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RADIATION HARDENING OF MAGNET COILS*

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1. INTRODUCTION

The first essential before embarking on the radiation hardening of electrical insulation—mostly magnet coils—in any beamline application, is to obtain a reliable estimate of the dose to the components. There are examples (switchyards at SLAC and LAMPF) where the degree of hardness specified was much higher than was required. Although experience shows that the cost premium for substantial radiation hardening is of the order of 10%,[1] it has also become clear that well-designed beamlines have negligible losses: hardening is required only in the vicinity of targets, collimators or other beam intercepting devices. Where the beam is deliberately scraped, local shielding will minimize the associated radiation in the surroundings. Electron machines have their own special problems due to synchrotron radiation, so certainly coils and other electrical equipment should be kept away from the beam bend-plane.

Because proton beams interact with thick targets in the meson factories, TRIUMF, LAMPF and PSI (formerly SIN) have examples of very hard magnet coils near their target cells. The activation associated with these substantial doses

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requires remote-handling of the magnets, and poses the question of whether it is worth considering repairing a damaged magnet when it fails. As disposal of radioactive waste becomes more and more difficult, repair may become more attractive, but provision for it needs to be designed-in from the start. It is these problems of radioactive handling that add substantially to the cost of radiation-hardened magnets.

An interesting disposal idea originated at PSI in Switzerland—damaged magnets were incorporated into cast concrete shielding blocks for their target cells.

2. LEVELS OF RADIATION RESISTANCE

A. "Conventional"

A standard technique for insulating magnet coils is to use epoxy resin, reinforced with fiberglass. Standard resin systems, such as Novolac or Bisphenyl-A, with NMA hardener can be expected to tolerate 10^9 rads (10^7 Gray). Additives to avoid are the old Carbowax flexibilizer; in large part, flexibility can be maintained with flexible epoxies such as Dow's DER 732. One advantage of epoxy systems is the color change (darkening) that indicates exposure and allows replacement before failure.

All these epoxies can have their radiation tolerance enhanced by adding an inorganic filler, glass, or alumina. Some indication of the improvement to be expected can be found in Refs. 2 and 3. Note that Ref. 2 gives some of the few available data on electrical properties following irradiation; most radiation testing is done on the basis of mechanical properties. Table 1 gives the recipe currently in use at SLAC.

Other organic possibilities include polyimide (Kapton) for which DuPont makes very modest radiation-resistance claims. However, its resistance exceeds 10^{10} rads, and it is available as a film coating on magnet wire (H-film) as well as in tapes and sheets. As a copper-polyimide composite, it can be formed by printed-circuit techniques for pole-face windings and Lambertson magnets.

One organic to be avoided is Teflon, which although an excellent high-temperature insulation, is very poor in radiation fields. Care needs to be taken to eliminate its use in hook-up wire, and in factory-installed wiring in protective devices such as flow switches.

B. Inorganics

For maximum radiation resistance, organics must be avoided completely. There are techniques in the electrical engineering field which are largely inorganic, and adaptations of these lead to the highest levels of resistance.

Mica is a traditional insulation that withstands high temperatures and corona very well, in addition to radiation. Unfortunately, its physical format makes its application difficult in many circumstances. It has been modified by the electrical industry—reconstituted mica—to overcome the physical limitations, but often at the expense of its radiation resistance. One of the better composites is Mycalex, incorporating mica in a glass matrix. It can be hot-pressed onto substrates such as 400-series stainless steel (to match its expansion coefficient) and is useful in some applications: feedthroughs and standoffs, for example.

Several insulation systems have been developed for accelerator applications: a hard-anodized surface on aluminum conductors[4] and concrete, usually in conjunction with fiberglass.[5,6] However, the most widely used system found, for example, in the target cells of all the meson factories, LAMPF, PSI (SIN) and TRIUMF, is based on the use of magnesium oxide, "mineral-insulation" (m.i.) in the trade.[7] Two methods of using m.i. cable are possible in coils: direct water cooling and indirect cooling.

In direct water cooling, the conductor is fabricated with a central hole, and is cooled by direct contact of the water with the current-carrying conductor. This implies that there are insulating tubes between the conductors and the water headers which, for high-radiation service, are ceramic-to-metal parts.[7] Figure 1 is a sketch of an insulating assembly produced by industry[8] that has the advantages of:

(1) high aspect ratio of length to cross section of water, giving low leakage current;

(2) smooth internal bore—no diameter changes or pockets to accumulate deposits;

(3) substantial tube ends to act as sacrificial electrodes, if they are not adequately passivated to inhibit corrosion; and

(4) tube ends arranged so that installation does not apply tension to the assembly.

These features are a result of operating experience at Los Alamos.[9]

The characteristics of two commercially available sizes of hollow mineral-insulated square cables are given in Table 2.

Indirectly cooled mineral-insulated coils avoid the water-insulator problem by keeping the coolant in separate tubes and conducting the Joule heat through the magnesia and a metal matrix that includes the cable sheaths. To facilitate this heat transfer, the copper sheaths are soft-soldered together or cast in lead. Current densities over 20 A/mm^2 have been demonstrated by this technique,[10] though the power consumption, of course, is correspondingly high. Magnets with coils of this construction are in service at Los Alamos, TRIUMF, and PSI (SIN).[11]

For all applications where the magnet is in a high-radiation environment, so becoming activated, it is vital that the interlock systems be as radiation-resistant as the coils; that they be at least as reliable, and preferably incorporate redundancy and if possible an *in situ* test capability.

There is considerable experience in industry, world-wide, producing coils with mineral-insulated conductors. However, there have also been some disasters, and so consultation with an experienced user before committing to a contract would be prudent. Moulds to contain substantial amounts of lead-tin alloy must be of adequate strength to resist deformation; molten lead-tin dissolves copper, so the potting time has to be minimized.

The characteristics of two commercially available cables—solid-conductor and square cross section—are given in Table 3. The 0.53 in. square cable in particular has been developed for the maximum current density per unit of the overall cross sectional area.

3. SPECIAL CASES

Most accelerator beamlines include a few magnets with special requirements that challenge the magnet designer. Probably the most common "special case" is the current-sheet septum, since it is inevitable that beam spill takes place on the septum conductor. Some approaches support the conductor only at its edges, so that the insulation is removed from the beam center-line (BNL); Los Alamos has used polyimide successfully in its Proton Storage Ring. At SLAC, the Damping Ring septa have plasma-sprayed alumina on copper conductors in magnets with small vertical aperture.[12] Factors in their success are: (1) use of stainless-steel tubing for cooling water, brazed to the copper (it is not oxidized by the irradiated water); and (2) double-brazing of all the conductor parts for assurance that there is adequate filler metal. These coils, which are inside the vacuum chamber, are run at their full current rating before assembly into the iron.

4. ACKNOWLEDGMENT

Any account describing the usefulness of mineral-insulated cable in magnet coils for accelerator applications has to recognize the contribution of the late Sid Walker of Pyrotenax of Canada Ltd. to its successful development. Sid undertook the challenges of new configurations for the m.i. cable that the Trenton, Ontario, plant produced, and cheerfully pushed their technology to the limits that the magnet designers were after. If there were more like him, everyone's industrialization program would be a pleasure as well as a success.

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   CERN–ISR–MAG/PS–6464 (Paints);
   CERN–ISR–MAG/67–19 (Glass Reinforced);
   CERN–ISR–MAG/68–14 (Lubricants);
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TABLE 1: Alumina-loaded epoxy mix for coil potting; SLAC, 1969.

To make approximately one U.S. gallon of mixture:					
		Percent RM by Weight	English Pounds	English Ounces	Metric Grams
DER–332	Bisphenyl–A Epoxy	45.0	1	14	850.5
DER–732	Flexible Epoxy	55.0	2	5	1048.9
	Subtotal	100.0	4	3	1899.4
Additives:					
NMA	Hardener	96.5	4	1	1832.1
BDMA	Catalyst	1.7		1-1/8	31.9
Z6040	Silane Wetting Agent	1.0		3/4	21.3
Cab-o-Sil	Maintains Suspension	3.75		2-1/2	72.0
Al_2O_3	Inorganic, T–61	224.0	9	6	4252.4
	Subtotal	327.0	13	11	6209.7
Total weight per U.S. gallon			**17**	**14**	**8109.2**

NOTES:

DER–332 and DER–732 from Dow Chemical Corp.
NMA (nadic methyl anhydride).
BDMA (benzl di-methyl amine).
Al_2O_3 iron-free and soda-free alumina, 325 mesh, from E. V. Roberts or Schoof's, Moraga, CA.

TABLE 2: Mineral-insulated cable, square, hollow conductor.

Specifications	F.P.S.	Metric	F.P.S.	Metric
Overall size Corner radius	0.53 + 0-0.01 in. sq 0.063 in.	13.46 + 0-0.25 mm sq 1.6 mm	0.75 + 0-0.01 in. sq 0.063 in.	19.05 + 0.025 mm sq 1.6 mm
Conductor size, nominal	0.395 in. sq	10.03 mm sq	0.570 in. sq	14.48 mm sq
Conductor resistance, maximum	0.08 Ω/m ft	0.262 Ω/km	0.035 Ω/m ft	0.115 Ω/km
Insulation thickness, nominal	0.04 in.	1.02 mm	0.05 in.	1.27 mm
Insulation resistance (I.R.)	5 GΩ/m ft	1.5 GΩ/km	5 GΩ/m ft	1.5 GΩ/km
Dielectric strength	1.5 kV, ac, 1 min		1.5 kV, ac, 1 min	
Hole size, nominal	0.18 in. sq	4.57 mm sq	0.26 in. sq	6.60 mm sq
Water flow, minimum	0.75 USGPM at 1 psi/ft, 270 ft	0.05 l/sec at 22.6 kPa/m, 82 m	2 USGPM at 1 psi/ft, 230 ft	0.126 l/sec at 22.6 kPa/m, 70 m
Sheath thickness	0.03 ± 0.005 in.	0.76 ± 0.13 mm	0.035 ± 0.005 in.	0.89 ± 0.13 mm
Weight (nominal)	0.7 lb/ft	1.04 kg/m	1.4 lb/ft	2.1 kg/m
Maximum length	270 ft	82 m	230 ft	70 m
Materials: Conductor, copper, 100% IACS conductivity. Sheath, copper, commercial anneal. Insulation, compacted magnesium oxide. Shipping: Coiled to minimum diameter of 4 ft (1.2 m). Ends sealed against moisture.			Tests: (1) Immersion of cable (except ends) in water at room temperature to produce no change in I.R. (2) Internal water pressure of 450 psi (3.1 mPa) to produce no change in I.R.	

TABLE 3: Mineral-insulated cable, square, solid conductor.

Specifications	F.P.S.	Metric	F.P.S.	Metric
Overall size Corner radius	0.25 + 0-0.01 in. sq 0.032 in.	6.35 + 0-0.25 mm sq 0.8 mm	0.53 + 0-0.01 in. sq 0.063 in.	13.46 + 0-0.25 mm sq 1.6 mm
Conductor size, nominal	0.165 in. sq	4.19 mm sq	0.42 in. sq	10.67 mm sq
Conductor resistance, maximum	0.4 Ω/m ft	1.3 Ω/km	0.055 Ω/m ft	0.18 Ω/km
Insulation thickness, nominal	0.02 in.	0.51 mm	0.03 in.	0.76 mm
Insulation resistance (I.R.)	5 GΩ/m ft	1.5 GΩ/km	5 GΩ/m ft	1.5 GΩ/km
Dielectric strength	1.25 kV, ac, 1 min		1.5 kV, ac, 1 min	
Sheath thickness	0.02 ± 0.005 in.	0.51 ± 0.1 mm	0.02 in. ± 0.005 in.	0.51 ± 0.1 mm
Weight (nominal)	0.17 lb/ft	0.25 kg/m	0.8 lb/ft	1.2 kg/m
Maximum length	1000 ft	305 m	475 ft	145 m
Materials: Conductor, copper, 100% IACS conductivity. Sheath, copper, commercial anneal. Insulation, compacted magnesium oxide. Shipping: Coiled to minimum diameter of 4 ft (1.2 m). Ends sealed against moisture.			Test: (1) Immersion of cable (except ends) in water at room temperature to produce no change in I.R.	

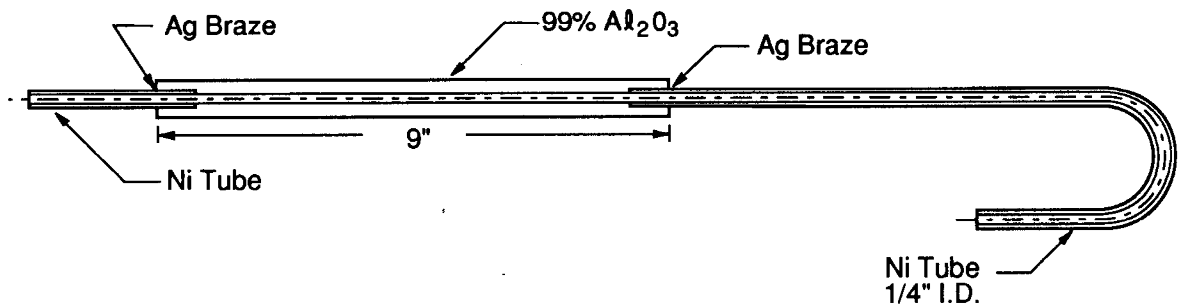

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Fig. 1 Water Insulator (Ceramaseal)

Scale 1/2" = 1"