MINERAL-INSULATED CONDUCTORS FOR MAGNET COILS

A. Harvey
Los Alamos Scientific Laboratory*
Los Alamos, New Mexico 87544

ABSTRACT

Data are presented on the characteristics of mineral-insulated (magnesium oxide) copper conductors developed for high radiation environments. Two conductor types are described, a solid conductor which can be cooled externally, and a hollow, direct-water cooled, conductor. In the solid conductor designs, the thermal conductivity of the insulation is dominant, and data are presented on attainable current densities. For hollow conductors, specifications are presented for a range of sizes, which include manufacturing limits adapted to the inherently irregular shape of the conductor. Examples of mineral-insulated coils are illustrated.

"Mineral-insulated" is a trade term from the wire and cable industry, applied to conductor insulated with a metal oxide, usually MgO. The oxide, in the form of a compacted powder, is held in place around the conductor by an outer metal sheath. Primarily developed for its ability to withstand high temperatures, this insulation is also highly radiation-resistant, and has been used in applications within nuclear reactors for many years.[1] Now accelerator beam-handling magnets are requiring the same degree of radiation hardening: the quadrupoles adjacent to the LAMPF primary targets are expected to be exposed to 10^{11}-10^{12} rads/year. This would result in short coil lifetimes with any organic insulation system.

This mineral-insulation system can be applied to two conductor formats useful in magnet technology, 1) solid copper, and 2) hollow copper intended for direct water cooling. While the coil cooling criteria in the second case are conventional, the first format has a unique advantage in the case of a mineral-insulated coil. That is that the heat developed in the conductor has to pass through insulation only once, before it is transferred through a matrix of metal sheaths, to the external heat sink. When added to the already-high conductivity of compacted magnesium oxide, this results in a high allowable current-density for a given temperature rise in a multi-layer coil. In addition, if no other factor is restrictive, the allowable temperature rise for a mineral-insulated coil can be higher than for an organically-insulated one, since there is no time-temperature degradation of magnesium oxide. In order to avoid problems in radiation fields due to residual activition, and formation of radiolytic gases, the magnesium oxide must be reasonably pure. The simplest practical test for purity is the insulation resistance, and a typical specification is 10,000 Megohms per 1000 ft length of conductor, at 100 V dc.

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Solid Conductor

This conductor format is useful in cases where low magnet powers are involved -- for example, in the LAMPF beam switchyard area where magnet pole tip fields generally do not exceed 5 kG, because of the use of an H^- beam. The conductor cost is significantly lower than for hollow-conductor m.i. cable. Fig. 1 shows several sizes of solid conductor cables, and Fig. 2 a quadrupole magnet wound with this type of conductor.

The allowable current-density in this conductor has been investigated using 10-layer coils, with a cooling coil on one side, soft-soldered together to ensure good heat transfer --- Fig. 3 shows a cross section of such a test coil. A typical temperature distribution in such a coil is shown in Fig. 4 (referred to mean cooling water temperature), and Table I lists the current-densities to produce various temperature rises in a 10-layer assembly of this type for several conductor sizes. However, there are irregularities in the current-capacities, because of the variation of sheath and insulation thickness with conductor size. For example, a conductor 0.25" sq will have a sheath 0.02"-thick, while 0.53" sq will use 0.03"-thick sheath. The corresponding insulation thicknesses are 0.04" and 0.06". The 0.44" sq cable tested had a particularly poor packing fraction for its size, 38.5%. The smaller size conductors have a higher permissible current-density because the ratio of sheath cross section to conductor is higher. From Table I we can derive current ratings for this coil format and 40C° temperature rise. These are given in Table II. The coil power dissipation, as always, depends on the current density.

For applications where the coil is larger, or a lower surface temperature is required to avoid undue expansion of adjacent iron magnet parts, additional cooling coils can be added, as shown in Fig. 5.

Hollow Conductor

The design of coils using a mineral-insulated hollow conductor follows the same considerations as that for conventional hollow conductor. Additional factors to consider are the reduced packing factor (30-50%) and the difficulty of making joints. It is the practice at LASL to use lengths of conductor matched to the water circuits, so that terminations are used rather than conductor joints. A typical termination, all inorganic, is shown in Fig. 5. The important point to note is that a fluxless braze must be used for the MgO seal, as flux degrades the insulation resistance severely and is very difficult to remove.

It has been our experience that the thermal conductivity of the MgO insulation is sufficiently high to prevent significant relative movement between the sheath and inner conductor, which would strain the ceramic seal. The bellows assembly shown on Fig. 6 prevents the water manifold from straining the water-circuit insulator.

A picture-frame magnet using m.i. conductor, 0.53" sq, 750A rating, is shown in Fig. 7; it has rubber hoses on the water circuits. The specification for this conductor is given in Fig. 8. A coil for a picture-frame 90° spectrometer magnet, wound from 0.375" sq conductor rated at 350A, is shown in Fig. 9.

A conductor for 1500-2000A has been designed (Fig. 10); it has a packing factor of 0.47, and a minimum bend radius of 2".

Conclusion

Mineral-insulated square-section copper cable permits the use of completely inorganic magnet coils in high radiation environments. The cable is rugged so that winding is easy, and the winder does not have to apply any insulation. Representative bend radii were given in a previous paper.[1]

It is LASL practice to apply the terminations in-house. Three magnets, one using hollow conductor and two solid conductor, have been in use at this Laboratory, though not in a radiation environment, for several months now without any problems. Trim coils using m.i. cable have been in service on LRL's 88" cyclotron for many years.[2]

TABLE I

CURRENT DENSITY AND TEMPERATURE RISE IN
10-LAYER SOLID m.i. CABLE TEST COIL

ΔT C°	Cable Size in. sq.	Cond. Area $in.^2$	Current A	Current Density $A/in.^2$
30	0.26	0.019	125	6,580
57	0.26	0.019	162	8,520
40	0.375	0.067	237	3,540
60.5	0.375	0.067	285	4,250
70	0.375	0.067	302	4,500
32	0.412	0.067	173	2,580
43	0.412	0.067	199	2,970
59	0.412	0.067	225	3,360
79	0.412	0.067	248	3,700
95	0.412	0.067	276	4,110
16	0.44	0.074	100	1,350
23	0.44	0.074	125	1,680
34	0.44	0.074	150	2,020
65	0.44	0.074	200	2,690

TABLE II

ALLOWABLE CURRENT FOR 40C° ΔT IN 10-LAYER COIL

Cable Size in. sq.	Nom. Size AWG	Cable Packing Factor %	Current A	Current Density $A/in.^2$
0.25	10	28.4	140	7,500
0.412	2	39.5	190	2,850
0.53	2/0	42	225	1,900

References:

1. Mineral-Insulated Magnets for High-Radiation Environments, by A. Harvey and S. A. Walker, IEEE Trans. Nuc. Sci., NS-16, No. 3, pp. 611-612, June 1967.
2. Trim-Coil Construction for the Berkeley 88 in. Cyclotron, by L. R. Glasgow and R. J. Burleigh, Nuc. Inst. & Methods, 18, 19, 576-581, 1962.

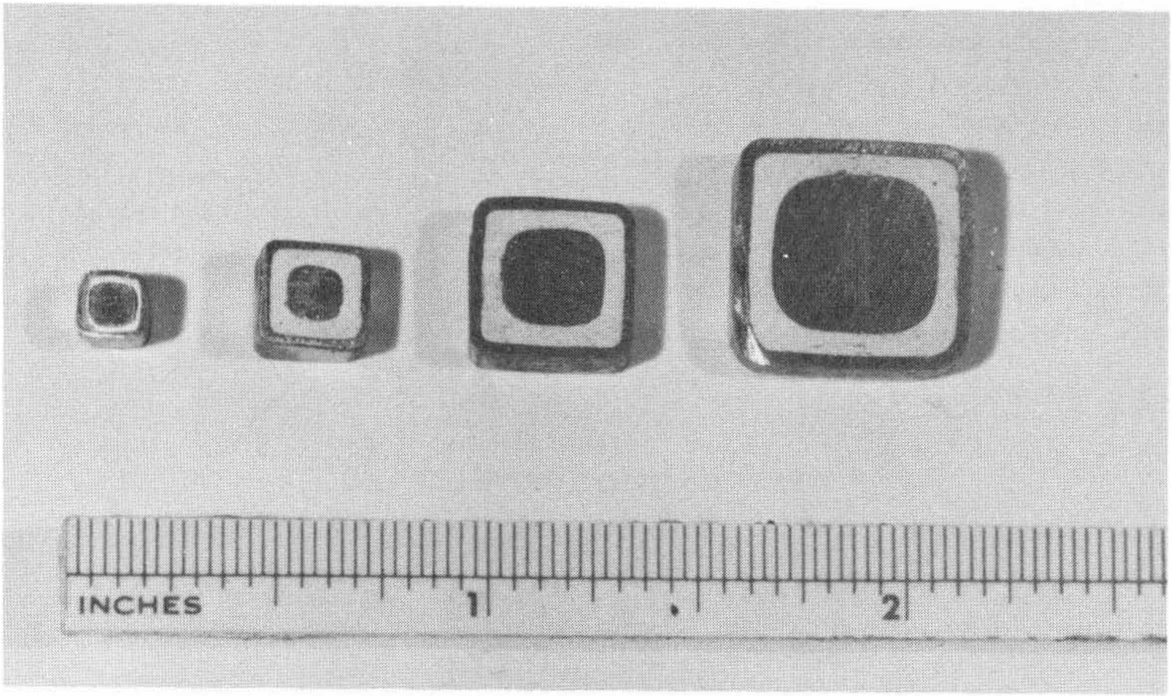

Fig. 1. Square, solid-conductor, m.i. cables.

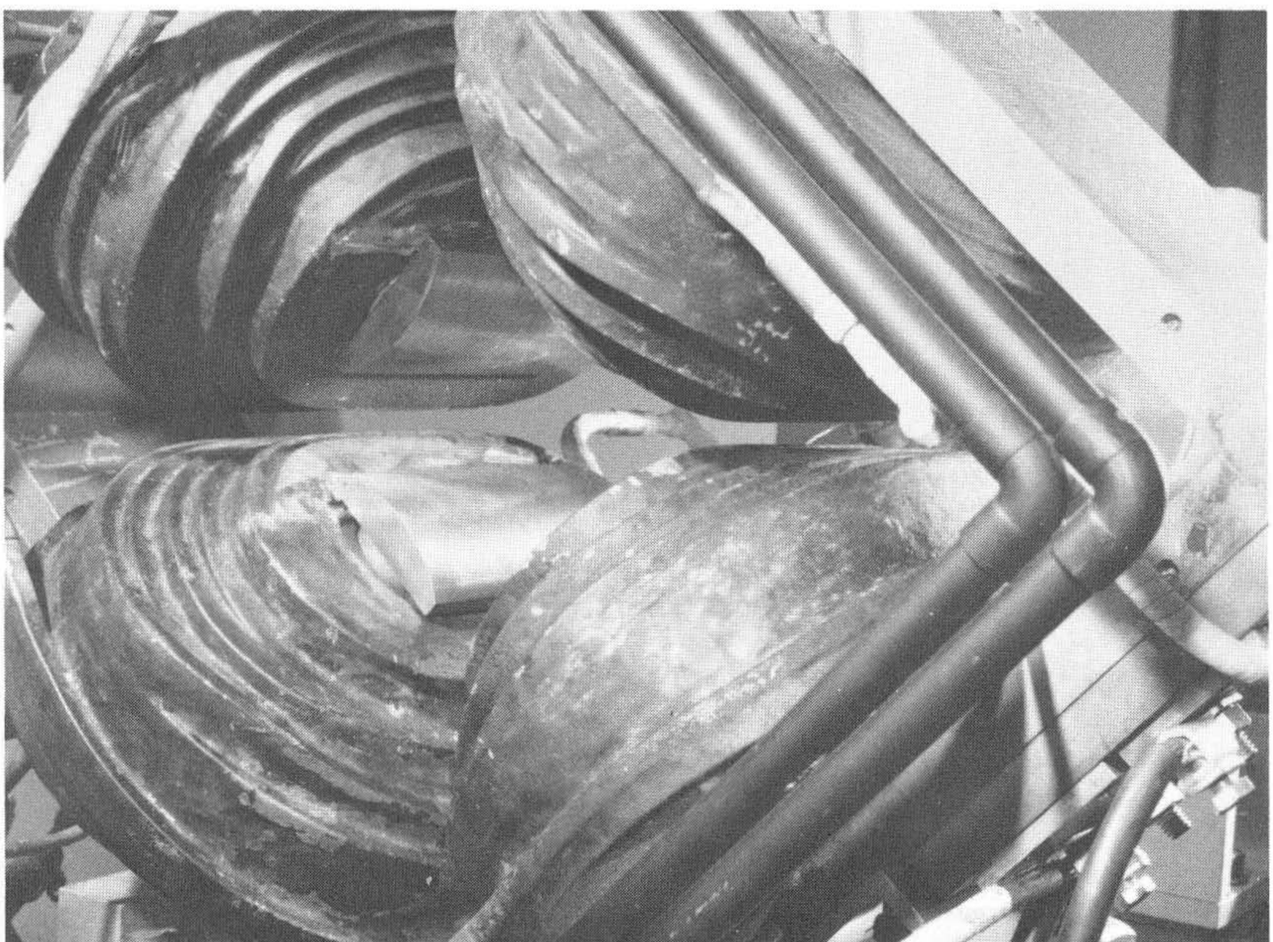

Fig. 2. 4-in. bore quadrupole wound with solid conductor, m.i. cable, externally cooled.

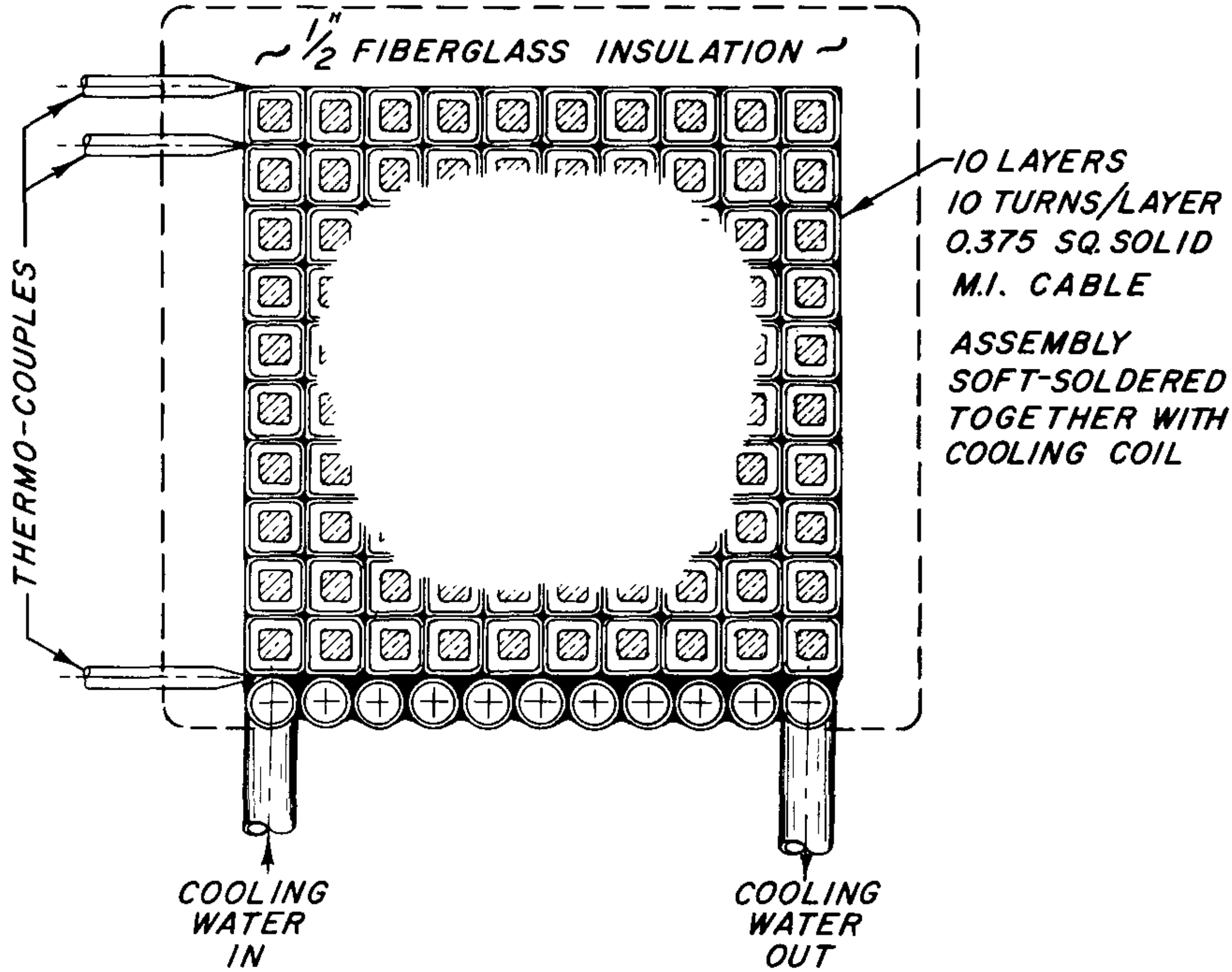

Fig. 3. Test coil.

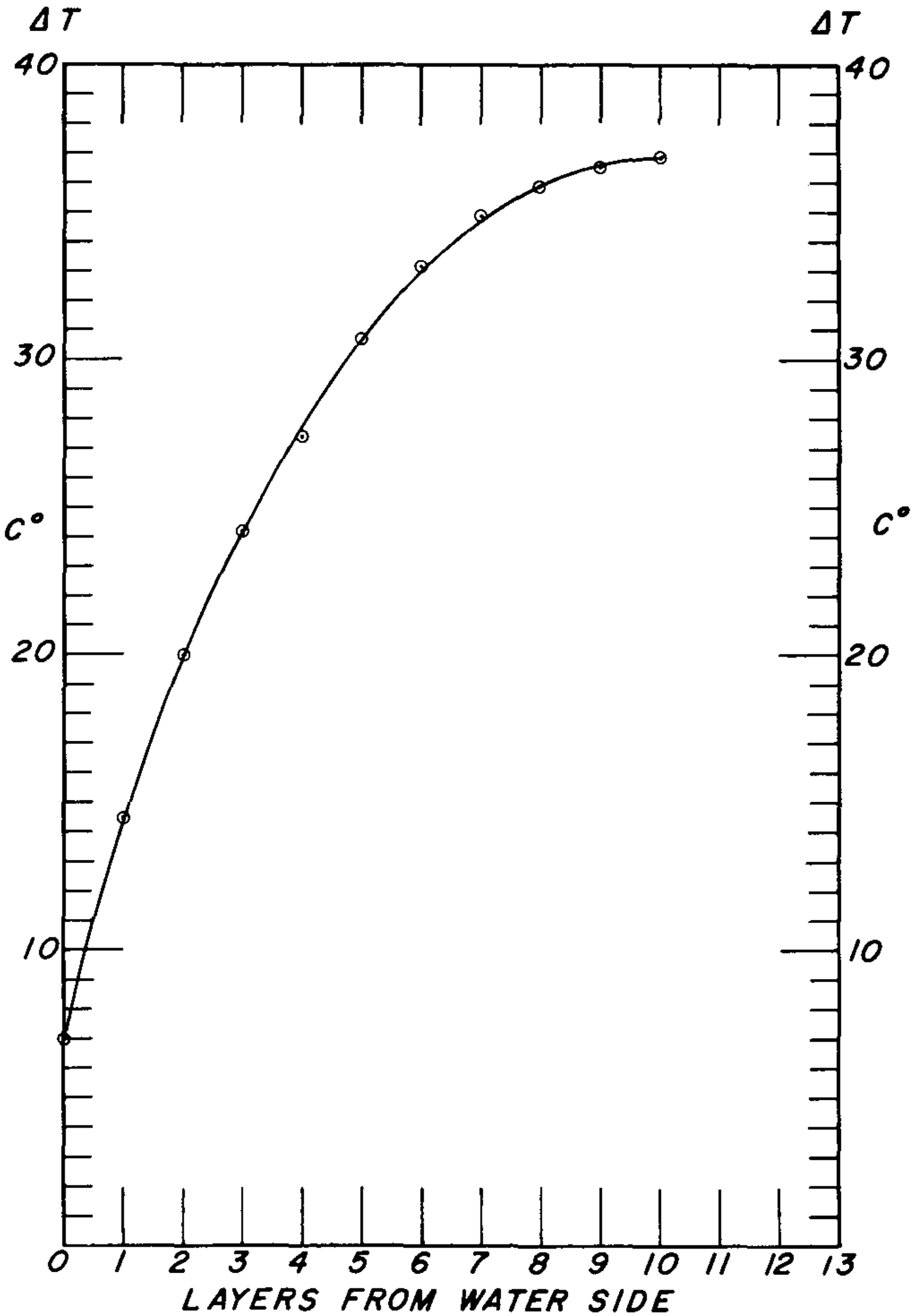

Fig. 4. Temperature distribution in solid-conductor m. i. coil.

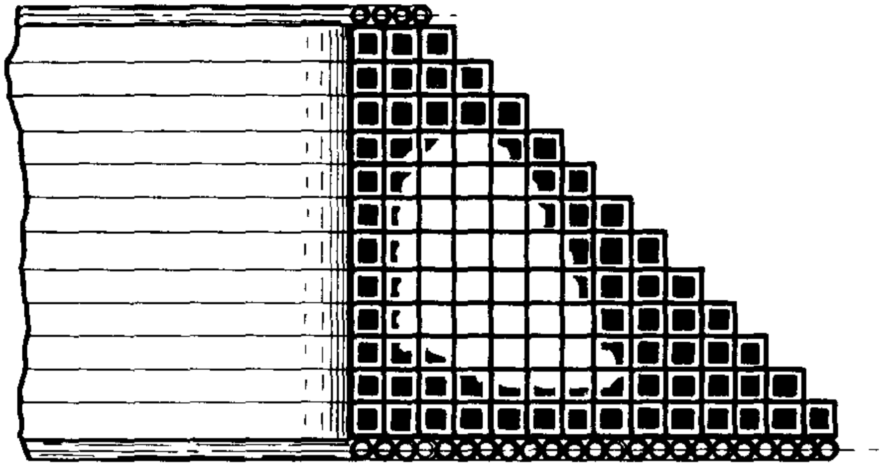

Fig. 5. 6-in. bore quadrupole coil. 102 turns of 0.412-in. sq solid m.i. cable. Cooling coils, 1/4-in. o.d. Cu tubing.

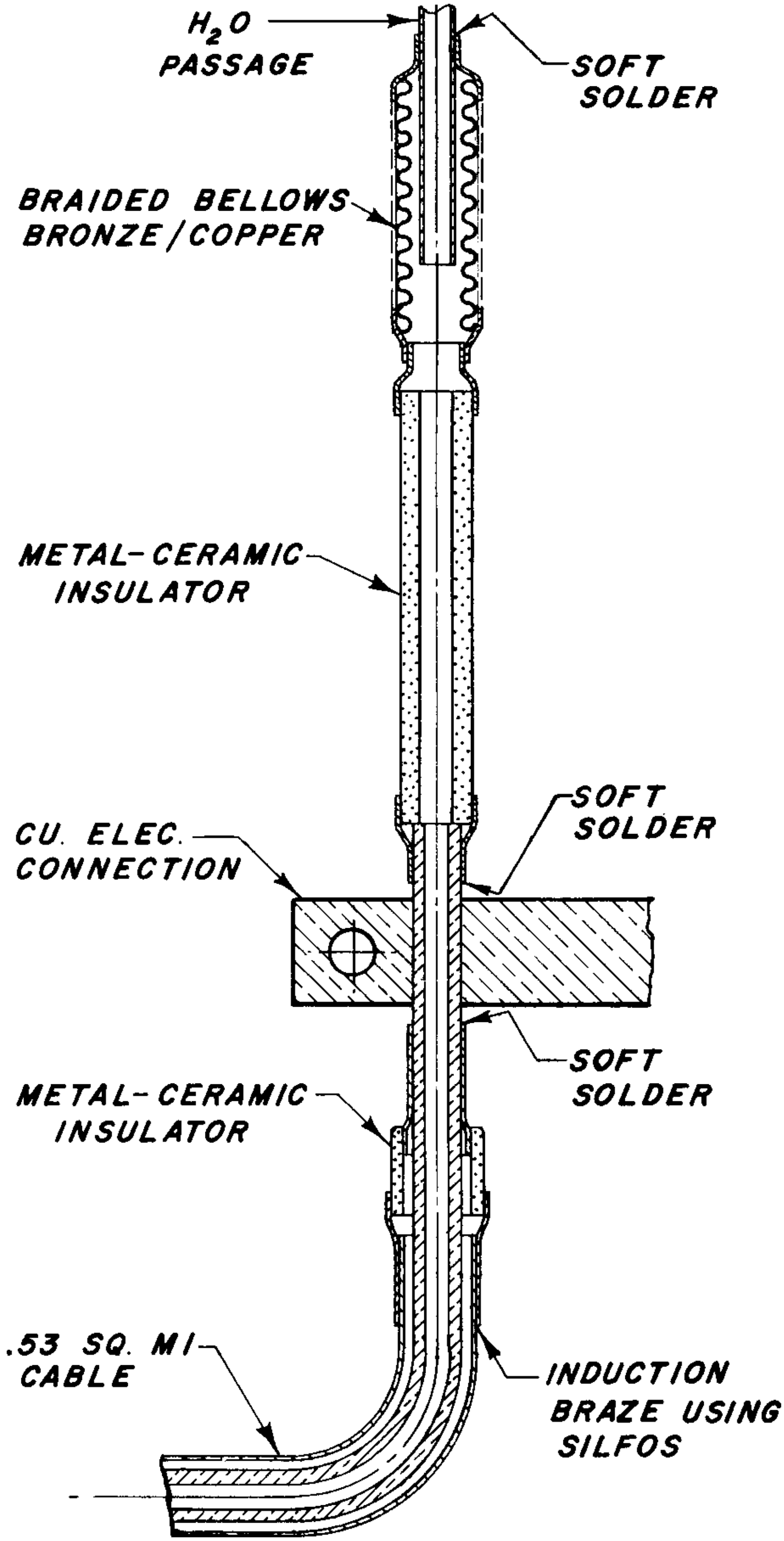

Fig. 6. Hollow m.i. conductor termination.

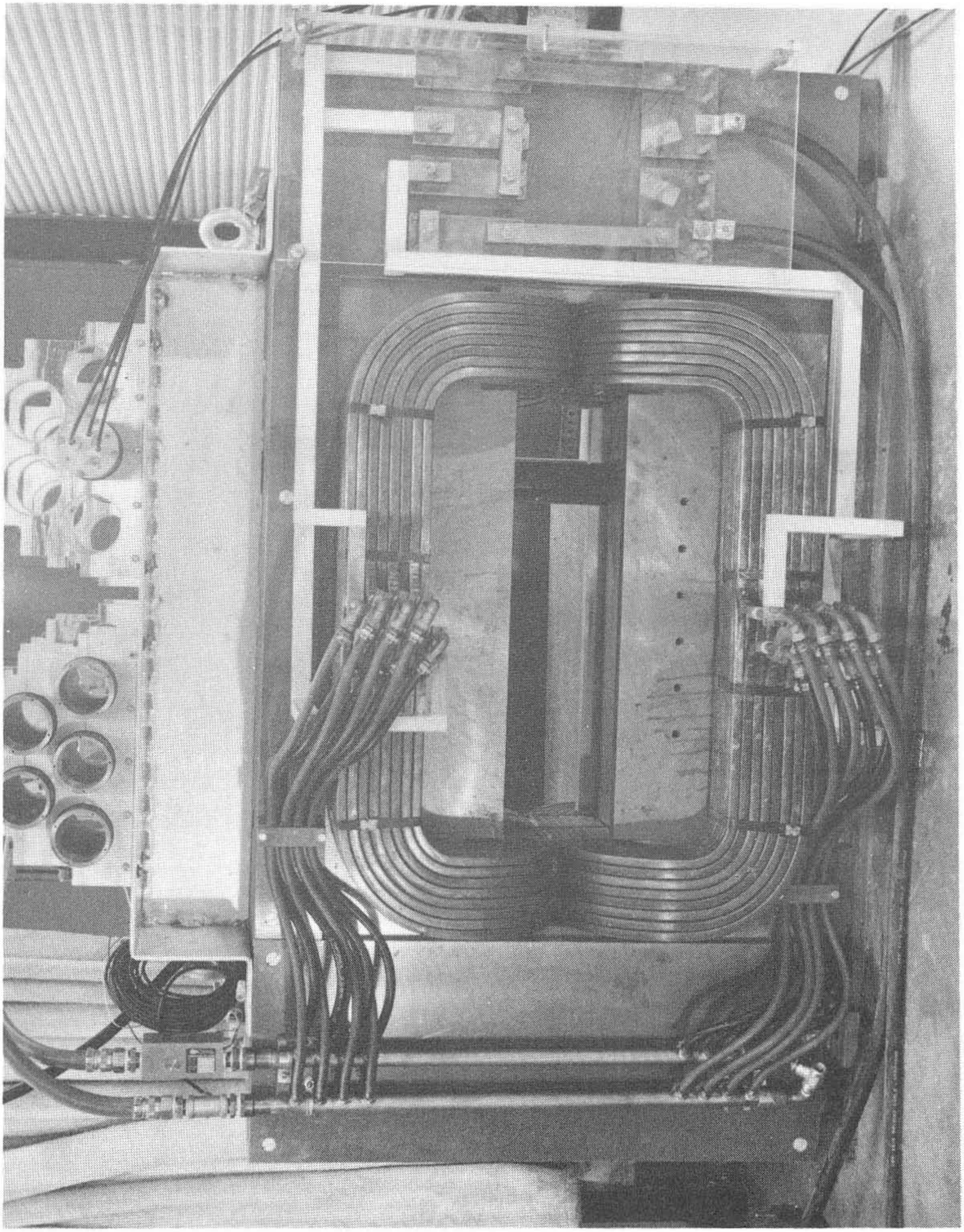

Fig. 7. 8-in. gap, 5-kG magnet wound with 0.53 in. sq hollow m.i. conductor.

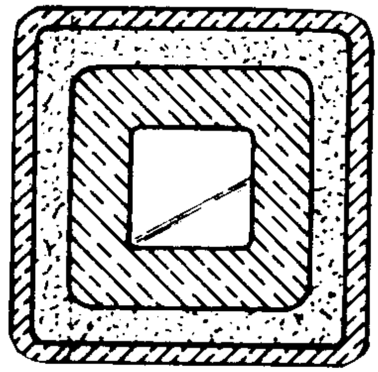

Fig. 8

Mineral Insulated Hollow Conductor, 750 A. Nom.

Specification: Overall size: 0.530" + 0.000 - 0.010" sq.
Corner Radius 0.032" max.

Conducter size: 0.36" nominal square outside
0.18" nominal square inside
0.050" minimum wall thickness

Insulation Thickness: 0.020" minimum
0.055" nominal

Sheath Thickness: 0.030" ± 0.005"

Materials: Conductor, copper, 100% I.A.C.S.
Max. resistance at 25°C: 0.091 ohm/1000 ft
Insulation, compacted magnesium oxide
Sheath, copper, commercial anneal, free of nicks, burrs and scratches

Tests: Insulation resistance, inner conductor to outer sheat > 10,000 Megohm/1000 ft at 25°C, 100 V DC
Dielectric strength, > 1,500 V R.M.S. inner conductor to sheath, 1 min.
Water tests: 300 p.s.i. water in central hole to produce no change in insulation resistance
Immersion of coiled cable (except ends) in warm water for 30 min. to produce no change in insulation resistance

Water Flow: 0.5 USGPM, with max. pressure drop 100 psi per 100 ft

Lengths: See Order

Shipping: Coiled to minimum diameter of 4 ft. All ends of insulation sealed against moisture. Tube ends plugged.

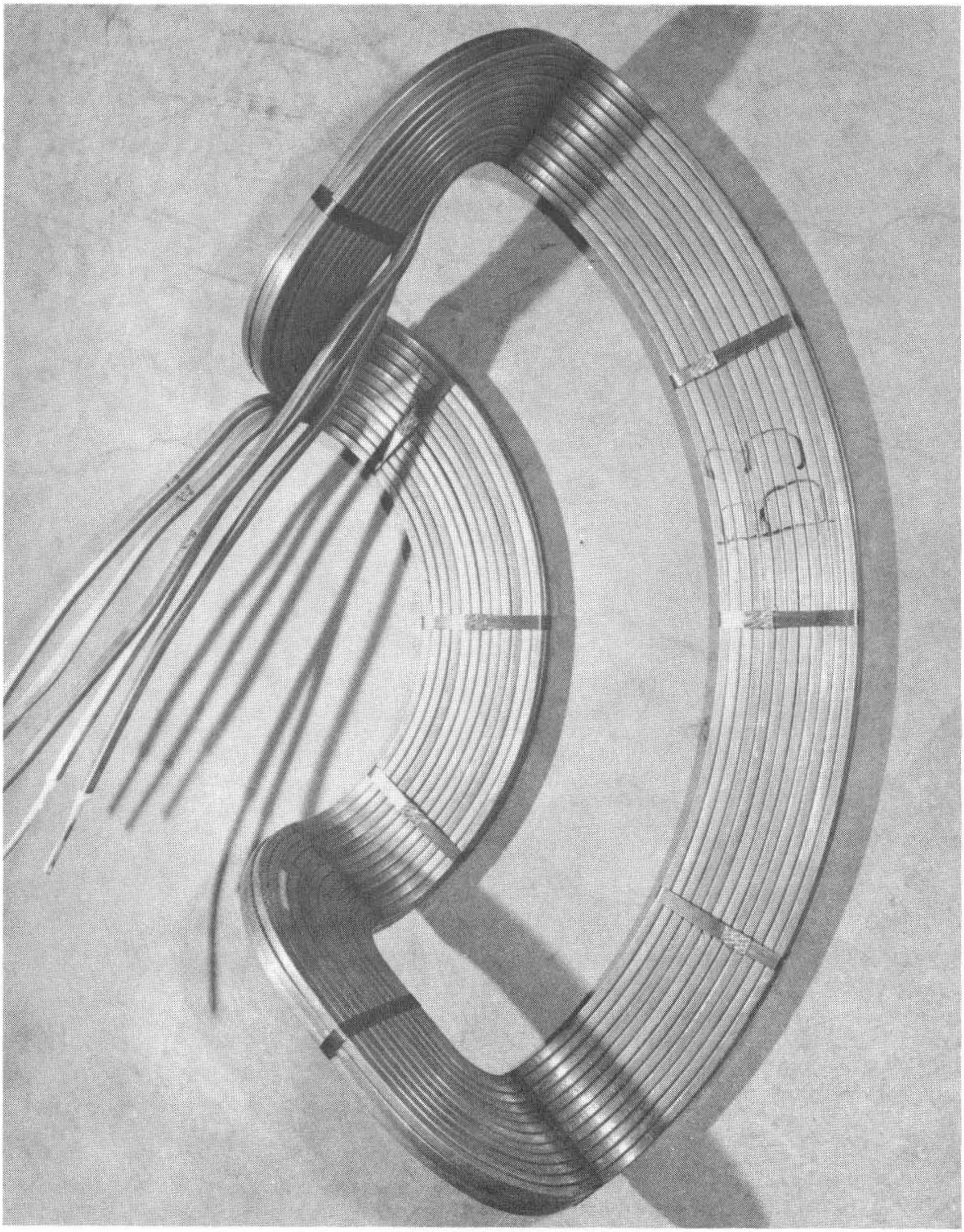

Fig. 9. Coil for 90° spectrometer magnet wound from 0.375-in. sq hollow m.i. cable.

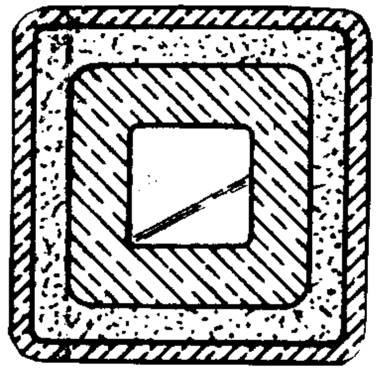

Fig. 10

Mineral Insulated Hollow Conductor, 1800 A nom.

Specification: Overall size: 0.75" +0.00", -0.01" square
Corner radius: 0.032" max.
Conductor size: 0.56" nominal square outside
0.25" nominal square inside
0.12" min. wall thickness
Insulation thickness: 0.06" nominal
0.03" minimum

Sheath thickness: 0.03" ± 0.005"

Materials: conductor: copper, 100% I.A.C.S.
max. resistance at 25°C: 0.035 ohm/1000 ft
insulation: compacted magnesium oxide
sheath: copper, commercial anneal. Free of nicks, burrs and scratches.

Tests: Insulation resistance, inner to outer > 10,000 M ohm/1000 ft at 25°C, 100 V dc
Dielectric strength, > 1,500 V R.M.S. inner conductor to sheath, 1 minute.
Water test: 300 psi water in central hole to produce no change in insulation resistance

Water flow: 1.5 USGPM, with max. pressure drop 200 psi/100 ft

Minimum length: See Order.

Shipping: Coiled to minimum diameter of 4 ft. All ends of insulation sealed against moisture. Tube ends plugged.