

TESTS OF INSULATION SYSTEMS FOR Nb₃SN WIND AND REACT COILS

R. Bossert, G. Ambrosio, N. Andreev, G. Whitson, and A. Zlobin

Fermi National Accelerator Laboratory
Batavia, IL, 60510, USA

ABSTRACT

Tests were performed to assess the viability of several cable insulation systems for use in Nb₃Sn accelerator magnets. Insulated stacks of cables were subjected to reaction cycles commonly used for Nb₃Sn coils. After reaction and epoxy impregnation, current leakage between turns was measured at pressures up to 180 MPa and turn-to-turn potentials up to 500V.

Systems consisting of S-2 glass, ceramic fiber, and E-glass were tested. Several methods of applying the insulation were incorporated, including sleeves and various spiral wrapped configurations. Methods of sample preparation and testing are described and results are reported.

KEYWORDS: Insulation, S-2 glass, ceramic, E-glass, Nb₃Sn coils.

INTRODUCTION

Several types of insulation are available for use in Nb₃Sn magnets. All of them consist of combinations of ceramic, S-2 glass and E-glass fiber. Several differences between these materials exist, including dielectric strength after reaction, availability in various thicknesses, and cost. Ceramic is known to have superior dielectric strength with respect to the other two materials. However, either of the other two materials may be sufficient in this respect, and both are significantly cheaper than ceramic, as shown in TABLE 1. Also, E-glass is available in thinner materials than the other two, which can potentially allow less insulation, and consequently more conductor, to be included within the coil cross section.

Cable stacks made from different combinations of these materials were built, reacted, and impregnated at the same temperatures and pressures used in current Nb₃Sn accelerator magnet applications. Leakage current was measured at a large range of pressures and electrical potential between turns, gradually increasing the pressure and voltage.

TABLE 1. Approximate cost of different insulation types.

Material	Insulation	Cost per Meter of insulation	Cost per meter of cable assuming 50% overlap for tape
Ceramic	125 μ m thick x 13mm wide tape	\$20.00	\$72.00
S-2 glass	125 μ m thick sleeve	\$10.50	\$10.50
E-glass	75 μ m thick x 13mm wide tape.	\$0.20	\$0.72
E-glass	125 μ m thick x 13mm wide tape.	\$0.20	\$0.72
S-2/E-glass combination	125 μ m thick x 13mm wide tape.	\$6.00	\$21.60

STACK CONFIGURATION

Cable

Cable used for these tests was NbTi Rutherford cable, as shown in FIGURE 1. NbTi cable was used because it fit the tooling that was available for these tests, and was readily available. Although the cable was not Nb₃Sn, care was taken to ensure that the insulation was subjected to all the same processes that would take place during the construction of a coil made with Nb₃Sn. Additional tests, using Nb₃Sn cable, are currently taking place.

Insulation Materials Used

The various types of insulation all consisted of fibers of three materials: Ceramic, and two types of fiberglass, S-2 glass and E-glass. These materials were configured in different ways.

To date, only ceramic and S-2 glass have been used in Nb₃Sn magnets. E-glass, although widely used in NbTi magnets, has not been demonstrated to withstand the high temperatures (650C and above) needed to react Nb₃Sn cable.

Types of Insulation Available

There were a limited number of insulation systems available for use at the time of this test, all using woven fibers. Ceramic tape was available at a size of 125 μ m thick x 13mm wide. [1] S-2 glass was available in a woven sleeve, 125 μ m thick. E-glass was also used in a tape form, 50 μ m thick x 13mm wide. A combination of S2 and E-glass tape, using S-2 glass in the “warp”, or longitudinal direction, and E-glass in the “fill”, or transverse direction, was also used. This was available in a tape, 125 μ m thick x 13mm wide. FIGURE 2 shows photographs of the four types of insulation used.



FIGURE 1. NbTi cable used for the insulation tests. It is 15.4mm wide identical to the cable used for the inner coils of the LHC interaction region quadrupoles.

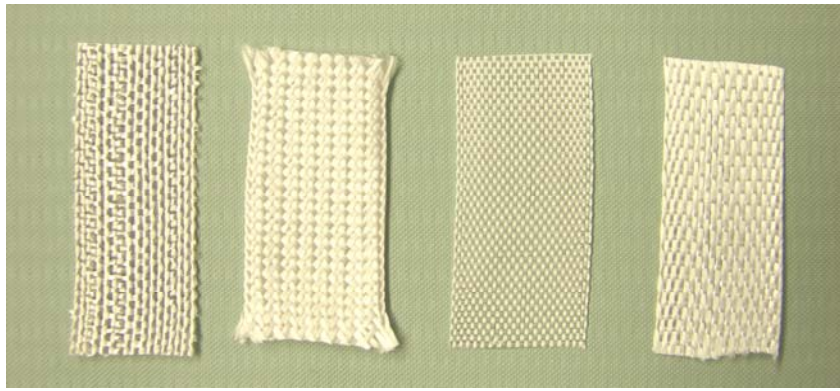


FIGURE 2. Types of Insulation. From left to right, 125 μm ceramic tape, S-2 glass sleeve, 50 μm E-glass tape, and 125 μm S-2/e-glass combination tape.

Types of Wrap Used

The insulation combinations described above were wrapped onto the cable in several different configurations. There were a total of five combinations used. The first, consisting of 125μm ceramic tape wrapped with a 50% overlap, is identical to that used on many Nb3Sn dipoles built at Fermilab. The second consists of the S-2 glass sleeve, and is similar to the system used on quadrupoles built for the LARP [2] [3]. Two different types of wraps were done with the 50 μm E-glass, one with 66% overlap, the other with two layers of 50% overlap each. The final system consisted of the S-2/E-glass combination with 50% overlap. Note that these systems encompass a range of total thicknesses between adjacent cables, (from 250 μm for the S-2 glass sleeve to 500 μm for the ceramic and S-2/E-glass combination), so the leakage voltage between turns is expected to vary with the total thickness of insulation. If less insulation between turns can be used, more conductor can be placed within the coil area, allowing higher fields to be achieved. To date, ceramic and S-2 glass are not fabricated in thicknesses less than 125 μm, while e-glass is commonly available in thicknesses of 50-75 and 125 μm.

TABLE 2 summarizes the five types of systems used.

TABLE 2. Type of Insulation systems used.

Material	Insulation	Wrap	Total thickness between turns
Ceramic	125 μm thick x 13mm wide tape	50% overlap	500 μm.
S-2 glass	125 μm thick sleeve	Pulled over cable	250 μm.
E-glass	50μm thick x 13mm wide tape.	66% overlap	300 μm
E-glass	50μm thick x 13mm wide tape.	50% overlap surrounded by another 50% overlap	400 μm
S-2/E-glass	125 μm thick x 13mm wide tape.	50% overlap	500 μm

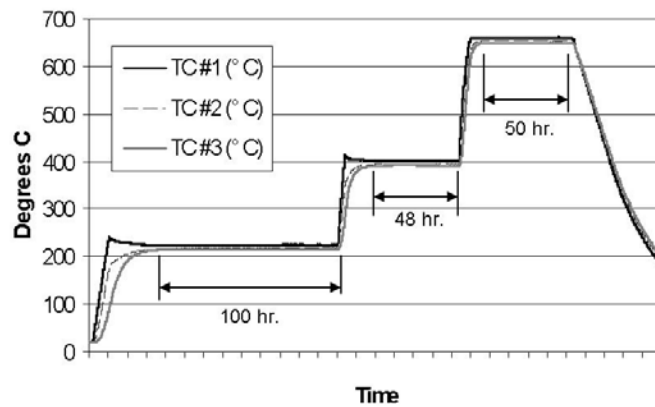


FIGURE 3. Typical reaction cycle for a Nb₃Sn coil. Actual cycle from RRP dipole coil fabricated at Fermilab is shown.

SAMPLE PREPARATION

During the fabrication process of a coil made with Nb₃Sn, the cable insulation is subjected to a wide range of temperatures and pressures. After winding, the insulated cable is painted with a ceramic binder (CTD1202X) [4]. The coil is then heated to 150°C for ½ hour while subjected to an azimuthal pressure of 35 MPa. This allows the binder to cure, setting the size of the coil and allowing it to be easier to handle when transferred to the reaction tooling. The coils are then reacted at an azimuthal pressure of 5-10 MPa. A typical reaction cycle is shown in Figure 3. [5] The maximum temperatures during reaction are usually between 635°C and 650°C.

After reaction, the coils are impregnated with epoxy under vacuum at an azimuthal pressure of approximately 5 MPa, then cured for 12 hours at 125°C to allow the epoxy to cure. The epoxy currently being used in coils made for the LARP as well as Nb₃Sn magnets at Fermilab is CTD-101K [6].

The procedure used to fabricate the cable stacks was designed to replicate this process as closely as possible.

Wrapping and Curing

Individual pieces of cable were cut to a length of 15cm and wrapped by hand according to the system specified for that particular test. Six pieces of cable were then stacked, with the trapezoidal cable cross section alternated, so the final stack cross section was rectangular. Cables were then coated with CTD 1202x binder, inserted into the fixture shown in FIGURE 4, and pressed to 35 MPa in a hydraulic press. The fixture was heated to 150°C for ½ hour. The sample stacks were removed and placed into the reaction fixture.

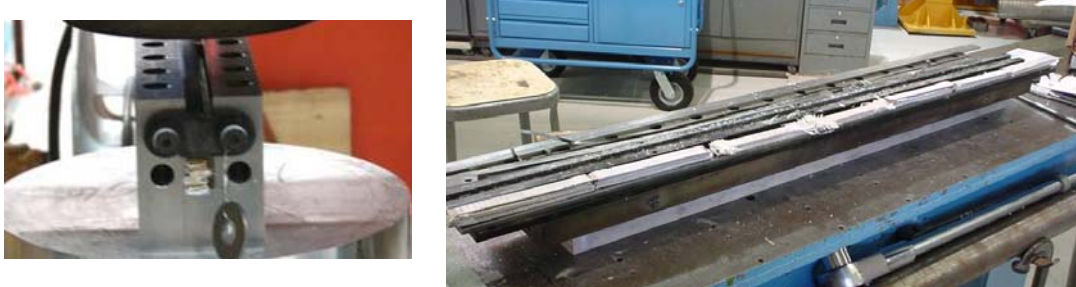


FIGURE 4. Cable stack curing fixture at left, cable stacks in reaction/impregnation fixture at right.

Reaction and Impregnation

The cured stacks were then placed inside a reaction/impregnation fixture as shown in FIGURE 4. The fixture was shimmed so that each stack was subjected to a pressure of 10 MPa, and bolted shut. The fixture was then placed into a reaction oven and heated to 650°C for a period of 48 hours.

After curing, the stacks were removed and the fixture was coated with mold release. After placing the stacks back into the fixture, the assembly was impregnated with CTD-101K epoxy and cured at 125°C

Final Preparation

Finally, the ends of the impregnated stacks were cut smoothly with an abrasive wheel at each end to lengths of approximately 12.5 cm and cleaned with alcohol. Wires were soldered to the ends, alternating the end on each turn. Insulating varnish was painted on the ends to prevent current leakage. The end of a completed stack is shown in FIGURE 5.

TESTING

Testing of stacks was done with the same fixture and hydraulic press used for curing (shown in FIGURE 4). The readout of current leakage was done with a digital volt meter.

Each stack was initially measured, with no applied load, at 100, 200 and 500 volts, between each turn. Connections were made to the wires soldered to the ends of each cable, and readings between each adjacent cable (turn) were taken and recorded. Load was then increased to a pressure of 15 MPa, and readings were again taken between each turn. This step was then repeated, in increments of 15 MPa, until the maximum pressure and voltage of 180 MPa and 500 volts was reached.

There were a total of 9 stacks measured, three of ceramic, one with the glass sleeve, one using the 66% overlap e-glass, two with the double-wrapped 50% overlap E-glass, and two with the S-2/E-glass combination tape. Since each stack had six turns, there were five turn “interfaces” measured for each stack.

RESULTS

Leakage current at the pressures and voltages described above is shown for the five types of samples in FIGURES 6-10. Included in the data shown in these figures are a few anomalous “high” readings (never exceeding 100 nA) often at lower pressures, possibly due to flexing at the ends of the stacks, where the bare cable ends are covered only with varnish.



FIGURE 5. Completed stack, with soldered wires.

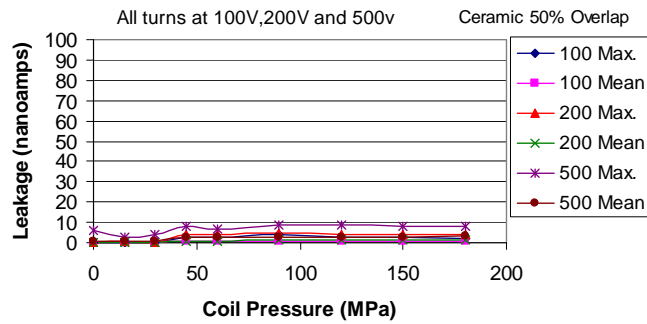


FIGURE 6. Turn-to-turn leakage for ceramic tape with 50% overlap. Maximum and mean values measured for the cable interfaces are shown. Data includes 2 stacks, or 10 cable interfaces.

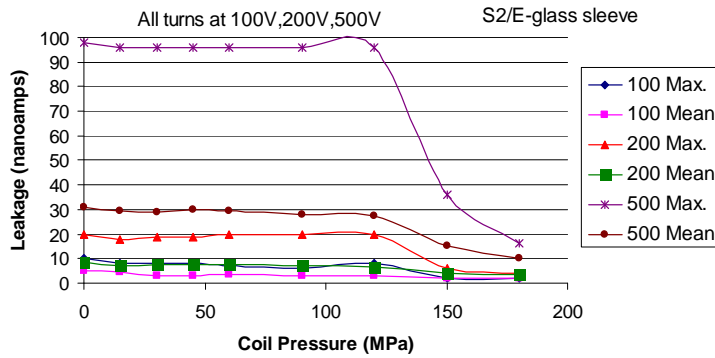


FIGURE 7. Turn-to-turn leakage for S-2 glass sleeve. Maximum and mean values measured for the cable interfaces are shown. Data includes 1 stack, or 5 cable interfaces.

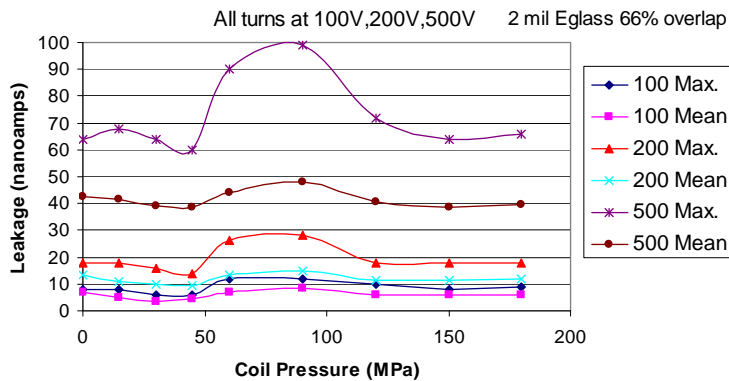


FIGURE 8. Turn-to-turn leakage for E-glass system with 66% overlap. Maximum and mean values measured for the cable interfaces are shown. Data includes 1 stack, or 5 cable interfaces.

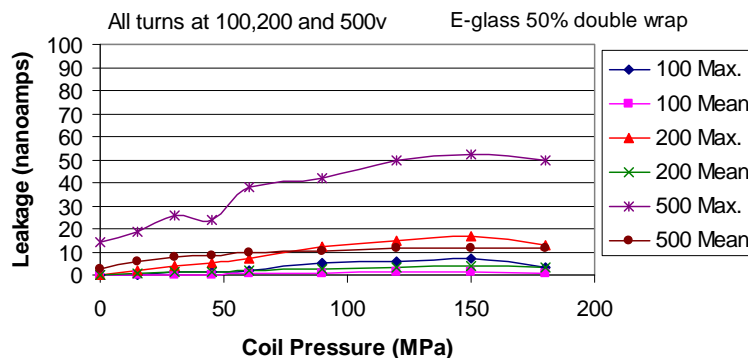


FIGURE 9. Turn-to-turn leakage for E-glass system with 2 layers of 50% overlap. Maximum and mean values measured for the cable interfaces are shown. Data includes 2 stacks, or 10 cable interfaces.

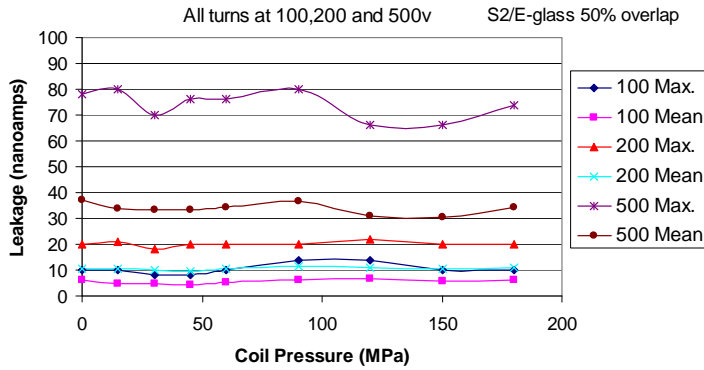


FIGURE 10. Turn-to-turn leakage for S-2/E-glass combination system with 50% overlap. Maximum and mean values measured for the cable interfaces are shown. Data includes 2 stacks, or 10 cable interfaces.

The maximum potential between turns in a Nb₃Sn magnet during operation, depending on magnet length and quench protection heater design, can reach levels as high as a few hundred volts. For the evaluation of these results, 300V was assumed. The maximum pressure that is applied to a coil azimuthally during construction or operation does not exceed 150 MPa. TABLE 3 shows the maximum and mean leakage for all the samples at 150 MPa. FIGURE 11 displays current leakage increase with respect to the voltage applied at a pressure of 150 MPa. Note that total insulation thickness between turns is not identical for all samples (see TABLE 2).

TABLE 3. Maximum and mean leakage at 150MPa.

Insulation system	Maximum Leakage (nΩ)			Mean Leakage (nΩ)		
	100V	200V	500V	100V	200V	500V
Ceramic 50% overlap	3	4	8	1	1	3
S-2 glass sleeve	2	6	36	2	4	15
E-glass 66% overlap	8	18	64	6	12	38
E-glass 50% x 2 overlap	7	17	52	1	4	12
S-2/E-glass 50% overlap	10	20	74	6	11	34

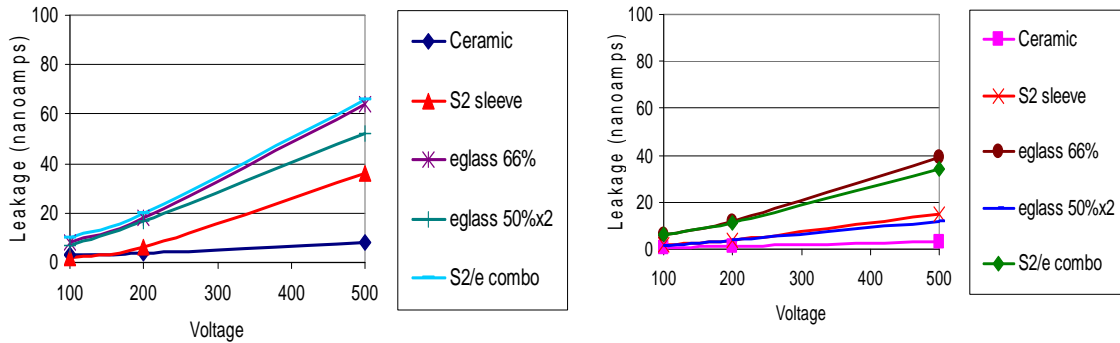


FIGURE 11. Leakage current increase with voltage at 150 MPa. Maximum leakage is shown at left and mean leakage of all interfaces tested is shown at right.

The highest leakage on any interface at 300V is under 40 nA, for a cable section that is 12.5 cm long. Extrapolated to a turn on a very long Nb₃Sn magnet where one full turn is about 10 meters long, this corresponds to a current leakage of 3.2 μA, far less than the maximum acceptable level.

CONCLUSION

Ceramic insulation clearly has the best dielectric strength of the systems used. However, it is not as readily available as the others and is much more costly than either the S2 or E-glass systems. E-glass is by far the least expensive and most readily available in a variety of thicknesses, and appears from these tests to be acceptable for use in Nb₃Sn magnets. In addition, the S-2 sleeve and S2/E-glass combination have been used successfully in Nb₃Sn magnets, and the E-glass-only systems appear to perform similarly to those systems. Further studies with all these materials are ongoing, and may demonstrate that e-glass can be used as cable insulation in High Field accelerator magnets made of Nb₃Sn.

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