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TM-906
2750.000
September 1979

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ABSTRACT

A prototype low current superconducting D.C. beamline quadrupole for Fermilab's High Intensity Laboratory has been built and immersion tested. Low current is achieved by wiring the 15 film-insulated strands of a cable in series. The magnet has a clear bore of 13.3 cm with a gradient of 51.4 Tesla/meter without iron at the short sample limit. Design, construction techniques, and test results are presented

For
Presentation
at the
1979 Cryogenic Engineering Conference
August 21-24, 1979
University of Wisconsin
Madison, Wisconsin

A PROTOTYPE LOW CURRENT SUPERCONDUCTING QUADRUPOLE FOR FERMILAB'S HIGH INTENSITY LABORATORY*

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INTRODUCTION

A low current saddle-type quadrupole using very similar cable and design criteria as its companion dipole[1] has been built and tested in a vertical cryostat. The low current is achieved by taking the 15 film-insulated strands of a cable and connecting them in series. With currents of approximately 250-350 A, it becomes economically possible to use a separate power supply for each of the magnets in the beamline. Magnet parameters are given in Table I.

COIL FABRICATION

Because electrical insulation must be maintained between the individual strands of the cable rather than just between turns, extreme care must be used in the manufacturing of these coils. We have, therefore, built these coils with the philosophy that they must be wound as tightly as possible without damaging insulation. They must be eventually compressed with moderate preload or thermal pressures in all directions.

The quadrupole field was obtained using the 2/3 rule.[2] However, the 4 layer coil was wound from two separate spools of wire with dipole type ends. The end turns of layers one and three and of layers two and four are directly above one another as shown in Fig. 1. This technique

*Work sponsored by the U.S. Department of Energy.

minimizes the number of wire splices. I so reduces the magnetic field in the coil ends by separating the end s and distributing the θ component of current in opposing direc s.

Each of the coils was wound with 60 lbs of tension directly on the bore tube around G-10 fiberglass-epoxy poles. As each half turn was laid down, it was clamped along its length at 30 psi. With both half turns down, the pressure was increased momentarily to 300 psi. This procedure produced tight end turns. Figure 2 shows the tooling. Upon winding an entire layer, two pairs of split G-10 islands are placed in the vacant 30^{o} between the coils, and the winding fixture is removed. The hydraulic compressing fixture, shown in Fig. 3, is then pinned into the holes of the split islands. Each hydraulic cylinder pulls on every other steel band which in turn separates the split island and compresses the wire on the opposite side. The bottom of the conductor slides on a Teflon sprayed 0.006 in. G-10 sheet which permanently isolates each layer, while a 0.014 in. Teflon coated fiberglass cloth protects the top of the conductor from abrasion against the bands during compression. Neglecting friction, the conductor is compressed with 2700 psi in the azimuthal direction and 500 psi in the radial direction. At this point the magnet is baked at 380K for 2 hours. The heating step was initially included to cure the B-staged epoxy tape to insure a more rigid coil package. The tape we used had very little epoxy, but it was found that the heating procedure compressed each quadrant of conductor by an additional 0.150 in. on the average, probably from a change in the coefficient of friction. During heating, anodized aluminum end saddles are driven against the conductor, preloading the end turns with approximately 500 lbs. After the magnet has cooled, shims are tapped into the gap of the split islands. Conductor placement was within $\sim$ 0.050". One at a time, each 6-inch section of compression bands and hydraulics are removed as the magnet is banded with a one-inch pitch of Kevlar-49[3] braid. The 0.022" x 0.375" braid has a nominal breaking strength of 1750 lbs and provides an average radial pressure of 150 psi. The Kevlar is subsequently relaxed during the preloading of the outer support pipe. Its function is to provide an overall tight conductor package, maintain radial tolerances during winding, and to provide the helium cooling channels during operation. The last fabrication step is to apply the final preload with countersunk stainless steel bolts in the outer support pipe. A radial preload of 700 psi was chosen for our first run, and 1000 psi for the second. In addition, four large aluminum reinforcing rings were added outside the aluminum support pipe to reduce the bending moment in the bolts for the second run.

STRUCTURAL ANALYSIS

Under a biaxial load of 1500 psi, the conductor was measured to have a Young's modulus of 1.5×10^6 psi. From measurements to liquid nitrogen temperature at a constant pressure of 2160 psi, the estimated thermal strain to liquid helium temperature is 0.0038. These two values were used in all subsequent analysis.

Stresses in the conductor from preloading, thermal contraction, and electromagnetic loading must be considered. Our principal preloading mechanism is the bolts in the outer aluminum support pipe. If the conductor has not been wound tightly up to this point, the radial pressure cannot preload the conductor in the azimuthal direction. For calculations, it is seen that the conductor tends to behave as a fluid and nearly all the radial pressure from the support pipe is transmitted through to the bore tube.

Thermal stresses arise from the difference in thermal contraction between G-10 island/conductor combination and aluminum. The estimated thermal strain of the island/conductor package at 4.2K is 0.0037. By choosing an aluminum rather than a stainless steel bore tube which our dipole counterpart uses, radial preload pressure is sacrified for azimuthal pressure. The conductor can be thought of as being wedged between the islands when cooled to 4.2K. On cooldown an additional 200 psi radial loading should be gained, although strain gages on the outer pipe indicate a small loss of preload for the first run. The strain gages were unusable for the second cooldown, but the thermal strain of the conductor is smaller when cooled under greater pressures.

The electromagnetic force calculations were provided by S.C. Snowdon.[4] When considering the first octant, the radial component of force and the x component of the θ component of force of each conductor are distributed on the outer support pipe. Equations 1 and 2 give the internal bending moments and tensile loads in a pipe subjected to uniformly distributed loads shown in Figure 4 as derived from integrating point loads. [5]

$$M = -wR^2[(\frac{4\theta_0}{\pi} + \cos\theta_0 - \sin\theta_0)\cos\theta - 1] - wR^2[1-\cos(\theta-\theta_0)\ \langle\theta-\theta_0\rangle^0 \qquad 1)$$

$$T = -wR[(\cos\theta_0 - \sin\theta_0)\cos\theta - 1] - wR[1-\cos(\theta-\theta_0)]\ \langle\theta-\theta_0\rangle^0 \qquad 2)$$

where M is the bending moment, T is the tensile load in lbs/inch, w is the distributed load in lbs/inch, and the brackets $\langle\ \rangle^0$ indicate unity for $\theta \geq \theta_0$ and zero for $\theta < \theta_0$.

A superposition of these uniformly distributed loads at various angles approximates the electromagnetic loading on the outer support pipe. The y component of the θ component is assumed to be carried by the conductor and bore tube. Figure 5 is the distribution of electromagnetic loads on the outer support pipe. The maximum stress in the aluminum support pipe is 10,000 psi at 323 amps. In addition to the redistribution of radial forces, approximately 1700 psi of the tangential preload at the G-10 island is lost on the conductor as it is pinched towards its midplane. The pinch force is 2500 psi at the conductor midplane. Table II is a summary of conductor stresses for the second run.

ELECTRICAL

Figure 6 shows the electrical connections. The dump resistors are center tap grounded with a 100Ω resistor. This reduces the possible voltage to ground in half, but still limits the current in case a fault to ground develops during magnet discharge. Furthermore, the magnet was wired in such a manner as to keep sections with the greatest voltage differences the furthest physically apart. The cable was wired in series with each strand lying next to its two closest electrical neighbors. Each half of the magnet on either side of ground is completely isolated from the other half by islands and a 0.006 in. thick G-10 sheet between layers. Three out of the 15-strands could not be used. Two pairs of strands developed electrical shorts at the crossover between layers and had to be wired in parallel. The third wire is a plain copper wire which was used to propagate the quench by shunting current through it. At no time were the two copper wires connected together or to ground. When a voltage imbalance is detected, the SCR disconnects the power supply, and simultaneously an auxiliary power supply can energize stainless steel heaters sandwiched between the conductor and the G-10 islands. Three modes of energy extraction were tried and are shown in Fig. 6. At least one of the two copper wires was always left open or connected to the data acquisition system. The safety leads were always connected and provide an alternate path for current to bypass the quenching section.

TEST RESULTS

Figure 7 is the quadrupole training curve. With the first cooldown 94% of short sample was reached before we decided to increase the preload and add four reinforcing rings. Before the preloading was changed, all the bolts in the outer support pipe were totally relaxed. From previous experience with low current dipole racetrack coils and from the Energy Doubler program,[6] it is expected that little if any training from the first cooldown is retained for the second. On the second cooldown, the short sample limit was reached within three quenches. Thus, the 1000 psi radial preload gives good training behavior with minimum conductor stresses.

The original design gradient was not quite reached. Had the two shorted pairs been available, it is probable that 56 T/m without iron could have been reached.

It is especially desirable with this style of low current magnet to minimize the voltages during a quench by selecting the smallest value energy dumping resistor which is consistent with avoiding a wire burnout. Stainless steel strip heaters along the islands, and an inductive and direct coupled hot wire techniques were all tested to measure their effects on quench propagation. If both copper circuits are open, AC losses in the wire are ignored, and quenching does not occur, the square root of the joule heat dissipated in the external resistors must be proportional to the magnet current prior to firing the SCR. This is curve A in Figure 8. Curve B, called coasting without heaters, refers to tripping the SCR prior to a spontaneous quench. Above the 100 amp level some of the energy is released in the

4.2K environment. Near the short sample limit 35% of the energy is dissipated internally. The effectiveness of the heaters is difference between curves B and C. The stainless steel heaters have a typical surface heat flux of 18 watts/cm^2 with an average heat input of 3500 joules and a maximum temperature of 120K as measured with chromel constantan thermocouples. Curve E is the inductive hot wire technique. This circuit was found to be not nearly as effective as the directly coupled copper wire, curve F, where roughly half the total energy is absorbed by the coil at 250 A. Changing the polarity of this copper loop made little difference in the quench propagation at all current levels. From 40% to 60% of the energy which is removed at room temperature is dissipated in the 1.43Ω current limiting resistor of the copper loop which is to be expected from the ratio of the resistances. Obviously, if both copper loops were used, quench propagation would have been further improved.

Based on adiabatic conditions, the integral $\int I^2\, dt$ can be equated to a maximum hot spot temperature in the superconducting windings.[7,8] A measured value of RRR = 70 was used in these calculations. Under normal conditions a 337 A coast without heaters had the highest theoretical hot spot temperature of 250K. A 200K hot spot was the worst case for any of the current driven hot wire runs. The low external resistance of 0.83Ω of this circuit caused this comparatively high temperature but reduced the peak voltage to ground by 60%. At 273 A with both copper loops open, the SCR and stainless steel heaters failed to trip during a quench. The magnet was self-protecting and experienced a 275K hot spot in the quenching loop. The safety leads probably saved the magnet from a burnout.

The thermal stability of the magnet was investigated by powering the stainless steel heaters and one of the copper loops. For one of the stainless steel heater tests, the magnet current was set at 308 amps. With a surface heat flux of 0.03 watt/cm of cable, 0.057 joule/cm induced a quench. Next the current was adjusted to 333 amps, 97% of short sample. This corresponds to a thermal temperature reserve of only 0.15K.[9] Fifty-three watts of heat was dissipated in one half the magnet by one of the copper wires for 6-1/2 minutes before quenching occurred. In the highest field region of the magnet, the power density was 0.0027 watts/cm. The relatively porous nature of this conductor allows this stable performance even with currents very close to the short sample limit.

FUTURE

Twenty-six full length, 10 foot, quadrupoles are eventually required. To reduce the costs, the full size quads will be two layer, 4-1/2" clear bore magnets using a copper to superconductor ratio wire of 1.8:1 or smaller. There is no plan to place this prototype in the High Intensity Lab. Beam quenching sensitivity will be tested with one of the low current dipoles.

ACKNOWLEDGMENTS

The authors wish to thank John Satti, Peter Mazur, Brad Cox, Stan Snowdon, Joe Heim and Paul Mantsch for their suggestions. A special thanks goes to Steve Anderson who was in charge of magnet construction and who helped perfect the many special techniques. We also wish to acknowledge Roger DeNeen, Jesse Guerra, Diane Garcia, Steve Dochwat, Stan Tonkin and Len Sawicki who helped with the construction and test set-up.

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Table I

Magnet Parameters

Cable:	15 polyester polyamide-imide insulated strands
Spiral Cable Wrapping:	0.1 mm (0.004 in.) thick B-staged fiberglass epoxy tape
Cable Dimensions:	2.21 mm x 8.87 mm (0.0863 x 0.349 in.)
Bare Strand Diameter:	1.02 mm (18AWG)
Conductor:	206 Filaments of Nb45 wt % Ti with a 1/2 in. pitch
Cu/NbTi Ratio:	2.9
Effective Coil Length:	88.4 cm (34.8 in.)
Total Magnet Length:	116.5 cm (45.88 in.)
Cold Bore I.D.	13.3 cm (5.25 in.)
Inductance:	2.8 henries
Short Sample Current:	343 amps at 4.4 K
Peak Field on Conductor:	4.5 tesla
Cable Current Density:	2.10×10^4 amp/cm^2
Maximum Current Achieved:	First run: 323 amps (48.4 T/m) Second run: 343 amps (51.4 T/m)
Maximum Stored Energy:	165 kJ
Design Gradient Without Iron:	53.5 T/m (13.6 kG/in)
Design Gradient With Iron:	56.3 T/m (14.3 kG/in)
Bore Tube:	8.76 mm (0.345 in.) thick 2024-T4 aluminum
Outer Support Pipe:	17.5 mm (0.688 in.) 6061-T6 aluminum
Number of Layers:	4
Inner Coil Radius:	7.56 cm (2.975 in.)
Outer Coil Radius:	11.30 cm (4.45 in.)

Table II

Estimated Stresses on Conductor

343 amp

(All units in psi)

	Preload	Cooldown	357 Amps	Total
$\sigma_{rr}(r = 3")$	- 950	0	+ 400	- 550
$\sigma_{rr}(r = 4.5")$	- 1000	- 200	- 700	- 1900
$\sigma_{\theta\theta}(r = 3")$				
at island boundary	- 1150	- 700	+ 2300	∿ 0
conductor midplane	- 1150	- 700	- 20	- 2000
$\sigma_{\theta\theta}(r = 4.5")$				
at island boundary	- 1100	- 600	+ 2200	∿ 0
conductor midplane	- 1100	- 600	- 450	- 2150

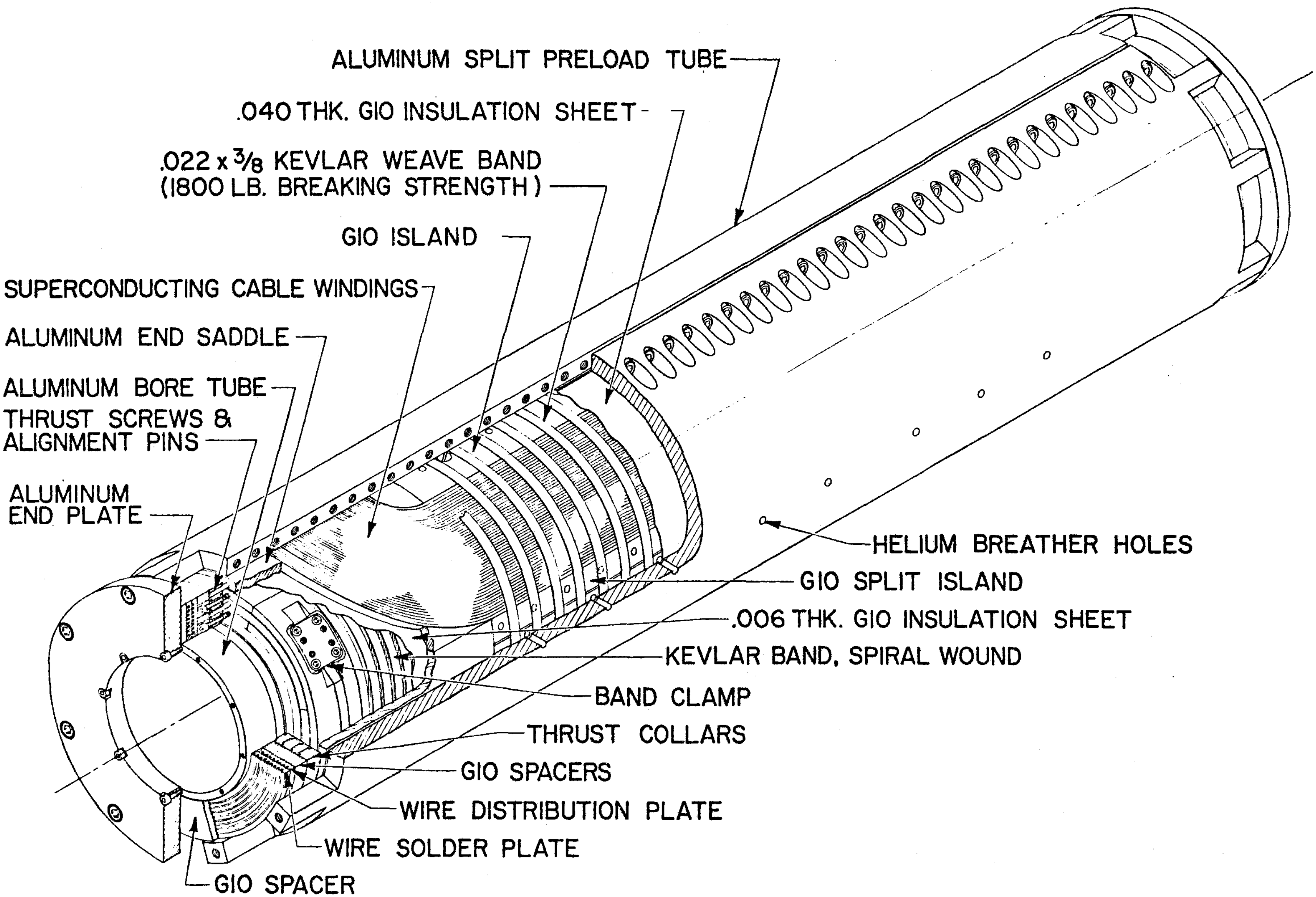

Fig. 1 Cutaway view of magnet. The third and fourth layers are shown.

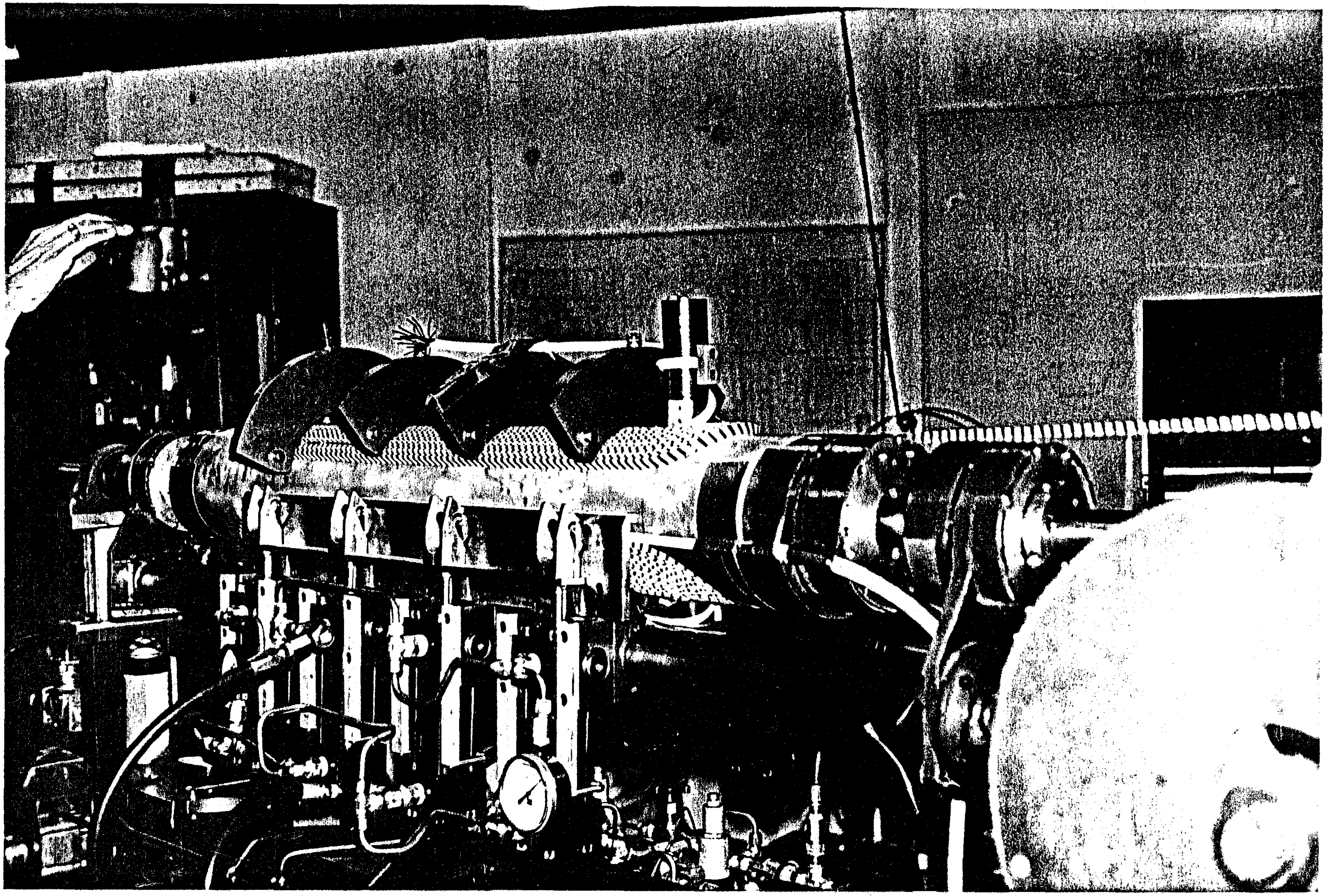

Fig. 2 Coil winding set-up.
Hydraulic cylinders
clamp on the top brackets.

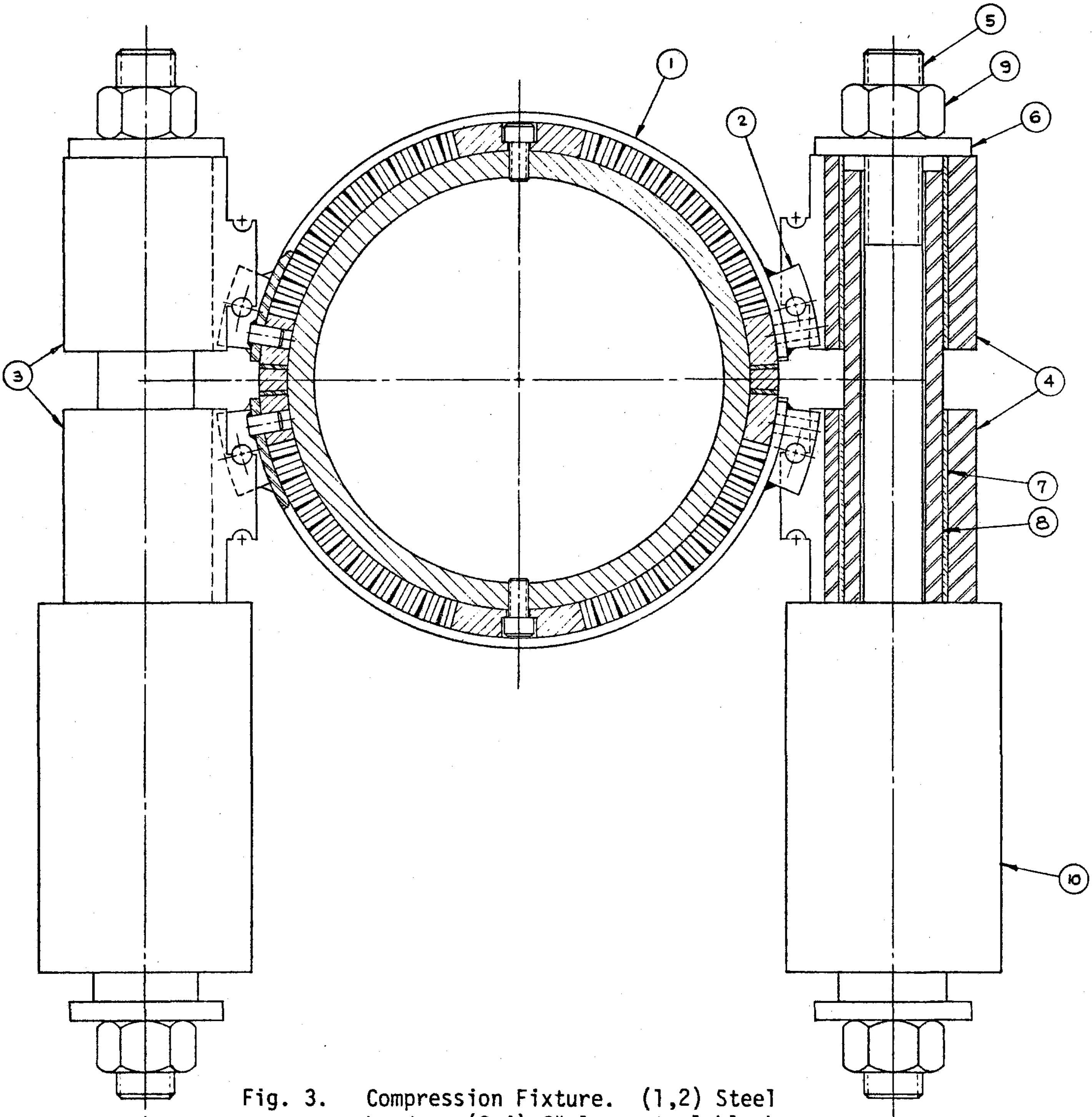

Fig. 3. Compression Fixture. (1,2) Steel bands; (3,4) 6" long steel blocks; (7) bronze bushing; (8) hardened steel shaft to resist bending moment; (10) hollow corehydraulic cylinder.

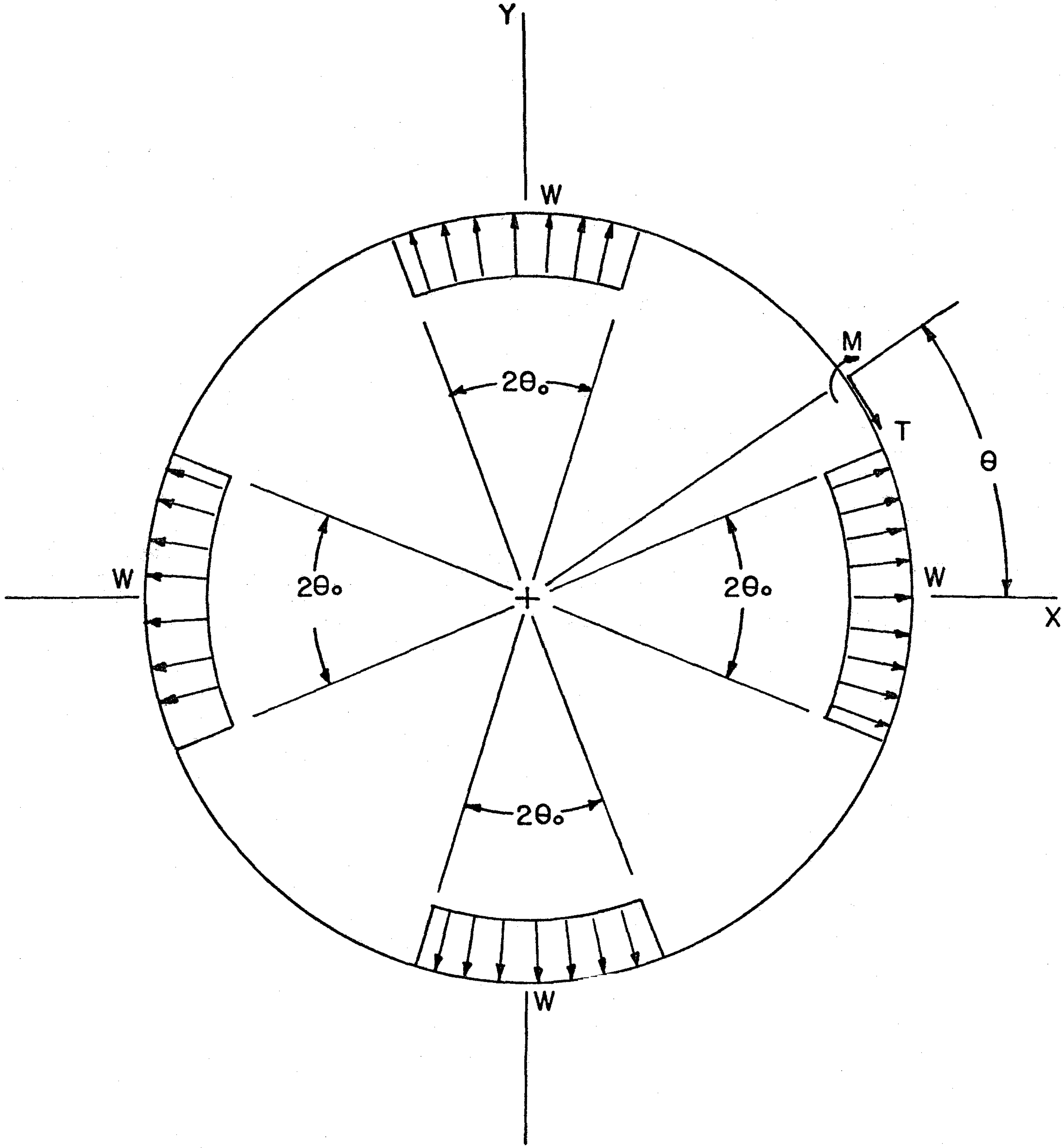

Fig. 4 Definition used in Eqs. (1) and (2).

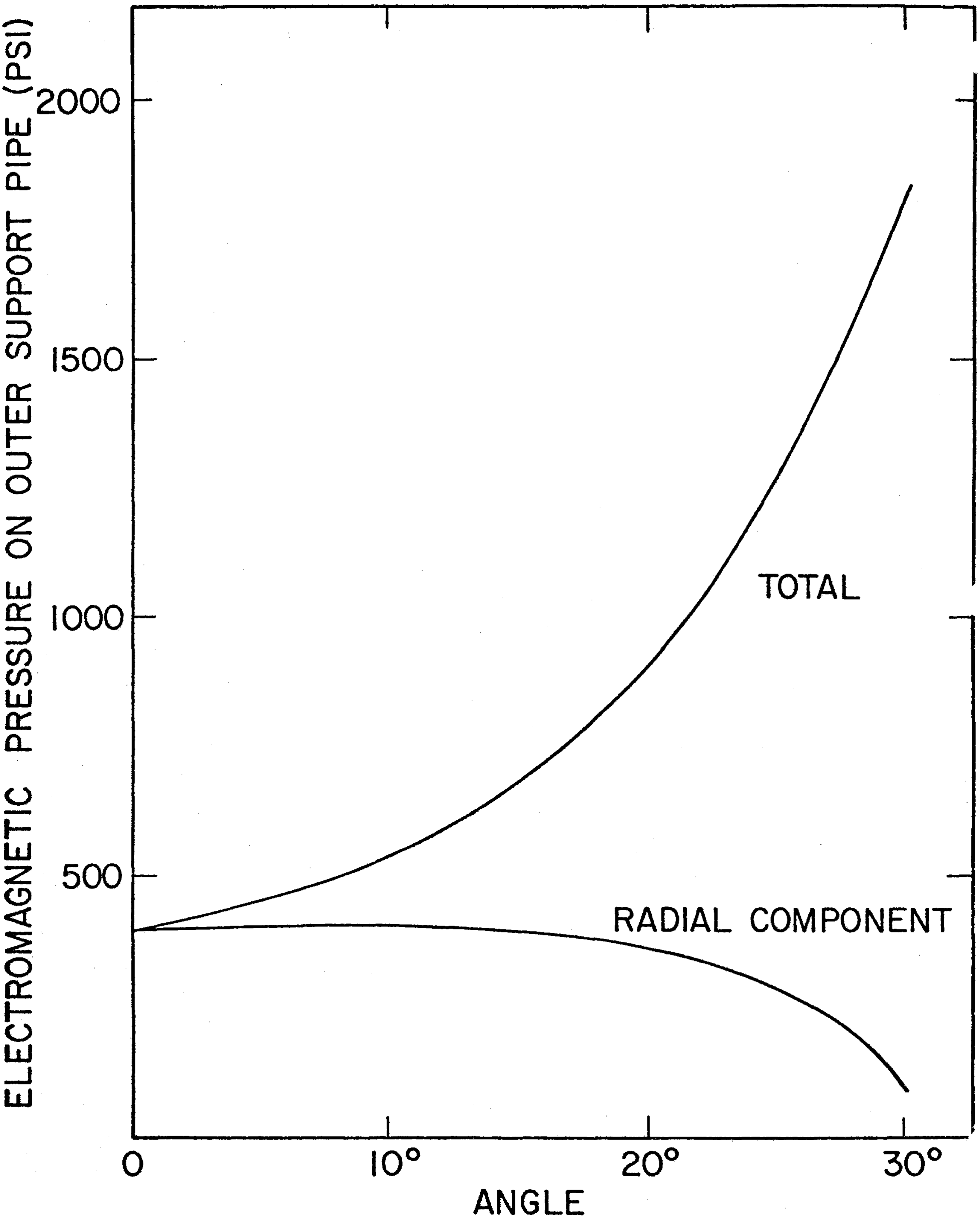

Fig. 5 Electromagnetic loading of outer support pipe at 340 amps.

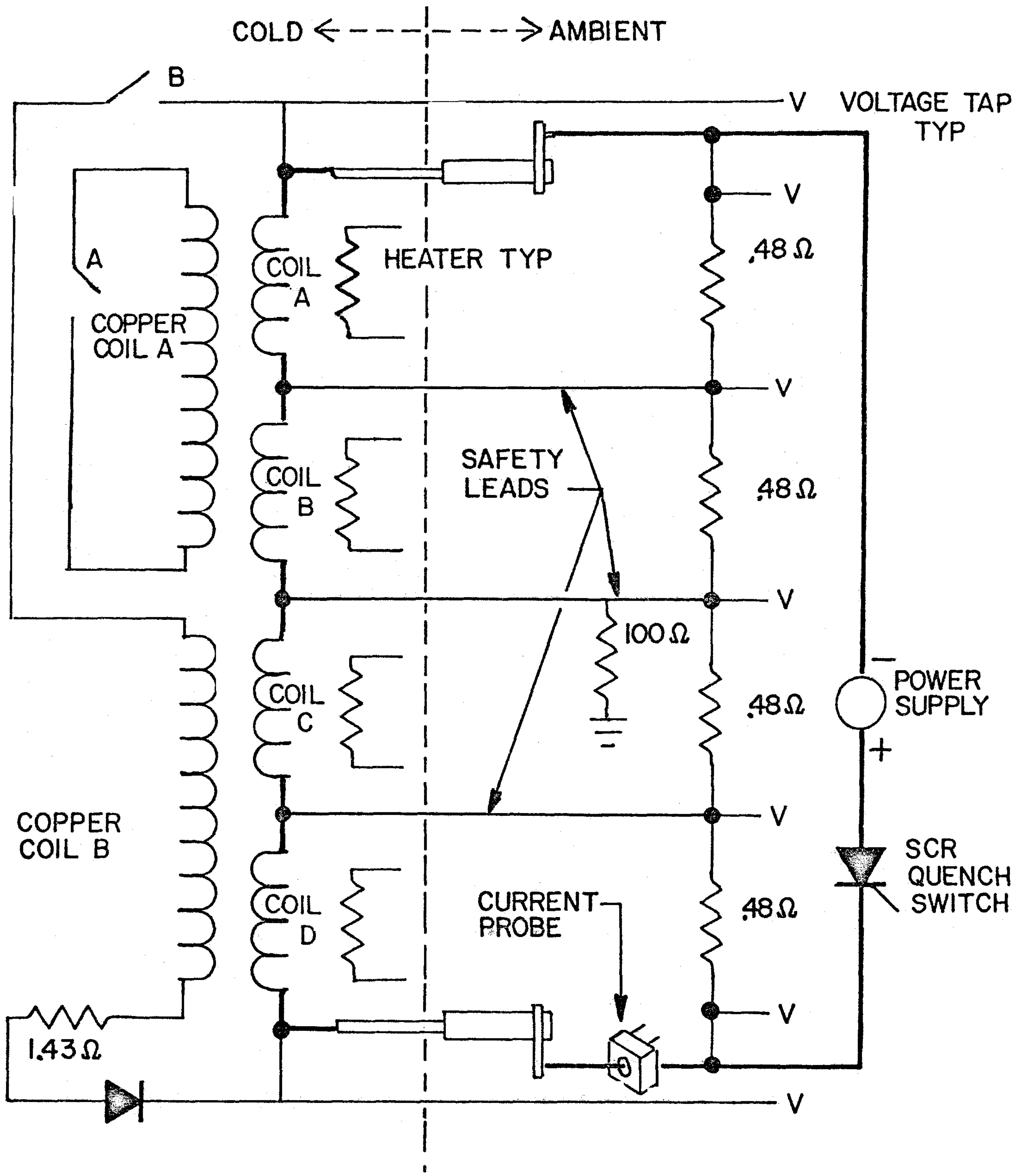

Fig. 6 Electrical connections. Close Switch A for inductive hot wire technique; Close switch B for directly coupled hot wire. The copper coils are one strand out of 15 in the cable.

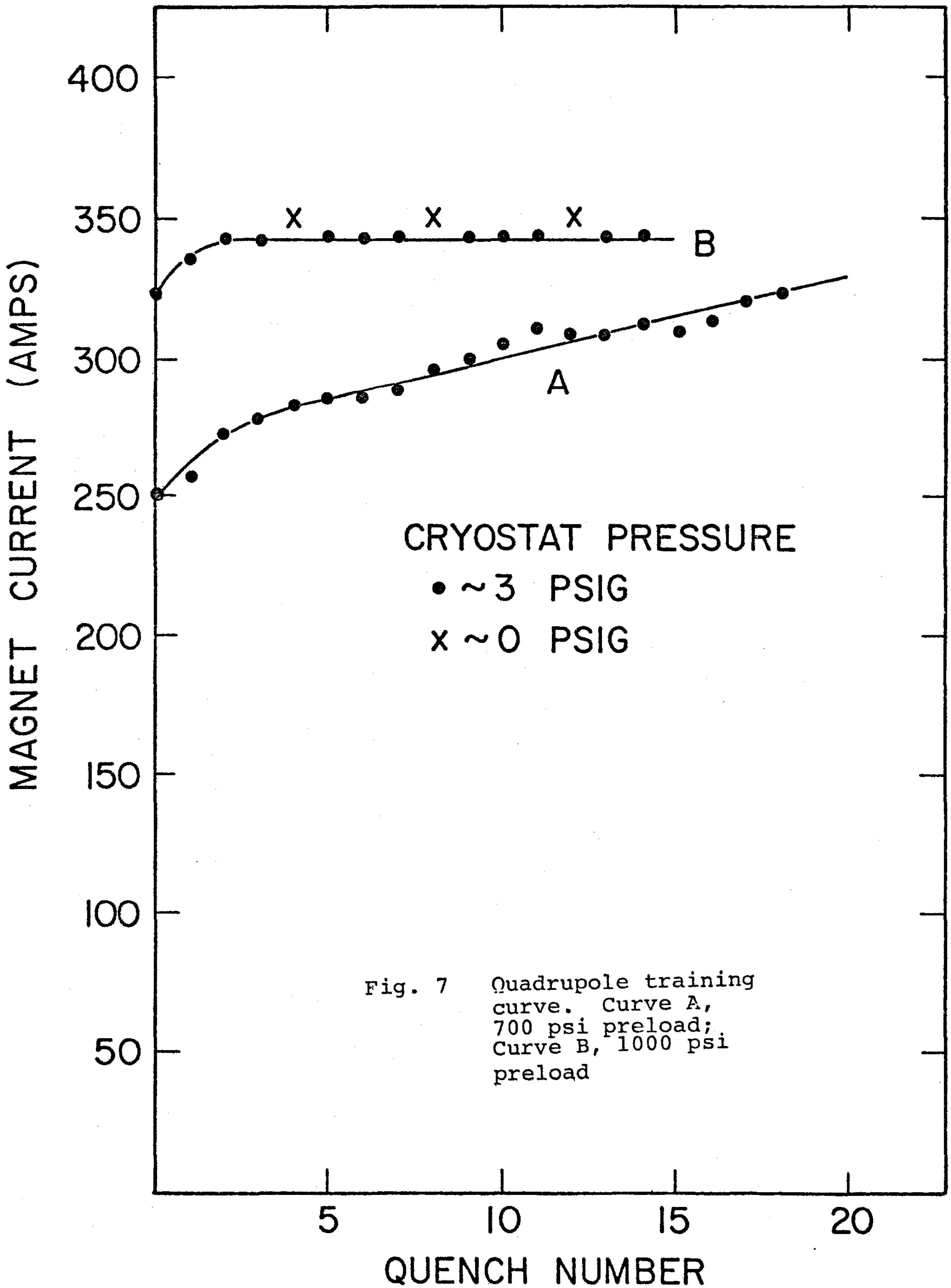

Fig. 7 Quadrupole training curve. Curve A, 700 psi preload; Curve B, 1000 psi preload

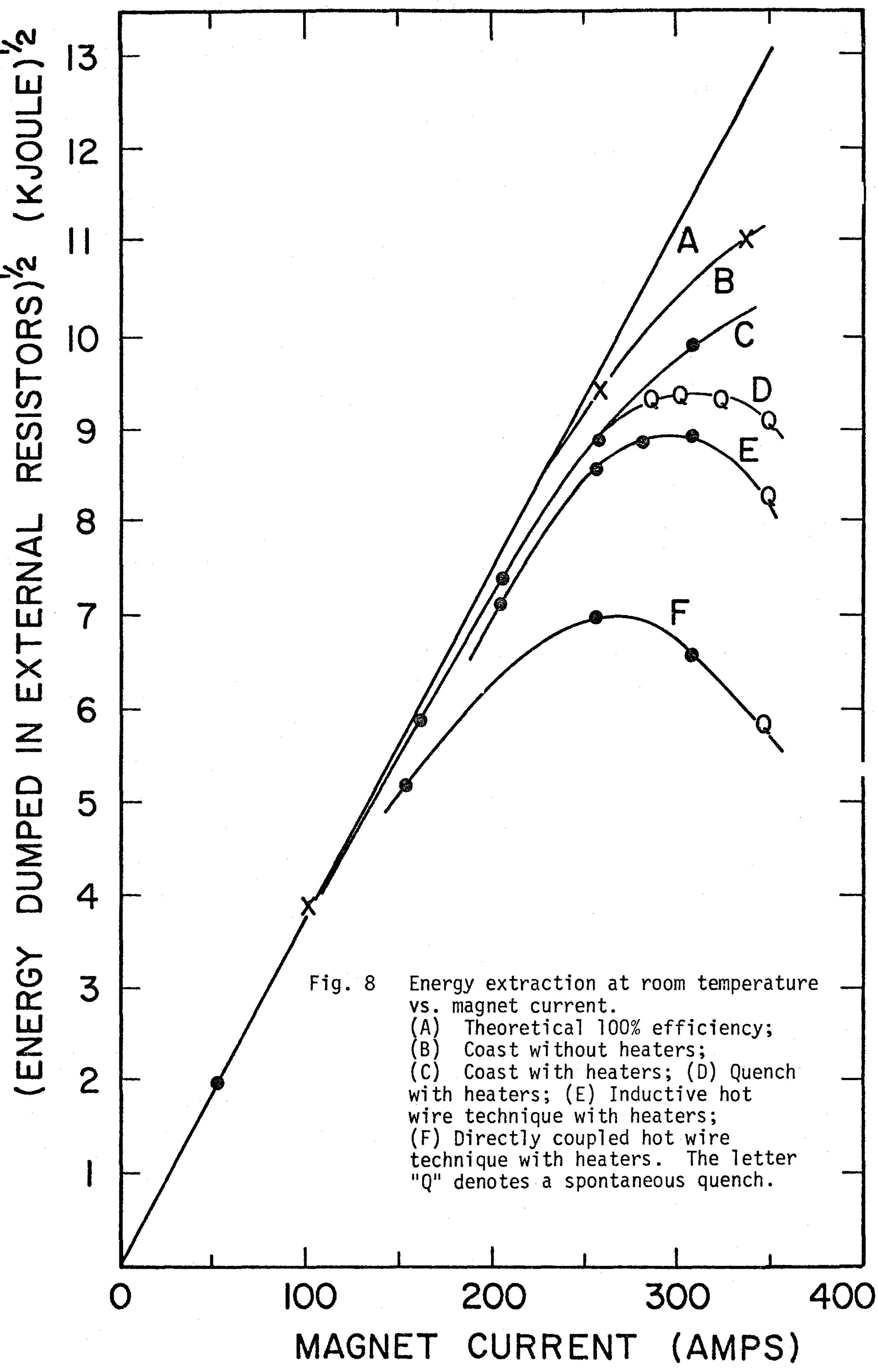

Fig. 8 Energy extraction at room temperature vs. magnet current. (A) Theoretical 100% efficiency; (B) Coast without heaters; (C) Coast with heaters; (D) Quench with heaters; (E) Inductive hot wire technique with heaters; (F) Directly coupled hot wire technique with heaters. The letter "Q" denotes a spontaneous quench.