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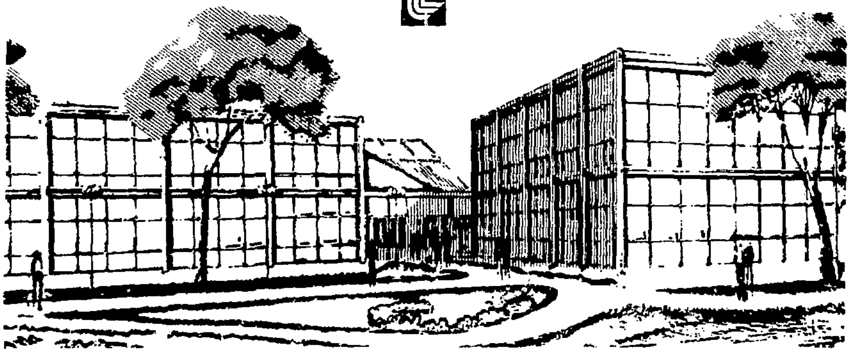

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ELECTRICAL INSULATION FOR LARGE MULTIAXIS SUPERCONDUCTING MAGNETS*

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Summary

Interturn and interlayer insulation for superconducting magnets serves as both a coolant network and an electrical barrier. When these functions are coupled with a multiaxis geometry and fast neutron radiation exposure, design and material selection become a complex engineering problem. This particularly applies to the interturn insulation, which, by the very nature of the path it must follow, must not only bend normal to the face of the insulation strip but about the edge as well.

The winding of the Baseball II magnet demonstrated that the speed of winding was predominately governed by the application of interturn insulation. Two types of insulation were used for this purpose, each located in alternating arc locations. Both types were specifically tailored to this particular conductor size and were difficult to purchase and/or fabricate. Although some seven miles of interturn insulation was used in this magnet, this can hardly be termed a mass production item by industry standards. When the need for relatively short lengths (1000-2000 ft) is combined with the larger requirement, it becomes apparent that the cost, procural time, and availability of the insulation is not a trivial matter.

The design parameters of proposed magnet systems require that many engineering problems governing design and selection of superconductors must be resolved. This implies a number of conductor configurations and test solenoids. A more universally adaptable insulation is desirable so as not to impede these tests.

We propose a machine that will produce interlayer insulation using a punch press and readily obtainable punches and fixtures. The machine would be easily adaptable to changes in conductor size and configuration. Such a machine would allow production of on-site short runs or subsequent loan to industry for production runs. We handcrafted samples using this principle of fabrication and investigated some of the many patterns obtainable.

A preliminary literature search pertaining to radiation damage to organic materials pointed to the need for an environmental test procedure suitable to our insulation scheme. We obtained very little information on radiation damage at liquid helium temperatures, but learned that damage is environment-dependent. More quantitative data on specific parameters is needed. Thus, we proposed a test procedure, which included the testing of properties critical to the insulation network, and intend to fabricate insulation from readily obtainable materials which have been successfully used in the past. If we must use more exotic materials, insulation costs, associated procural times, and fabrication problems could produce a major burden on an already difficult task; the tests are, therefore, paramount.

Introduction

The nature and location of insulation for multiaxis superconducting magnets is shown in Fig. 1. The primary components of the network consists of barrier, interlayer, and interturn insulation. The interturn insulation may be further subdivided into that portion between turns of either the pancake or helical windings. Ideally, the interturn insulation for both windings would be the same: in practice, this is difficult to achieve. All insulation must provide passage for the liquid helium coolant.

Baseball II

The method selected for interturn insulation of the helical windings for Baseball II[1] was a series of spaced dots adhesively fixed to one of the adjacent conductors. The dots were constructed and applied as shown in Fig. 2.

There is an inherent risk in this type of construction because failure of the adherent could allow migration of the dots under the environmental cryogenic temperatures and magnetic loads. For this reason, the slots in the interlayer insulation were sized to prevent dot migration, at least between layers of the magnet.

At first, we considered adapting this dot pattern to the pancake windings as well. However, without changing the interlayer configuration to conform to a non-migration pattern, this was impossible.

A second pattern was selected: ladder-type insulation (Fig. 3). Liquid helium enters a slot half the thickness of the insulation, moves through a central window, and exits through a slot at the other edge. This type of insulation is preferred because dot

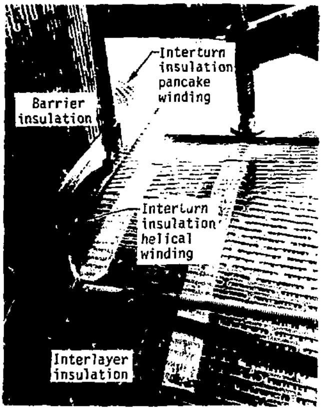

Fig. 1. Location of insulation.

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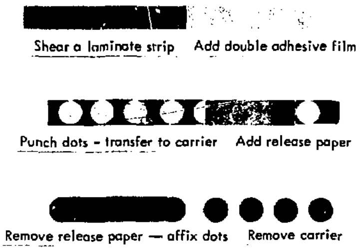

Fig. 2. Dot-type insulation.

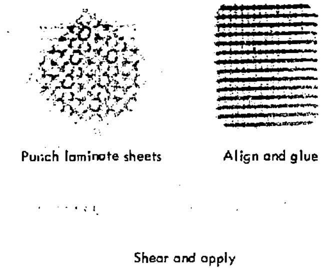

Fig. 3. Ladder-type insulation.

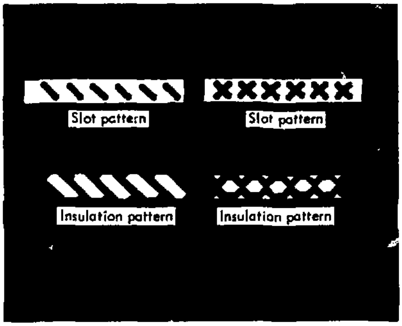

Fig. 4. Punched interturn insulation.

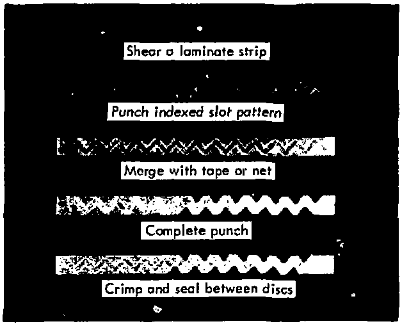

Fig. 5. Alternate patterns available.

migration cannot occur. It could not, however, be used in the helical location because of its inability to bend on edge.

Each of the two insulations performed as required. Both were extremely costly to produce. The dots were subject to an occasional mistransfer. The surface on which they were applied had to be wire-brushed or sanded, which extended the winding time considerably. Misalignment or improper shearing of the ladder insulation produced an unacceptable product.

The insulation for this magnet had to be custom designed and fabricated; clearly a different approach is required to suit today's rapidly changing superconductors.

A New Approach to Insulation Manufacture

Design parameters of proposed CTR magnets predict that several superconductor configurations must be investigated. This implies that a number of test solenoids be constructed.

A specific insulation will be coupled with each superconductor to be evaluated. A rapid change of insulation design for each conductor change is therefore desirable. A custom design for each and every configuration is not practical.

A practical approach to the problem is to construct a machine to fabricate insulation. It must be versatile, and must allow quick adjustment and/or substitution of components for each case considered. Such a machine is conceivable.

Refer to Fig. 5. With a punch press and laminate strip, a selection of punch patterns is available. This strip, when merged with a tape or net and subsequently repunched, produces a series of captured disks. When the tape or net is crimped and sealed between these disks the necessary coolant channel is provided. Further, this insulation is capable of being bent on edge as well as normal to its surface.

Such a machine also provides a means to produce short runs of various insulations in the laboratory as well as production runs with minimum design changes when a final pattern is selected. Two alternate patterns are shown in Fig. 5. Other slot and insulation patterns are obviously available.

Radiation Damage to Insulation

Insulation materials for superconducting magnets in the Fusion Engineering Research Facility (FERF) and future controlled thermonuclear reactors will be subject to radiation damage at cryogenic temperatures. For example, in FERF, the maximum uncollided 14-MeV neutron-flux has been calculated[2] to be $9 \cdot 10^{7}$ $n/cm^{2} \cdot s$. The average value of this quantity throughout the magnet volume will be approximately 100 times less than the maximum value. The average value of the total integrated neutron fluence (over all energies) has been calculated to be $3 \cdot 10^{10}$ n/cm^{2}-s. Because the magnet will be expected to operate for several years, the insulation materials must be able to tolerate without failure a total 14-MeV neutron-flux of 10^{16}-10^{17} n/cm^{2} and a total neutron (all energies) flux of 10^{18}-10^{19} n/cm^{2}.

Organic materials, generally plastics, are more radiation-sensitive than are either metals or ceramics, but they offer other desirable properties, both electrical and mechanical, as insulators in cryogenic magnets. *Within the field of organic materials, there are* several that are more resistant to radiation damage than others when irradiations are carried out at normal temperatures.

Some studies have been done with various plastics irradiated and tested at cryogenic temperatures, mainly at 77 K, and fewer at 20 K. For example, McKannan and Gause[3] showed that both Mylar* and Kapton were acceptable by tensile strength measurements at 20 K when irradiated in a reactor at a gamma dose of 10^{9} erg/g(c) and a neutron dose of $2 \cdot 10^{15}$ n/cm^{2}. Under the same conditions, a fluorocarbon (Kel F-81) showed poor radiation resistance at both room temperature and 20 K, but good resistance at 77 K. McKannan and Gause explain the increased resistance at 77 K to the presence of liquid nitrogen. We found only one report of a plastic material irradiated at 4 K. In this report,[4] the amount of hydrogen produced by irradiation of polyethylene with ^{60}Co gammas was measured. The result was a 30% reduction in the quantity of gas evolved (compared with that evolved at room temperature). The most *important point is that there have been no significant* studies on organic insulator materials at 4 K in radiation environments of 14-MeV neutrons or fission neutrons.

For practical reasons, the electrical and mechanical properties of various selected insulator materials should be measured after irradiation with 14-MeV neutrons at several doses, up to a total dose of 10^{16}-10^{17} n/cm^{2}. Both irradiation and testing would be carried out with the sample temperature maintained at 4 K. A significant goal is to report the degradation of specific material properties vs absorbed neutron dose.

Insulation material for the FERF magnet will have many forms, from thin films to large sheets and blocks. Specifically, combinations, such as small disks 6 mm in diameter and 1 mm thick spaced along a thin plastic ribbon about 0.03 mm thick are planned. Insulation material in the form of wire coatings and adhesives will also be present, requiring tests on materials from 0.03 mm to several millimeters thick. Materials previously shown to be radiation resistant (mainly at room temperature) would make up the majority of materials we would evaluate. A list of candidate materials includes: thin film and sleeves of Kapton, polystyrene, Mylar, phenyl silicones, and Parylene; sheets and blocks of epoxy-fiberglass (G-10), Vespel (*filled* polyimide from duPont), phenyl silicones filled with *fiberglass and/or other inorganic fillers, and poly*styrene (with fillers); and coatings and adhesives of *Formvar and polyimides.*

Planned Experimental Program

First Screening Test

Some form of screening must be done of the materials to be irradiated at 4 K. Because of the uncertain correlations between elevated temperature data and the 4 K environment, all irradiations should be done at 4 K. Therefore, we propose to irradiate candidate materials at 4 K in the form of very small samples, say, 1-mm cubes, at various fluences up to a dose of 10^{17} n/cm^{2}. These materials would then be examined at room temperature using both optical microscopy and scanning electron microscopy. This simple test is reasonable because the insulation is expected to cycle several times from 4 K to 300 K over the lifetime of the FERF magnet.

Second Screening Test

The above irradiations will be repeated on larger samples, which will be tested at room temperature for flexure strength: the most likely mode of failure for the materials in the FERF magnet. These results will show quantitatively the amount of degradation in a physical property of the insulation materials vs the absorbed dose.

Third Screening Test and Temperature Cycling Test

The irradiations will be repeated again and the electrical properties measured before and after irradiation to some intermediate dose level. We would then heat the sample to room temperature and monitor the change in the property vs temperature and time. The sample would then be cooled to 4 K and the cycle repeated one or more times. This will give us a measure of any changes in electrical properties vs temperature, temperature cycling (annealing) and neutron dose.

Gas Evaluation and Swelling Test

Samples shown to be radiation resistant by the screening tests would be tested to determine the amount and composition of gases released during 4 K-irradiation and subsequent warming to room temperature. This can be accomplished by sealing the sample in a gas-tight container and analyzing the gases using a mass spectrometer. The sample would also be measured before and after irradiation to determine the amount of volume swelling that may take place.

Final Tests

All materials shown by the above tests to be potentially useful as insulation material would be irradiated at several dose levels in the range from

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[*] Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Energy Research & Development Administration to the exclusion of others that may be suitable.

10^{14} to 10^{17} n/cm^2 with a broad spectrum of neutron energies and then tested at 4 K for flexural strength and dielectric strength in the presence of liquid helium. Other tests may also be performed as necessary to assure that these materials will perform satisfactorily as insulators.

Conclusion

Although one normally devotes considerable time in the selection and evaluation of conductors in sophisticated magnets, the insulation cannot be overlooked. Selection and fabrication of insulation could be one of the most time consuming and costly factors of the next generation of CTR magnets.

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