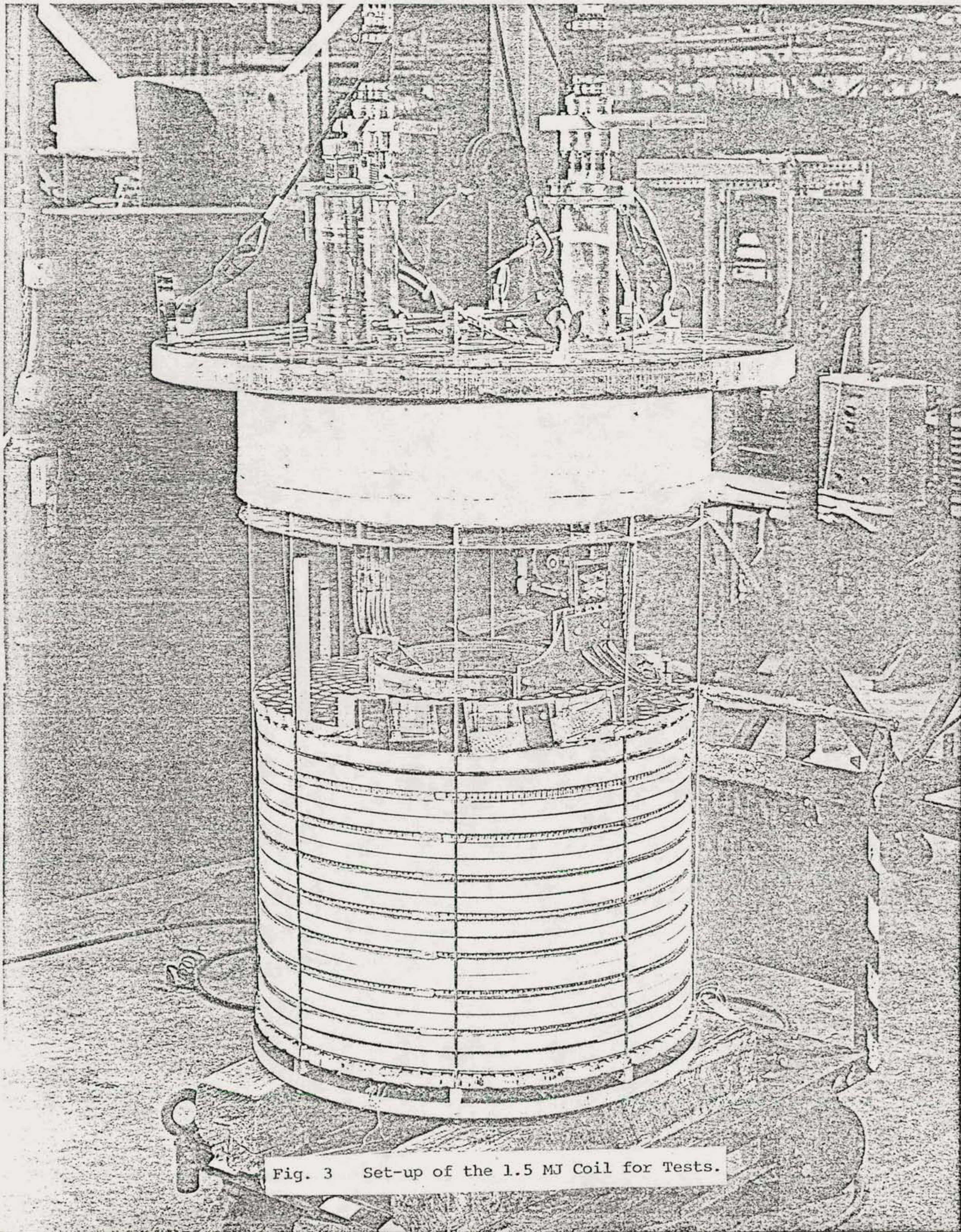


Fig. 2 Thirteenth Layer of the 1.5 MJ Coil Winding.



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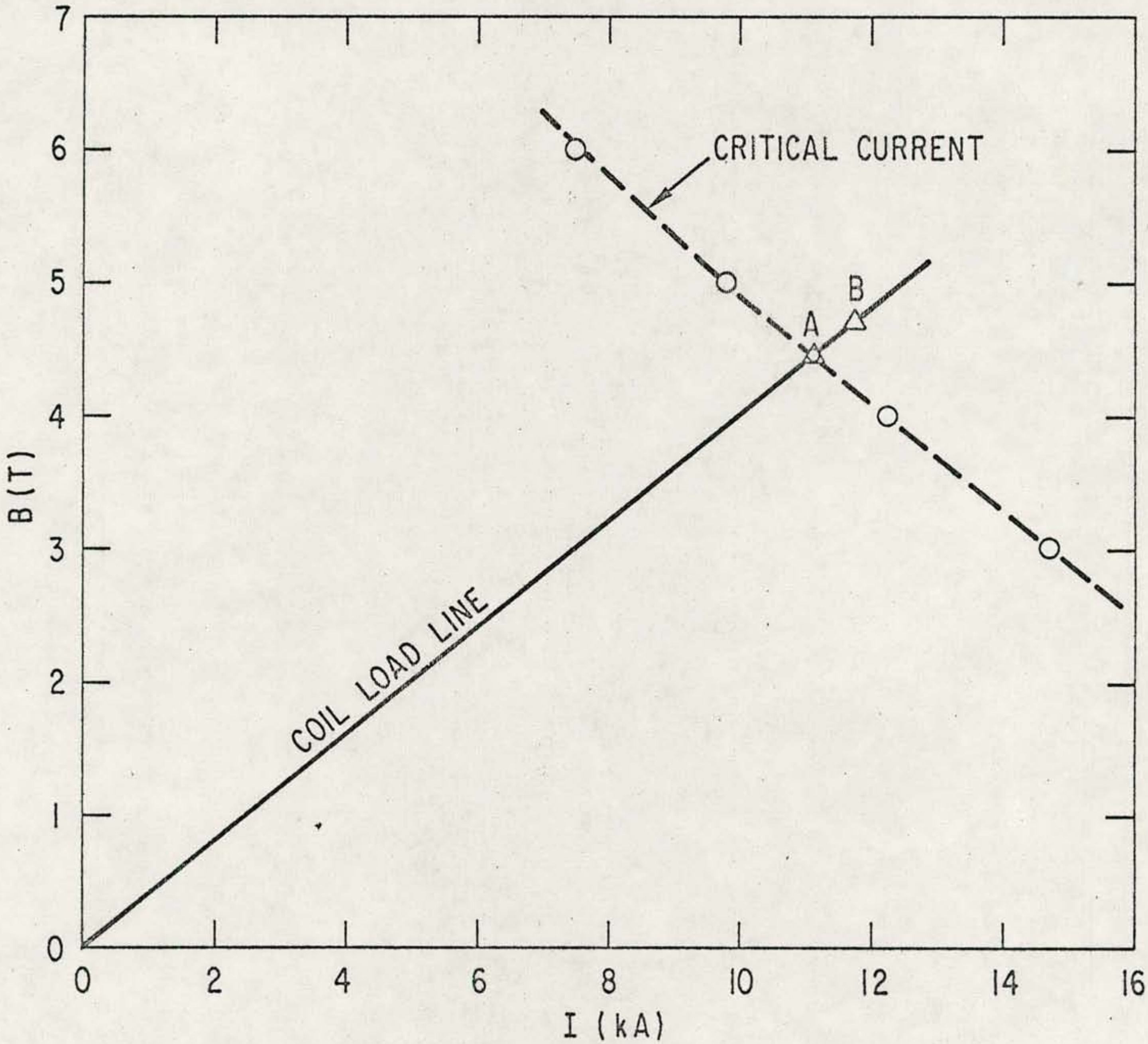
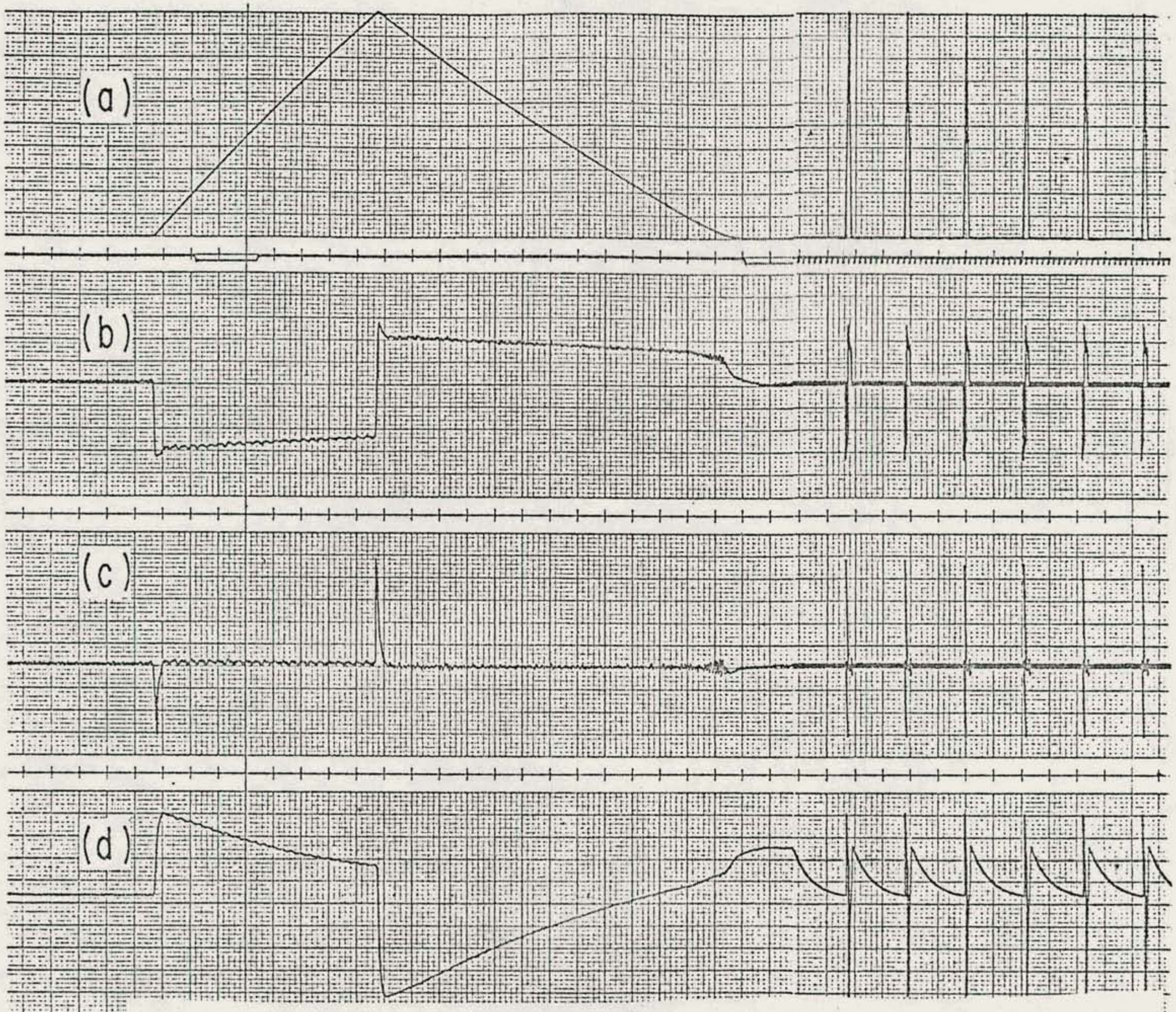


Fig. 4 Critical Current of the Short Sample Cable and the Load Line of the 1.5 MJ Coil.



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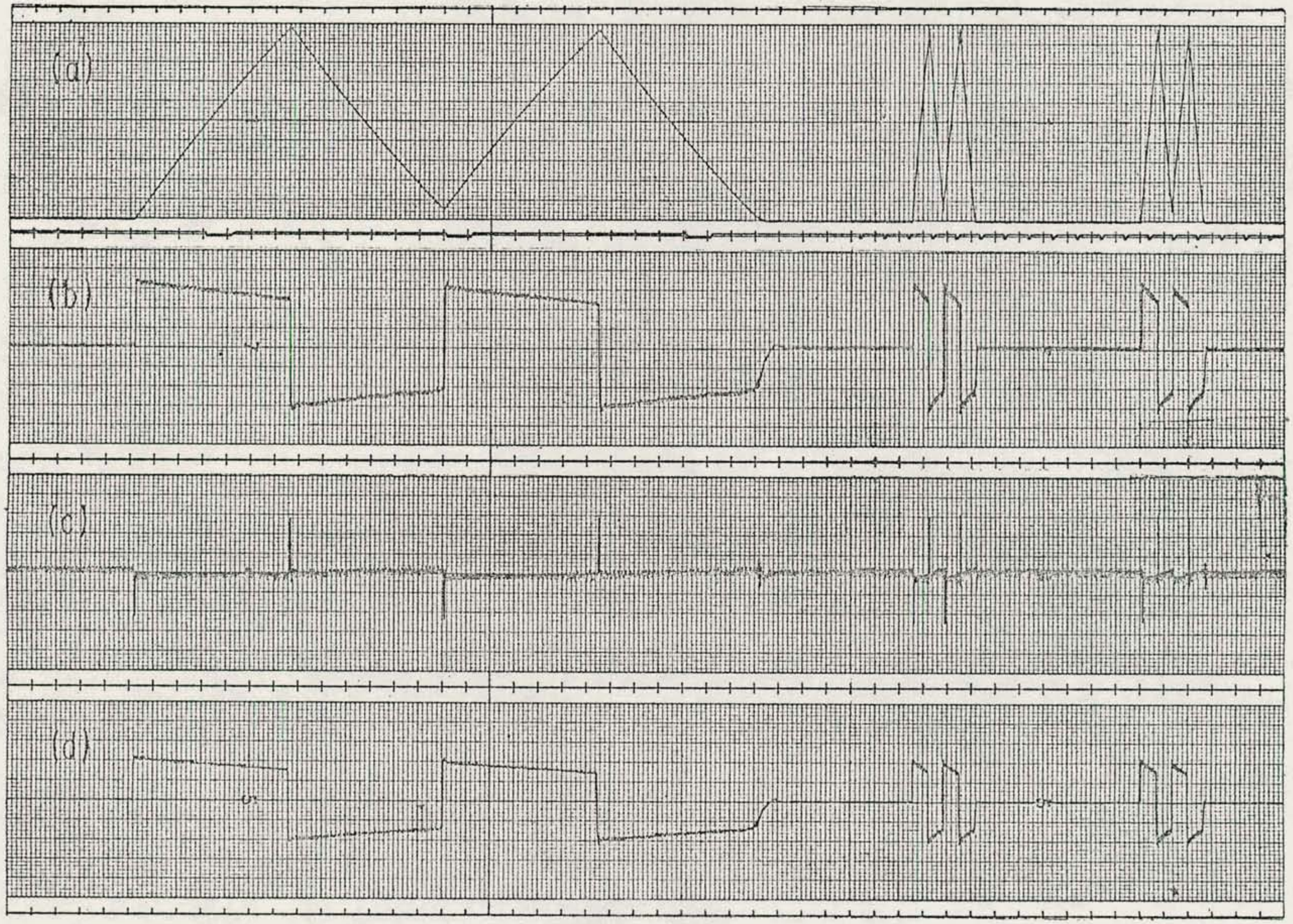

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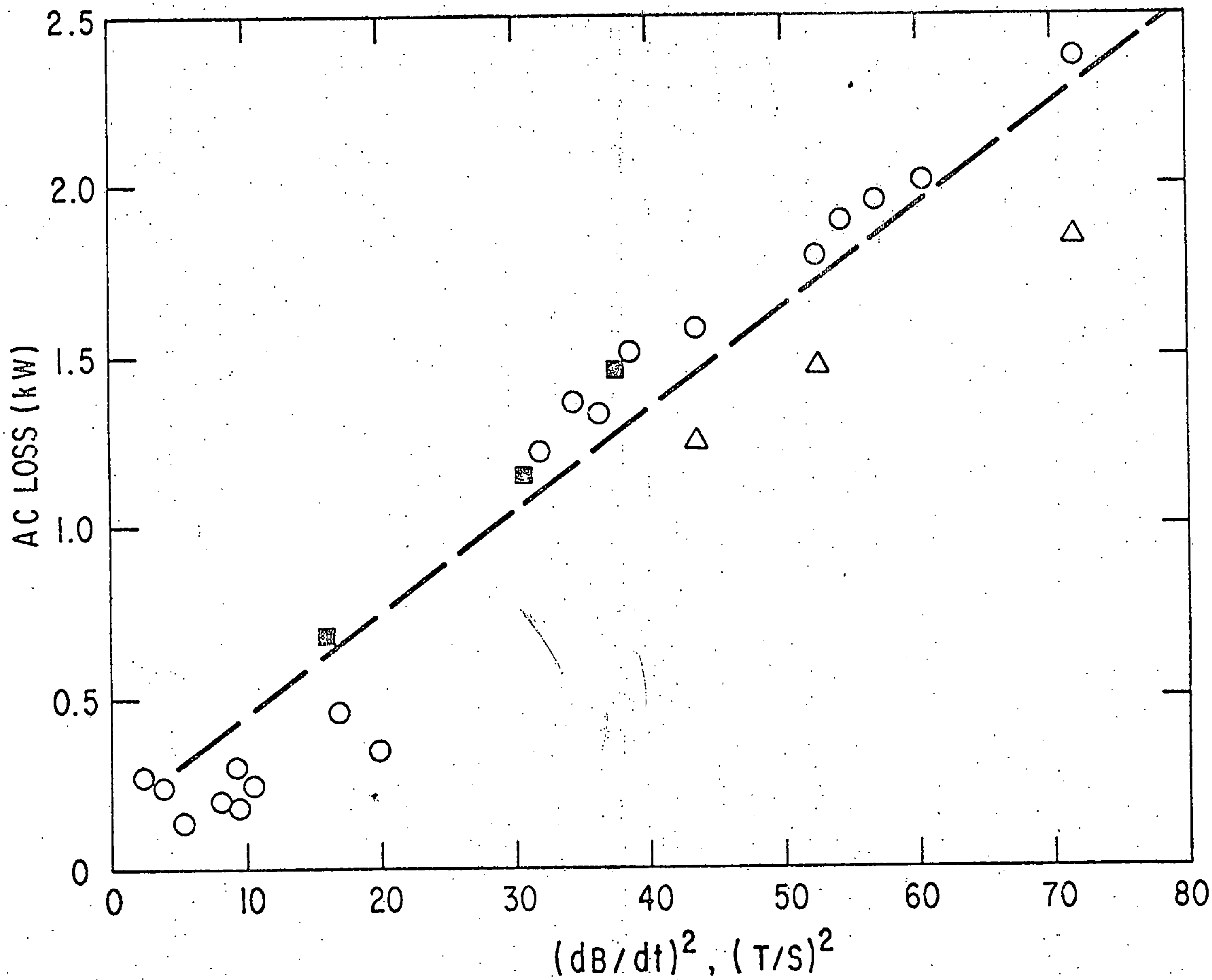

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