MINERAL-INSULATED MAGNETS FOR HIGH-RADIATION ENVIRONMENTS*

A. Harvey
Los Alamos Scientific Laboratory
University of California
Los Alamos, New Mexico
and
Atomic Energy of Canada Ltd.
Chalk River, Ontario, Canada

and

S. A. Walker
Pyrotenax of Canada Ltd.
Trenton, Ontario, Canada

Introduction

The electro-magnets used almost universally today to steer and focus beams of charged particles in accelerators, and in external lines to experiments, are subject to increasing radiation doses as accelerator energy and intensity rise. The most vulnerable part of the magnet is the electrical insulation on the windings, and this paper describes the use of an entirely inorganic material, magnesium or aluminum oxide, which has a radiation resistance orders of magnitude higher than currently-used insulations, generally an epoxy-fibreglass combination.[1] Already used in the electrical wiring industry for heat-resisting wiring, heating cable and hazardous installations,[2] electrical insulation by compacted metal-oxide powder has also shown its versatility in the nuclear reactor field. Mineral-insulated cable provides one of the few practical ways of installing electrical leads into nuclear reactor cores, for thermocouples,[3] heaters, or flux detectors.[4] Magnet coils for accelerator applications can be fabricated with this insulation, using either external cooling for low power magnets, or internal cooling for high powers, and the magnets show promise of great durability. Such coils are being investigated for use in the beam switchyard area of the LAMPF accelerator.

Conductor

Mineral-insulated copper conductor has been available for many years,[5] but in round cross-section. For coil-winding, a square or rectangular cross-section allows better packing. Figure 1 shows a variety of square, solid cables. The ohmic losses can be removed by external air or water cooling, and heat transfer within the coil can be improved by soft-soldering the entire assembly. With solid conductors, the heat generated in the conductor has to be transferred through the magnesium oxide insulation, and so its thermal conductivity is of major importance. Figure 2 illustrates how the thermal conductivity of MgO powder varies with density: normal manufacturing processes give a powder density of 2.2 g/cm^3, corresponding to a thermal conductivity of 16.4 Btu/°F/in./ft^2/h.

At higher current-densities, direct cooling of the conductor by water-flow in a hollow conductor is standard practice, and Fig. 3 shows mineral-insulated conductors in this format. The thermal ratings are the same as for other insulation systems using hollow conductors.

Of practical interest in coil manufacture is the minimum radius to which the conductor can be bent. The copper in both the conductor and outer sheath is normally supplied fully annealed. Minimum bend radii for some representative conductors in this condition are listed in Table I.

TABLE I

Minimum Bend Radii

Cable Outside Dimensions	Sheath Thickness	Minimum Inside Radius
Solid:		
0.165 in.sq.	0.012 in.	0.35 in.
0.25 in.sq.	0.015 in.	0.50 in.
0.40 in.sq.	0.030 in.	0.75 in.
0.58 in.sq.	0.035 in.	2.0 in.
Hollow:		
0.375 in.sq.	0.020 in.	1.25 in.
0.53 in.sq.	0.030 in.	1.75 in.

Failure occurs generally by over-stretching the sheath on the outside of the bend. Wrinking of the sheath on the inside occurs, but is not detrimental to the electrical properties of the cable. The bend radius may be restricted by the amount of keystoning which is acceptable. The cable withstands considerable deformation without electrical failure. It is possible, for instance, to produce a thin, wide cross section as is shown in Fig. 3, for special applications such as septum magnets. In such cases, the high impedance to the cooling fluid caused by the reduced cross section of the coolant passage must be tolerated.

Terminations must be provided for the cable, which seal moisture out of the magnesium oxide insulation. (The MgO powder generally used is a relatively inactive grade of calcined magnesite. It does not hydrolyze readily, but there is a rapid drop in insulation resistance with the ingress of moisture, and an end seal is desirable to prevent this.) The insulation resistance is a very good check on freedom from moisture (a dry cable has an insulation resistance of 10,000 megohms per 1,000 ft). To maintain the inorganic charac-

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* Work done in part under the auspices of the U. S. Atomic Energy Commission.

ter of the coils, ceramic terminations, already used with this type of cable,[6,7] must be used.

For connections, either a combination of two terminations may be used, or a joint based on normal hollow-conductor practice.[8] Figure 4 shows a section of such a connection. Pressing the outside to the finished dimensions of the cable streamlines the joint and fills all the interstices with alumina.

Acknowledgements

We would like to acknowledge the help of Group CMB-6 at Los Alamos Scientific Laboratory in the fabrication of some of the special conductors described here. The joint illustrated incorporates their suggestions.

References

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Figure 1: Solid mineral-insulated cables.

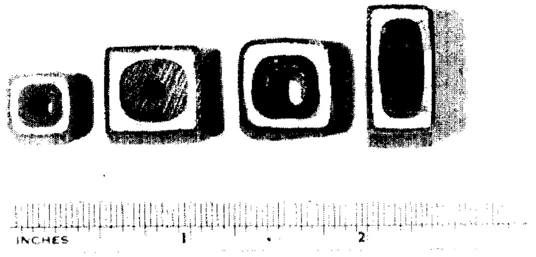

Figure 3: Hollow mineral-insulated cables.

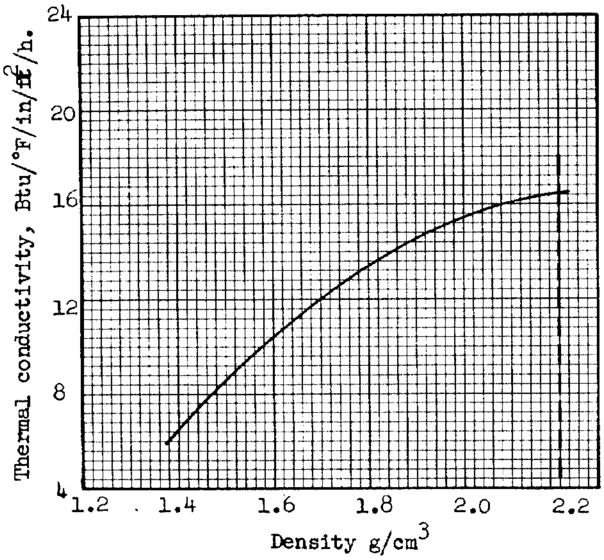

Figure 2: Thermal conductivity of packed magnesium oxide powder.

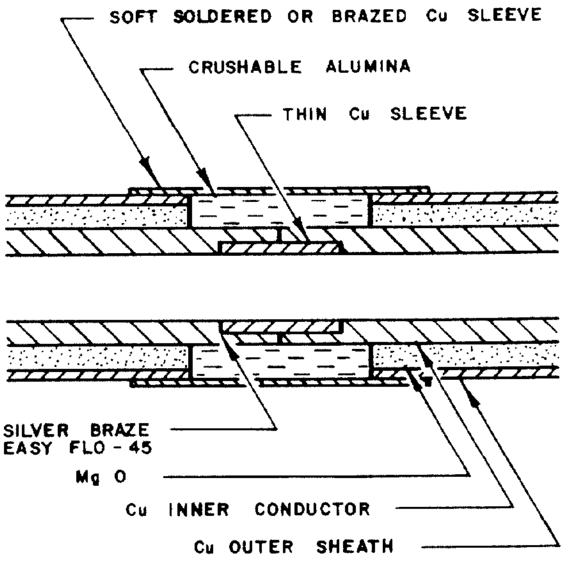

Figure 4: Hollow m.i. cable joint.