national accelerator laboratory

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SUPERCONDUCTING 20 kG DIPOLE MAGNET

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INTRODUCTION

A superconducting 20 kilogauss dipole model magnet has been designed, fabricated, and tested at the National Accelerator Laboratory. The magnet is of a type called "superferric" since it consists of an iron yoke and superconducting coil. Field uniformity is provided by iron surfaces machined to tight tolerences. Magnets of this type have been constructed[1] but dipoles suitable for particle beam bending magnets have not been built. Preliminary design studies have been made by Wilson[2] and Teng and Lari[3]. Potential power savings coupled with low initial cost make this type of magnet attractive. At the present moment we are considering DC magnets only.

DESIGN FEATURES

Figures 1, 2 and 3 show the assembled magnet and cryostat and Table I gives the design parameters. The magnet was designed to provide a clear aperture of approximately 4 × 10 cm. It was decided to refrigerate the iron to 4.2°K and to have a cold bore, that is, a beam tube at 4.2°K inside the magnet. This reduces the excitation required and allows the iron to directly support the magnet forces on the coil. The coil and

iron geometries were selected using the computer code TRIM. Mid-plane and ground-plane insulation spacers were chosen to give good low field uniformity. No real attempt was made to optimize the iron end shape, but a 45°, 1 inch bevel was provided.

The cryostat was designed to be small in overall diameter, with minimum vacuum spaces between elements at different temperatures. The liquid helium volume in the cryostat is quite small so an additional integral storage reservoir was used to allow for protracted operation.

CONSTRUCTION - MAGNET IRON

The magnet iron was procured as a half-round forging of AISI Type 1018 low carbon steel. The magnet is not laminated since only DC operation is contemplated. The outside was turned to the final diameter and the window milled to size. When assembled the gap is constant to within ±.003" over the entire aperture. Because the iron is very brittle at liquid helium temperatures, nothing was welded to the iron and the iron supported only the magnetic forces. The dead weight of the iron was about 750 lbs.

CONSTRUCTION - COIL

The coil form, consisting of mid and ground-plane spacers and beam tube, was fabricated as an integrated box structure of AISI Type 304 stainless steel. The spacers were perforated to allow liquid helium circulation. The coil was wound in the vertical plane, with 18 mesh plastic-fiberglass screen 0.014"

thick between layers. The ends were bent after the coil was assembled into the iron. When completed the coil was free of all turn-to-turn, layer-to-layer, and conductor-to-coil form shorts. The current leads were bifilar spiral wound on a single rod, cooled by the boil-off gas.

CONSTRUCTION - CRYOSTAT

The cryostat was fabricated entirely of AISI Type 304 stainless steel, except for the brass liquid nitrogen shield. The rectangular beam pipe/coil box interfaced at the end of the helium vessel and emerged from the cryostat as a 4 inch tube. Bellows in the beam tube allowed contraction and provided a long thermal path to room temperature. The dead weight of the iron was supported by two 3/16 inch stainless steel rods in tension. Back-off screws provided additional support for transit. The 15 liter reservoir was a commercial item, modified and mounted on one end of the cryostat. A vacuum insulated standpipe of similar height allowed the opposite end to vent. The entire assembly was welded together.

INSTRUMENTATION

Voltage taps were provided across each half of the coil and across the copper-superconductor joints at the current leads. Thermocouples were located on the iron and on the tension rods. Reservoir ullage pressure could be measured, as well as gas flow rates out of the system.

IRONLESS TEST

Prior to assembly of the coil into the iron, the coil was

tested by immersing it into a dewar of liquid helium. Aluminum plates on the sides of the coil held by tie bolts reacted the forces and restricted liquid helium penetration into the coil. The coil reached a maximum current of 260 amps, corresponding to a field of about 10 kG in the center of the loop. This was considered satisfactory performance and the coil was incorporated into the iron. The coil and iron together were not tested in this fashion.

OPERATING EXPERIENCE

The assembled magnet and cryostat were operated many times. Cooling the system became routine and was accomplished in about two hours. The magnet was energized almost every day for several weeks and operating experience gained. The cryogenic data is summarized in Table II. The modest cool-down requirements were achieved by introducing the LHe at the reservoir and venting the boil-off gas from the standpipe at the opposite end. The observed steady-state heat leak of about 3 liters/hr agrees with the predicted value to within 20%. The heat leak due to the current leads at 163 amps was about 10% of the total.

The magnet performance featured fast charge rates and good uniformity. Operating data is summarized in Table II and Fig. 4. It is highly desirable to be able to change the magnetic field in bending magnets in a few minutes. This coil is short-free, of low inductance, and can be charged and discharged quickly. Figure 6 shows that 20 kG can be reached at

charge rates up to about 2.3 amps/second (about 282 gauss/second average).

Preliminary magnetic field data was obtained with a F.W. Bell gaussmeter with a Hall element compensated for use at cryogenic temperatures. The absolute accuracy of the field measurements was about 0.1% and long term stability of ± 0.05% was observed. Transverse uniformity of the vertical field component at 10 kG and 20 kG is compared to the TRIM results in Fig. 7. The agreement is quite good for uniformities of less than 0.1%. Figure 8 shows the transverse field uniformity at central fields of 10, 17, 20, and 22 kG. The longitudinal dependence of the vertical component was studied to investigate end effects. Figure 9a shows the on axis end effect for 10 kG; and Fig. 9b shows the end effect for axial and off-axis data at 17 kG.

The coil was repeatedly quenched at various fields between 17 and 20 kG with no subsequent degredation of performance. During a quench at 22.5 kG an arc occured between the winding and the coil form, causing a short in the winding. The magnet was subsequently operated to 20 kG with slower charge rates. Computer analysis[4] indicates that voltages up to 200 volts can be developed during a quench at this field. Hi-pot tests on the wire insulation indicated a breakdown potential between 300 and 400 volts. The arc probably occurred at a weak point in the insulation.

FUTURE DEVELOPMENT

The success of this 2-1/2 ft. model has led us to consider a 10 ft. prototype. The prototype would use a lower current density to further reduce the threat of arcing and burn-out in the event of a quench. The prototype would also include improved liquid helium irrigation into the coil and a LHe reservoir of 50 to 100 liters. The design of this magnet is in the initial stages.

ACKNOWLEDGMENTS

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REFERENCES

[1] R.W. Fast, Rev Sci Instr 38, 1789 (1967).

[2] R.R. Wilson, NAL FN-173 (1968) (unpublished).

[3] L.C. Teng and R.J. Lari, NAL FN-179 (1969) (unpublished).

[4] Z.J.J. Stekly, private communication.

TABLE I

Design/Construction Parameters

Magnet

Type: Picture-frame iron with superconducting coil, iron at 4.2°K

Clear aperture: 4 cm full gap × 10 cm full width × 76.2 cm long

Mid-plane field: 20 kG

Mid-plane uniformity (20 kG): 0.1% over 2.10 in. aperture (full aperture less 1 full gap).

Full gap excitation (20 kG): 71,400 amp-turns

Total turns: 552 (12 layers of 23 turns each per half coil)

Current required to drive gap (20 kG): 129.3 amps

Packing factor (area of conductors/area of coil window): 54%

Cryostat

Type: Horizontal, liquid nitrogen shielded, cold bore

Overall dimensions: Vacuum vessel diameter: 13.0 inch (33.02 cm)

Cryostat volume above coil: 0.6 liters

Reservoir volume: 15 liters

TABLE II

Operating Parameters

Magnetic

Coil inductance: 0.6 H

Operating current (20 kG): 163 amps

Reluctance excitation (20 kG): 25% of gap excitation

Stored energy (20 kG): 8000 J

Flux (20 kG): 0.18 Wb

Uniformity: 0.1% over 2.10 inch aperture

Current density over coil window (20 kG, 163 A):
125 kA/in^2 (19.4 kA/cm^2)

Current density in conductor (20 kG, 163 A):
231 kA/in^2 (35.8 kA/cm^2)

Charge time to 20 kG: approximately 5 minutes

Maximum quench current: 200 A

Quench central field: 22.5 kG

Maximum field in conductor at quench: approximately 30 kG

Fraction of short sample current (30 kG): 90%

Quench current density over coil window: 153 kA/in^2 (24 kA/cm^2)

Quench current density in conductor: 283 kA/in^2 (44.4 kA/cm^2)

Cryogenic

Cooldown requirements (77°K to 4.2°K): ~75 liters; ~0.10 liters/lb.

Cooldown time (77°K to 4.2°K): 2 to 3 hours

Steady-state heat leak (zero current): 2.9 liters/hr (observed)

Steady-state heat leak (20 kG, 163 A): 3.2 liters/hr (observed)

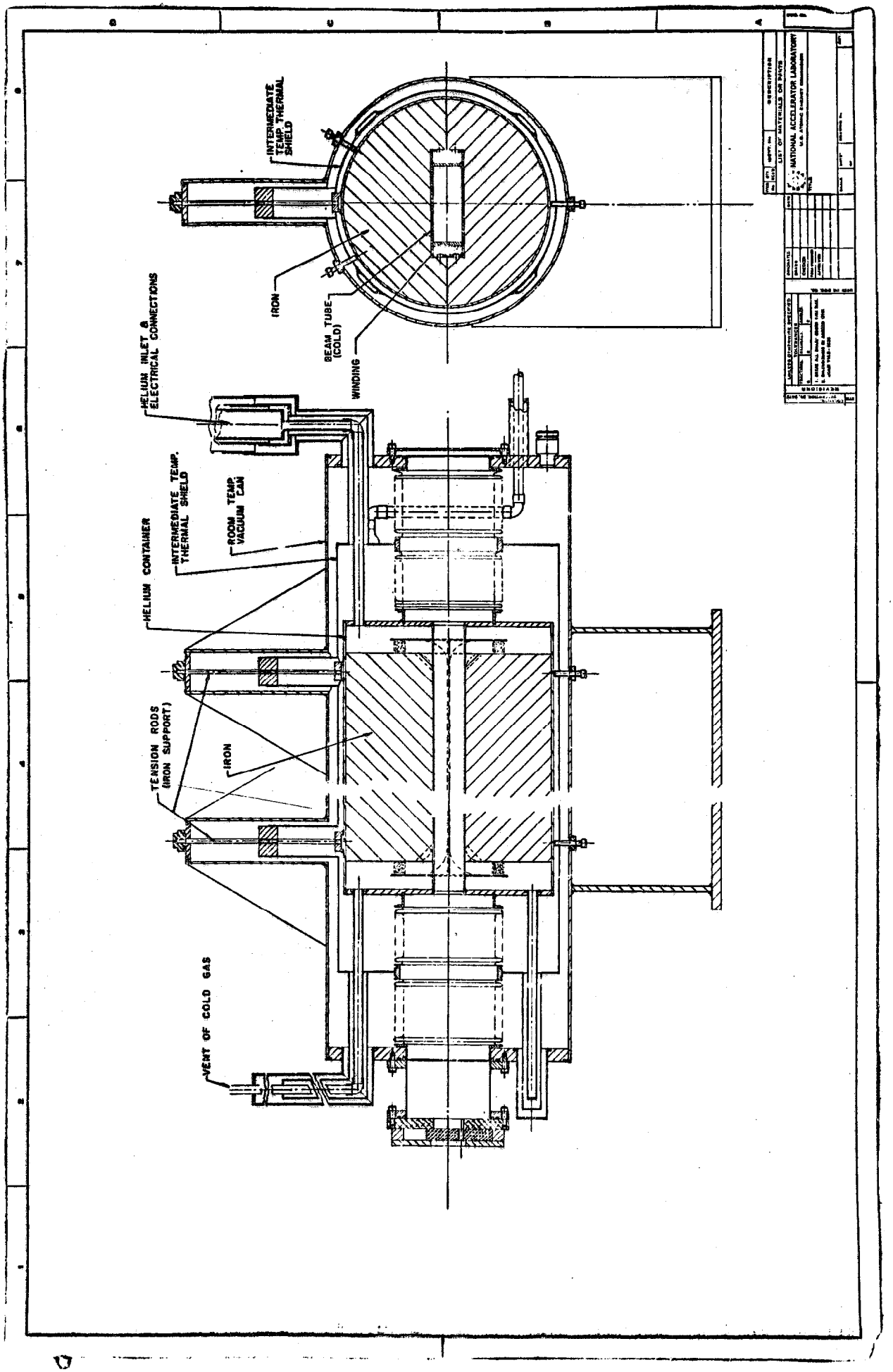

Fig. 1. Assembly drawing, 20 kG superferric magnet.

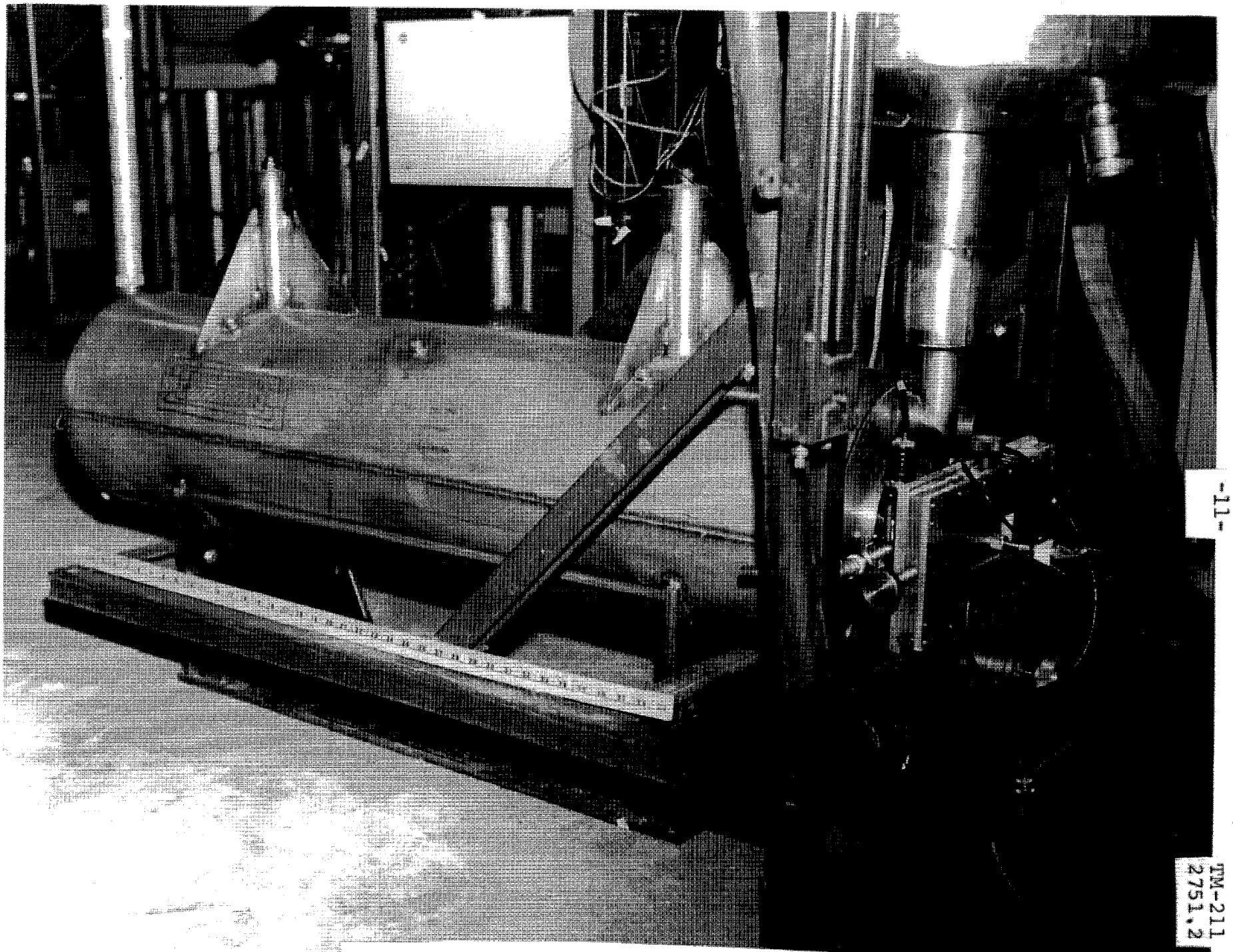

Fig. 2. 20 kG superferric magnet crystat.

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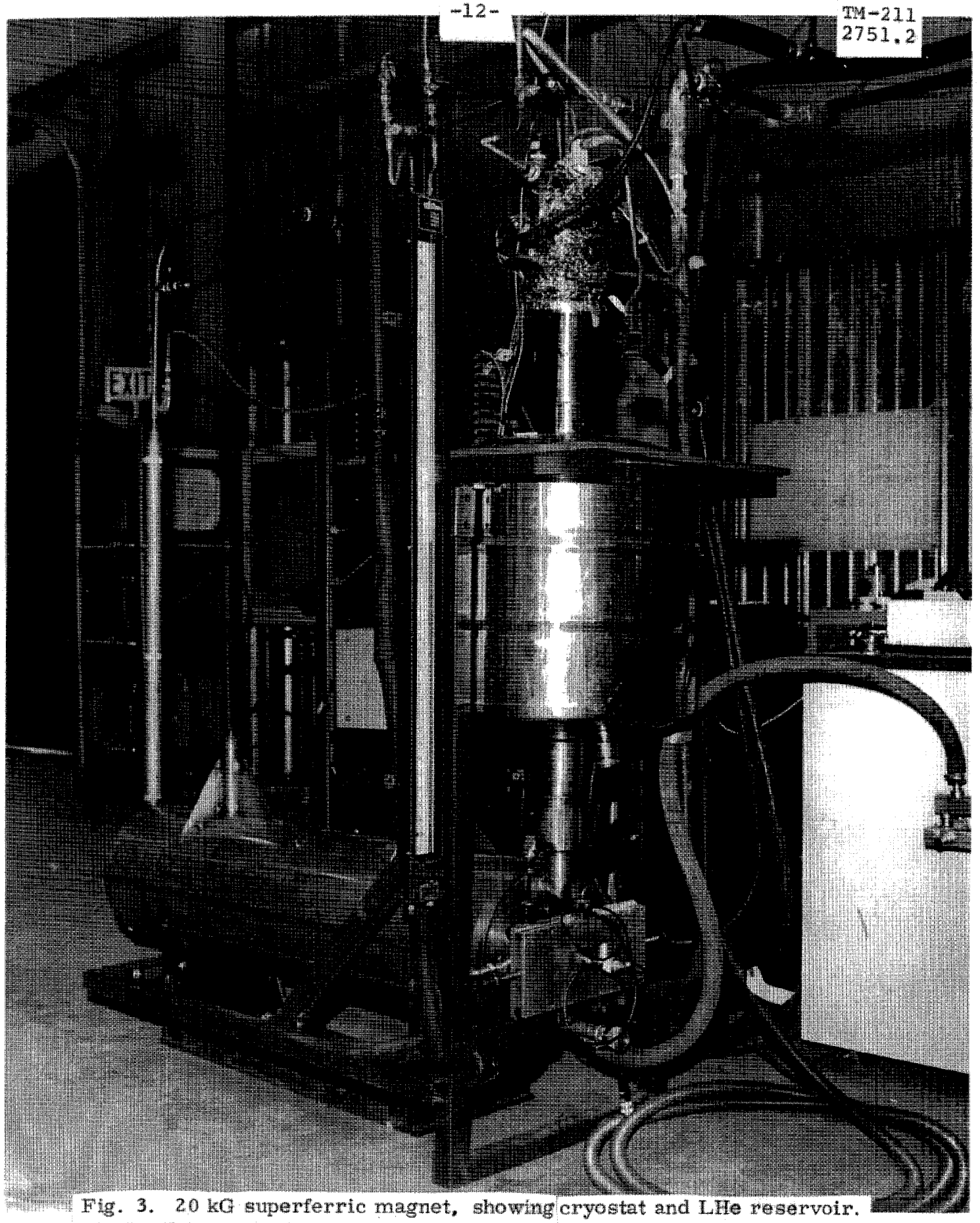

Fig. 3. 20 kG superferric magnet, showing cryostat and LHe reservoir.

Short-sample performance of Airco conductor; magnet load lines.

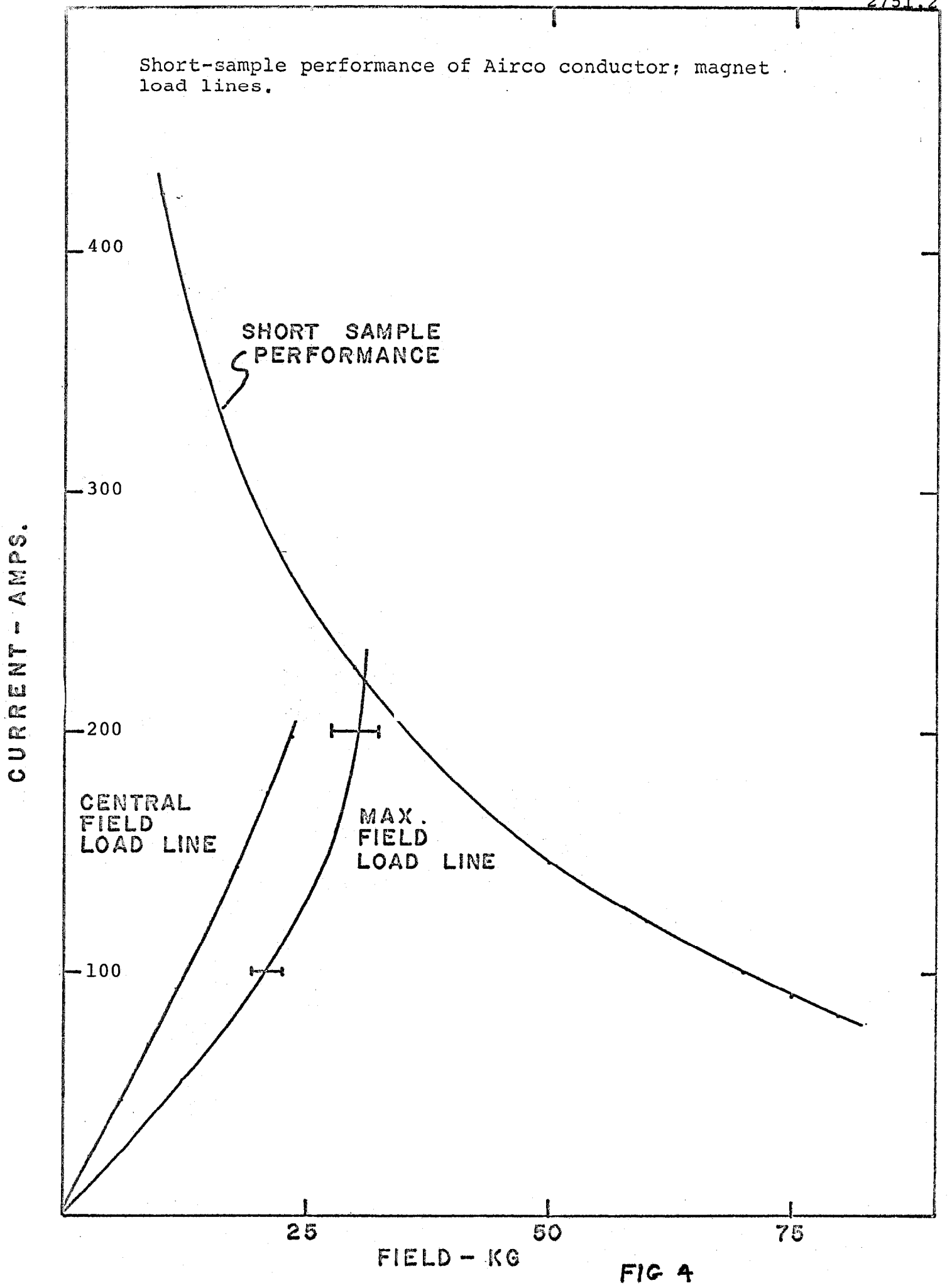

FIG 4

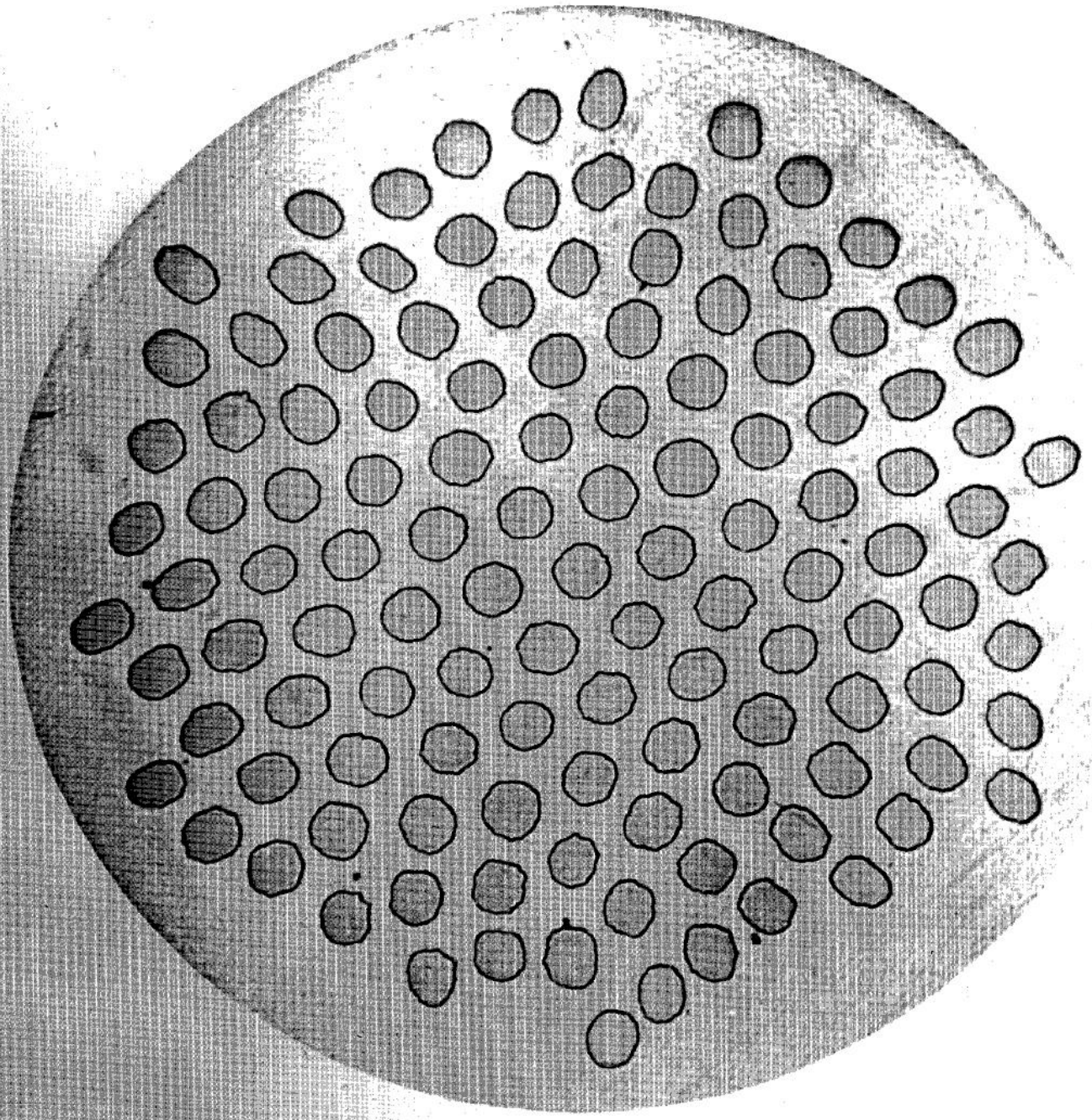

Fig. 5.

Photomicrograph of 0.030 in Airco superconducting wire. Photo courtesy Airco Central Research Laboratory.

Material: Nb-Ti in Cu
No. S.C. strands: 121
Twist: 2 turns/in
Cu/S.C. ratio: 3 to 1
Insulation: Ebanol C & Glyptal

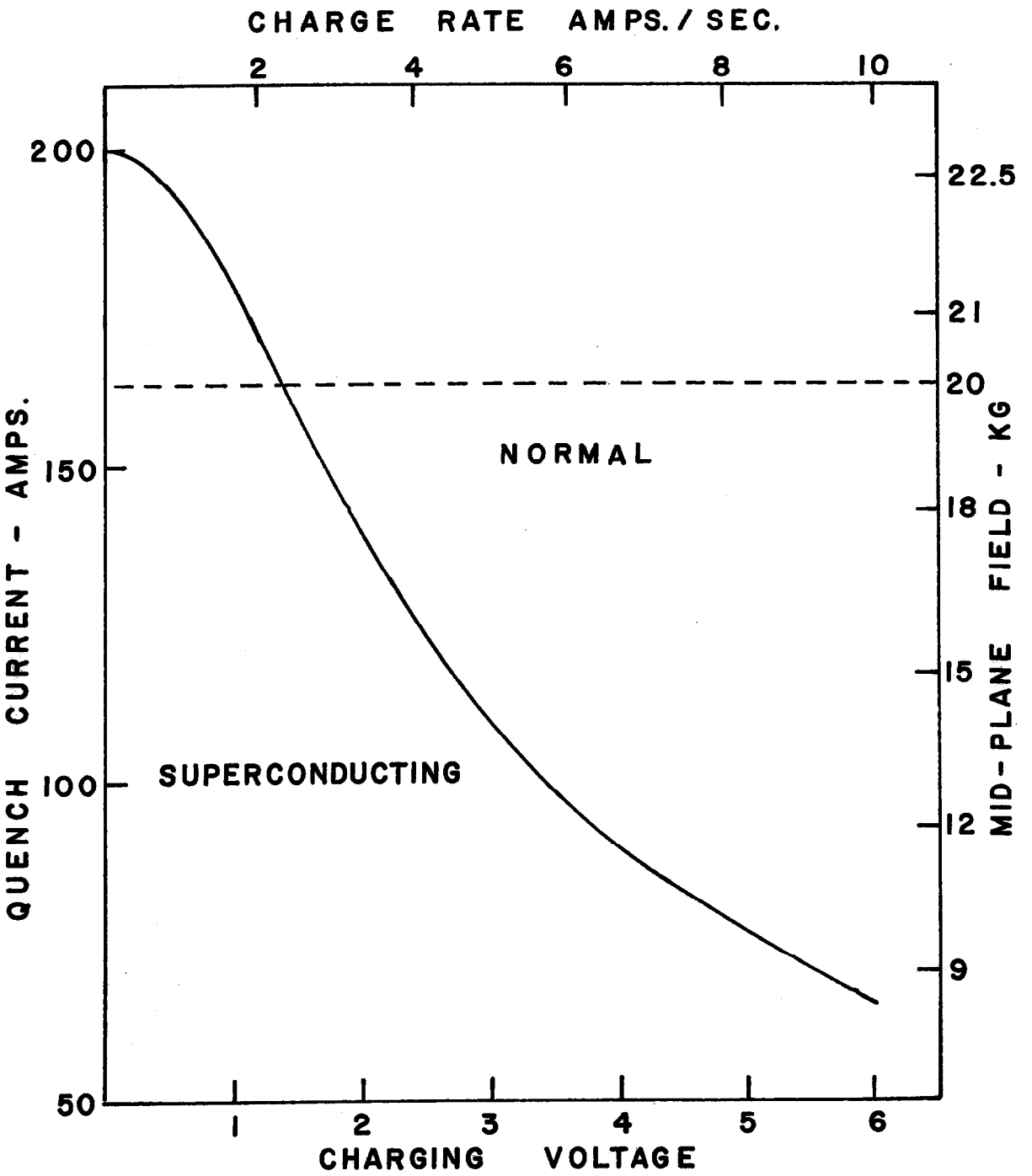

FIG. 6

Charge rate sensitivity of superferric magnet.

Measured vertical field transverse uniformity compared with TRIM calculations.

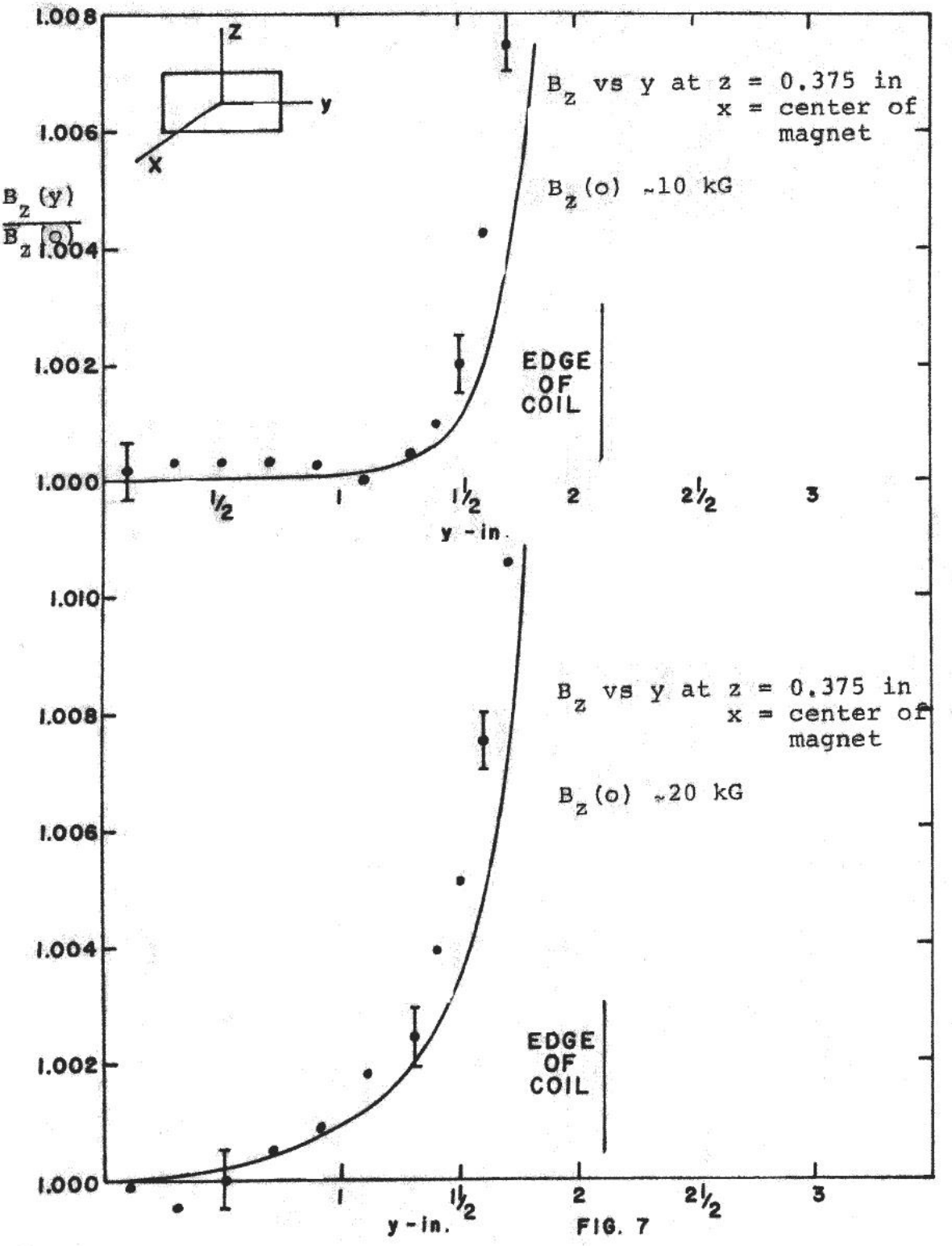

FIG. 7

Measured vertical field uniformity at several values of central field.

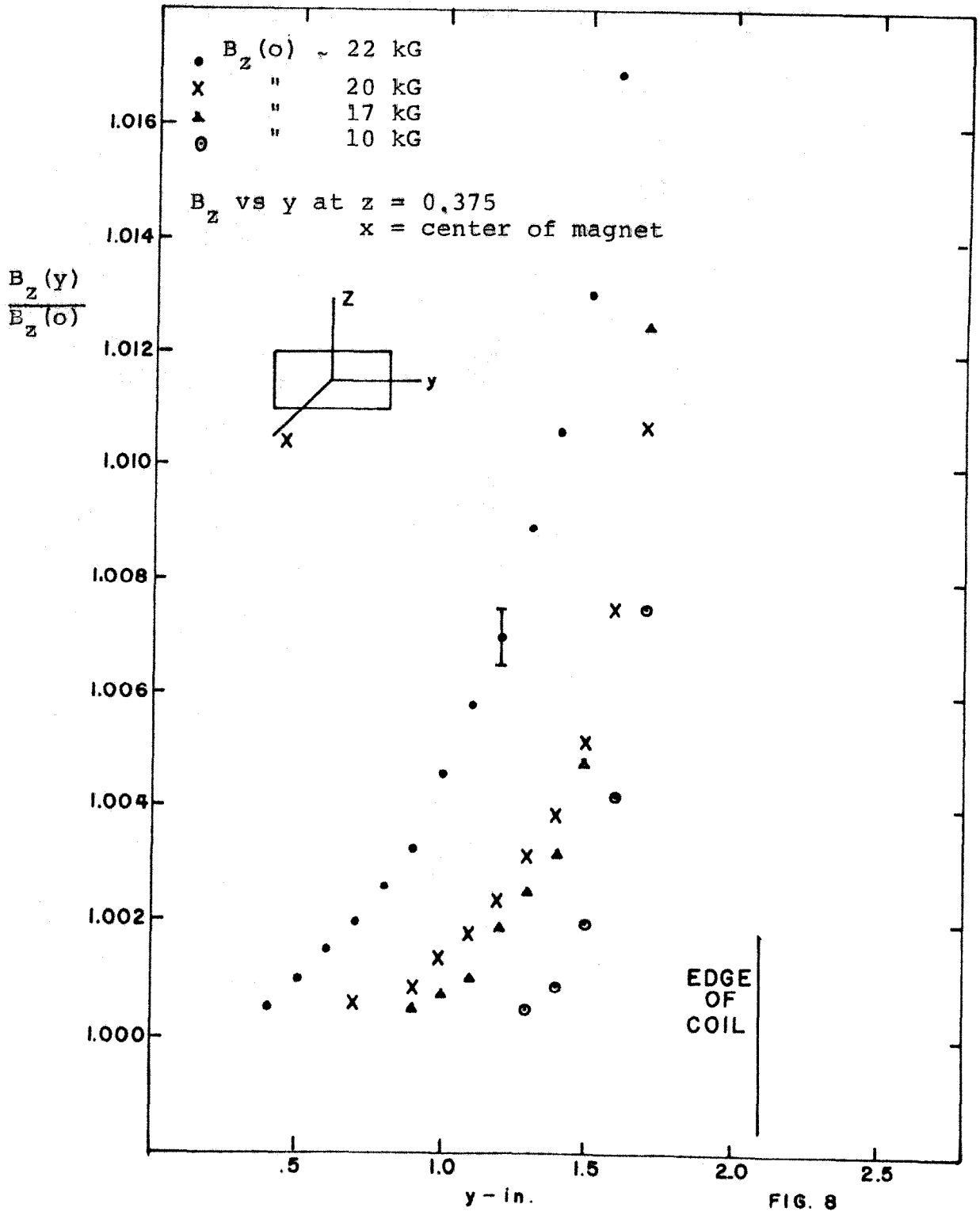

FIG. 8

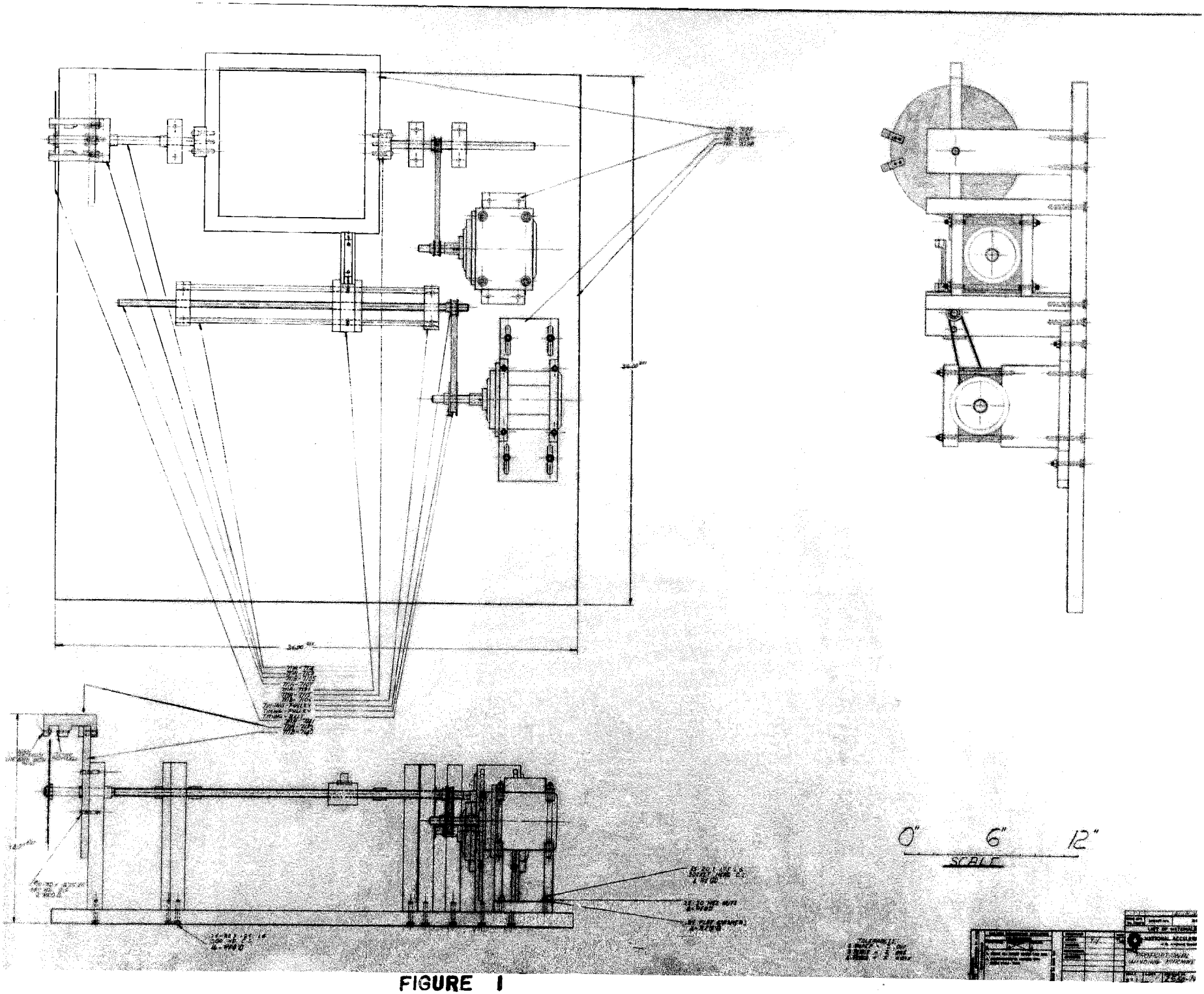

FIGURE 1

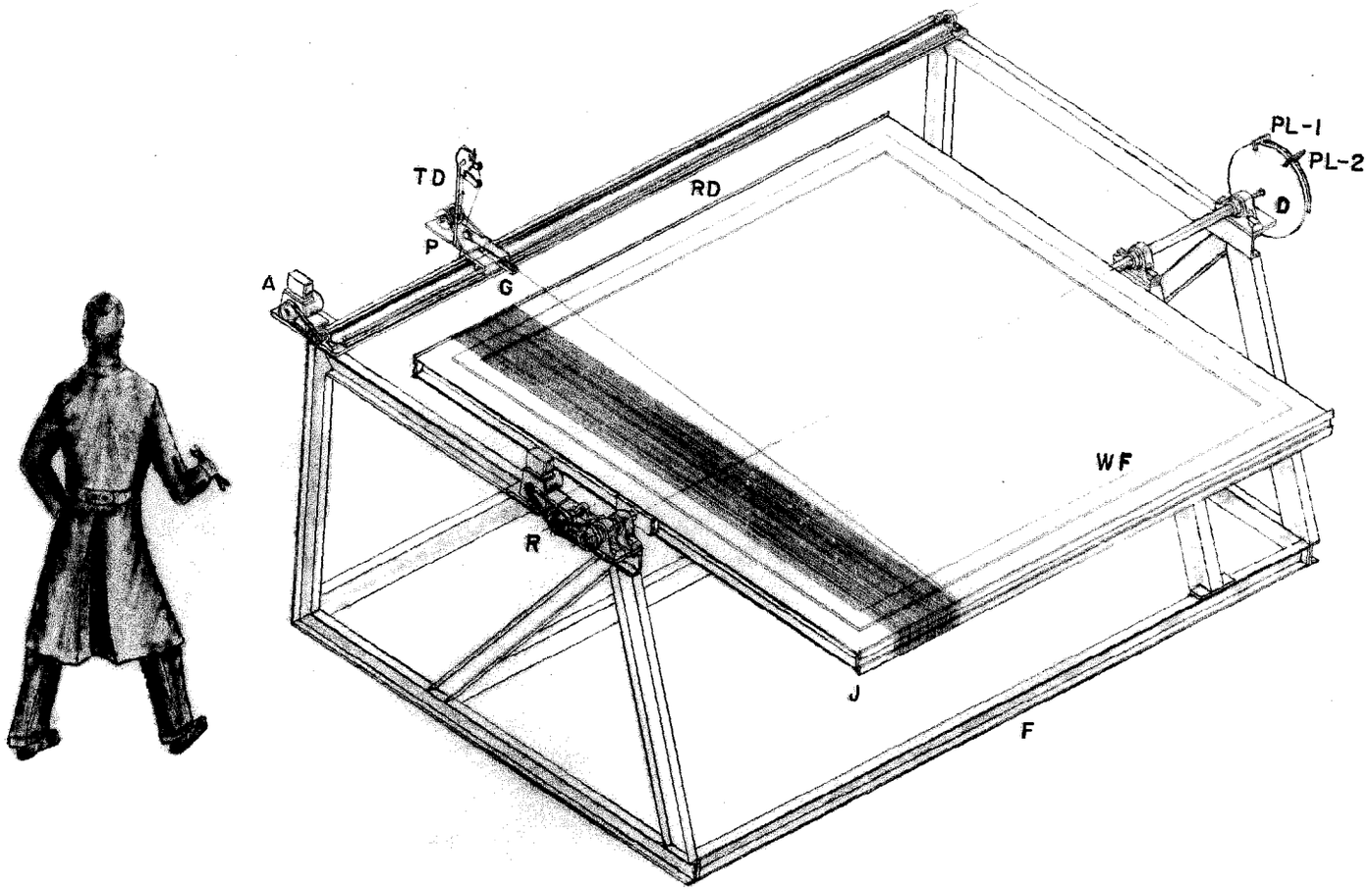
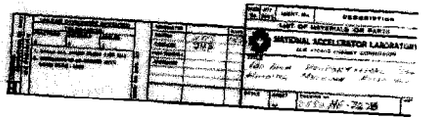
FIGURE 2