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FINAL REPORT:

DOE SPI-PHASE 1: TASK 2(C)

**HTS COIL DEVELOPMENT AND
FABRICATION**

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Final Report: HTS Coil Development and Fabrication

Task Description:

The objective of this subtask (Task 2C) was to develop HTS coil technology aimed specifically at SC generator applications. Bi-2223 tape produced in a separate subtask (Task 2A) was first wound and tested in a small circular coil. This small coil winding experience led us to develop a tape strengthening method using a lamination process and to develop a turn insulation method using a paper wrap process. A prototype racetrack coil was wound using 2500 feet of the laminated and insulated Bi-2223 tapes. The racetrack coil was cooled to 20K in a vacuum dewar using a unique closed-cycle helium gas refrigeration system.

Small Test Coil:

A small circular test coil was fabricated in order to evaluate the handling and performance characteristics of the the Bi-2223 tape. The coil was wound using a zero-tension de-reeling method in order to avoid straining the dead-soft annealed silver matrix material. A formvar insulated copper wire was co-wound with the tape to provide turn-to-turn insulation and 0.003" glass was wound between layers (layer-to-layer insulation). The coil was suspended in a vacuum dewar and cooled using a thermal connection to a two-stage Gifford McMahon cryocooler, as shown schematically in Figure 1.

Several shortcomings of the Bi-2223 tape were observed during the fabrication of the small test coil. The most obvious was that the dead-soft annealed silver matrix required very low tension (essentially less than 0.5 lb) during winding to avoid overstraining the superconductor, which made the winding process a delicate one. Even with the low winding tension, we observed some strain-related degradation in the tape critical current. Secondly, the lack of insulation was not fully remedied by the co-winding approach we used. The loose tape turns tended to drift over the co-wound wires and traversing was cumbersome and labor intensive, even on this small circular coil. Clearly the tape requires strength enhancement and insulation in order to be practical in a commercial manufacturing environment. A program to develop a laminated strengthener and paper insulation was initiated.

Tape Lamination and Insulation:

As described in references [1-3] in the Appendix, a significant effort was dedicated to the development of processes to laminate and insulate the Bi-2223 tape material. We modified existing methods and equipment developed at GE Medical Systems (for use with Nb₃Sn tape) to laminate and insulate the Bi-2223 tape. As described in detail in references [1-3], the lamination process successfully produces Bi-2223 tape capable of handling winding tensions of up to 2 pounds. A 20-30% degradation in the tape I_c occurs during the lamination process. However, we observed up to 100% degradation of I_c during handling of the bare tapes. The 0.0015" 'cigarette-wrap' insulation provides good dielectric insulation between turns and layers with a minimum of additional coil build.

Racetrack Coil Fabrication:

Twenty-three discrete lengths of the bare Bi-2223 tape from IGC were laminated, insulated, and joined together using solder splices to form a continuous winding. As described in [3], the finished coil consists of 51 layers with 23 turns per layer, yielding a total of 1165 turns. A heat exchanger was wrapped around the outer surface of the coil and then overbanded with fiberglass cloth. This coil assembly was then vacuum-pressure impregnated using a low viscosity epoxy to produce a mechanically robust potted coil structure with the heat exchanger bonded to the coil outer surface. The coil assembly was suspended in a vacuum dewar and cooled to a temperature of 16K using a prototype closed-cycle helium gas refrigeration system, described in [4], which circulates cold helium gas from the refrigerator through the coil heat exchanger.

Racetrack Coil Test Results:

Prior to testing in the vacuum dewar, the potted coil assembly was tested at 77K by immersion in a liquid nitrogen bath. The coil carried up to 9 amperes in a thermally stable condition. Currents above 9 amperes generated a level of heating in coil that exceeded the 77K surface cooling available, leading to an unstable temperature (and voltage) rise in the coil. Coil voltages were measured transiently at 77K up to 15 amperes. Table 1 lists the steady-state and transient ramping data at 77K. In the vacuum dewar with helium gas cooling the coil stabilized at 16K with zero current. The coil stabilized at 20K with a current of 30 amperes. The maximum stable current level was 34 amperes at a coil temperature of 25K. Currents in excess of 34 amperes led to a transient (runaway) temperature rise in the coil. Table 2 lists the steady-state and

transient ramping data at 20K. As reported in [5], additional transient ramping tests were run at higher current levels and higher ramp rates up to 62 amperes. Analytic calculations of coil ac and ohmic losses with temperature rise compare well with experimental measurements [5]. The test results and analysis presented in [3] and [5] give a high level of confidence that the satisfactory performance of a full-scale generator field coil can be achieved.

Summary

The development and fabrication of a Bi-2223 racetrack coil for generator applications has been completed. IGC has demonstrated the capability to produce 100 m lengths of Ag-sheated Bi-2223 tape reliably and consistently. Lamination and insulation processes have succeeded in improving the strength, handling, and winding characteristics of the Bi-2223 tape. Low resistance solder splicing of individual tapes to form a continuous winding of more than a thousand turns has been demonstrated. Using a low-tension winding system laminated and insulated Bi-2223 tapes can be used in layer wound racetrack coil geometries of appreciable size. The implementation of a helium gas-cooled heat exchanger to conduction-cool an epoxy impregnated HTS coil has also been demonstrated for the first time. The remote siting of a refrigerator coldbox with insulated transfer lines connecting to the coil is the first step towards demonstrating the helium gas refrigeration of a rotating HTS coil.

References

- [1] C. King, K. Herd, T. Laskaris, and A. Mantone, "Evaluation of a Strengthening and Insulation System for High-Temperature BSCCO-2223 Superconducting Tape", International Cryogenic Materials Conference, Columbus, Ohio, 1995.
- [2] C. King, D. Grey, A. Mantone, K. Herd, and T. Laskaris, "Mechanical Stabilization of BSCCO-2223 Superconducting Tapes", 1996 Applied Superconductivity Conference, Paper MT-9, Pittsburgh, PA, August 1996.
- [3] K. G. Herd, L. Salasoo, E. T. Laskaris, R. A. Ranze, C. G. King, P. Haldar, and J. Hoehn, "Development and Fabrication of a Bi-2223 Racetrack Coil for Generator Applications", 1996 Applied Superconductivity Conference, Paper LI-6, Pittsburgh, PA, August, 1996.
- [4] K. G. Herd, "Remote Cooling System for a Superconducting Magnet", U.S. Patent 5,485,730, Jan. 1996.
- [5] L. Salasoo, K. G. Herd, E. T. Laskaris, H. R. Hart, and M. V. K. Chari, "Test Results for a Bi-2223 HTS Racetrack Coil for Generator Applications", 1996 Applied Superconductivity Conference, Paper LI-7, Pittsburgh, PA, August, 1996.

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FIGURE 1: SMALL TEST COIL SETUP

TABLE 1: 77K Test Results

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& Development

- Coil 'steady-state' ramping data:

I(A)	V _{term} (mV)	N*I (A-turns)	Q _{coil} (W)
1	-	1,165	-
2	1.5	2,330	0.004
3	4.2	3,495	0.014
4	12.0	4,660	0.052
5	41.0	5,825	0.21
6	119.0	6,990	0.71
7	272.5	8,155	1.90
8	558.0	9,320	4.46
9	1079.0	10,485	9.71

- Coil 'transient' ramping data:

I(A)	V _{term} (V)	N*I (A-turns)	Q _{coil} (W)
11	2.96	12,815	18.8
12	4.55	13,980	32.6
13	5.82	15,145	75.7
15	10.0	17,125	147.0

- 'Steady-state' means the coil reached thermal equilibrium with the LN₂ bath.

TABLE 2: 20K Test Results

GE Corporate Research
& Development

- Coil cooldown time: 2 days
- Coil bottoming temperature: 16K
- Coil 'steady-state' ramping data (reached thermal equilibrium):

<u>I(A)</u>	<u>V_{term}(mV)</u>	<u>N*I (A-turns)</u>	<u>Q_{coil} (W)</u>	<u>T_{coil} (K)</u>	<u>T_{lead+} (K)</u>	<u>T_{lead-} (K)</u>
5	-	5,825	-	18.6	23.3	25.1
10	1.5	11,650	0.015	18.6	23.4	25.3
15	3.0	17,475	0.045	18.6	23.5	23.5
20	8.0	23,300	0.16	18.7	23.8	25.5
25*	10.0	29,125	0.25	19.1	20.6	20.1
30*	50.0	34,950	1.30	20.2	21.5	21.3
34*	100.0	39,610	3.40	25.1	26.7	26.5

*Lead heat stationing to heat exchanger tubing added.

- Coil 'transient' ramping data:

<u>I(A)</u>	<u>V_{term}(mV)</u>	<u>N*I (A-turns)</u>	<u>Q_{coil} (W)</u>	<u>T_{coil} (K)</u>
40	210.0	46,600	8.40	20.3