Lessons Learned from Testing the SMES CICC
Adventures at 200 kA and Above

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Outline

- Design Criteria
- Design Evolution / Test History
- Lessons Learned

Conductor Design Requirements

ELECTRICAL

- 200 kA Design Current
- ~ 3 T Background Field
- Minimize AC Losses
- Low Cost Dump Shunt

STRUCTURAL

- Cooldown Strain
- Lorentz Loads
- Reasonable Bend Radius

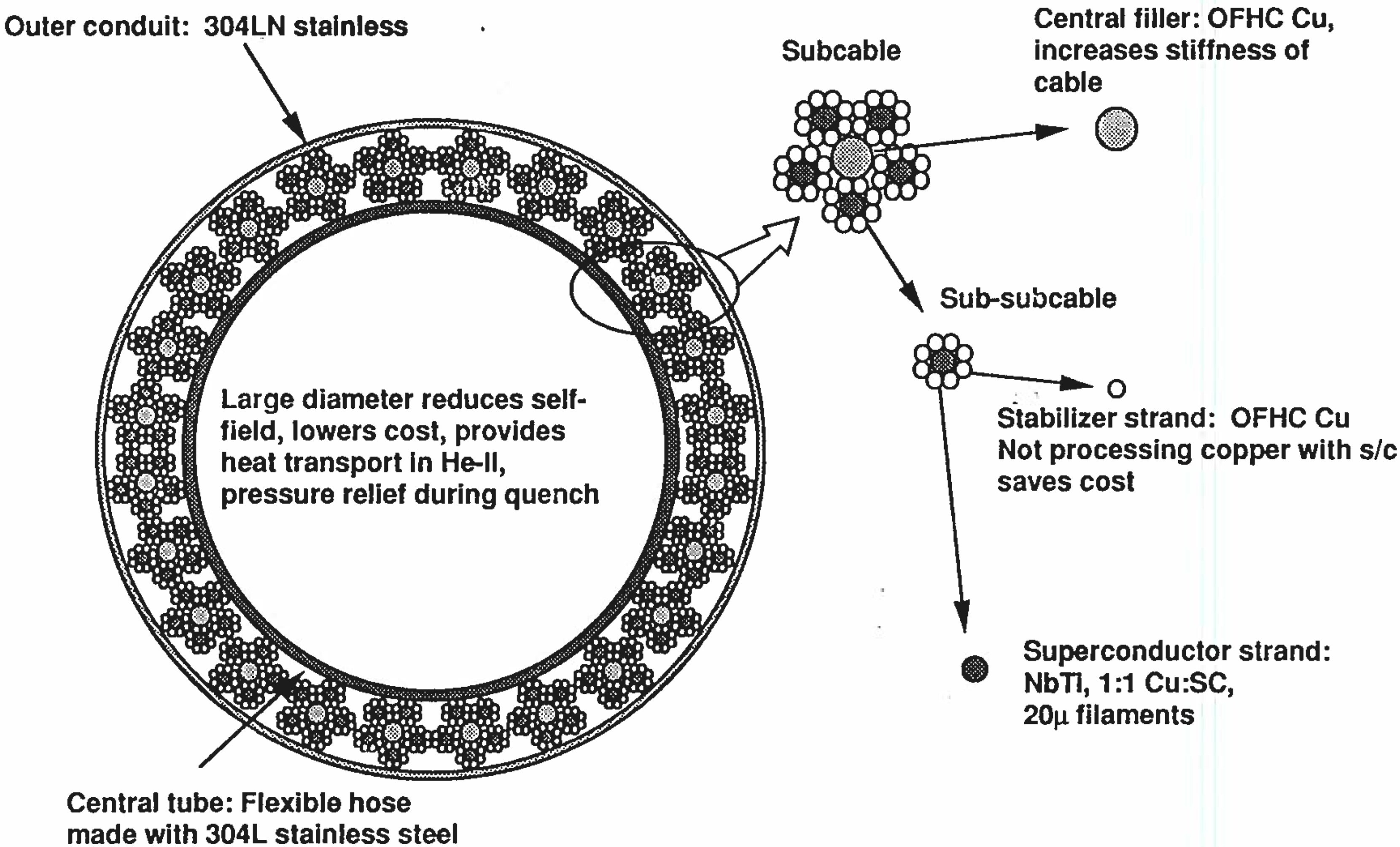
THERMO-HYDRAULIC

- Stability for Reliable Operation
- Leak-Tight He-II System
- Fast Propagation for Coil Protection
- Moderate Quench Pressures

MANUFACTURING

- Maintain Superconductor Integrity
- Continuous Processes
- Standard Processes
- Inspectable / Controllable Processes

200 kA Design Solution for SMES: 1st Iteration



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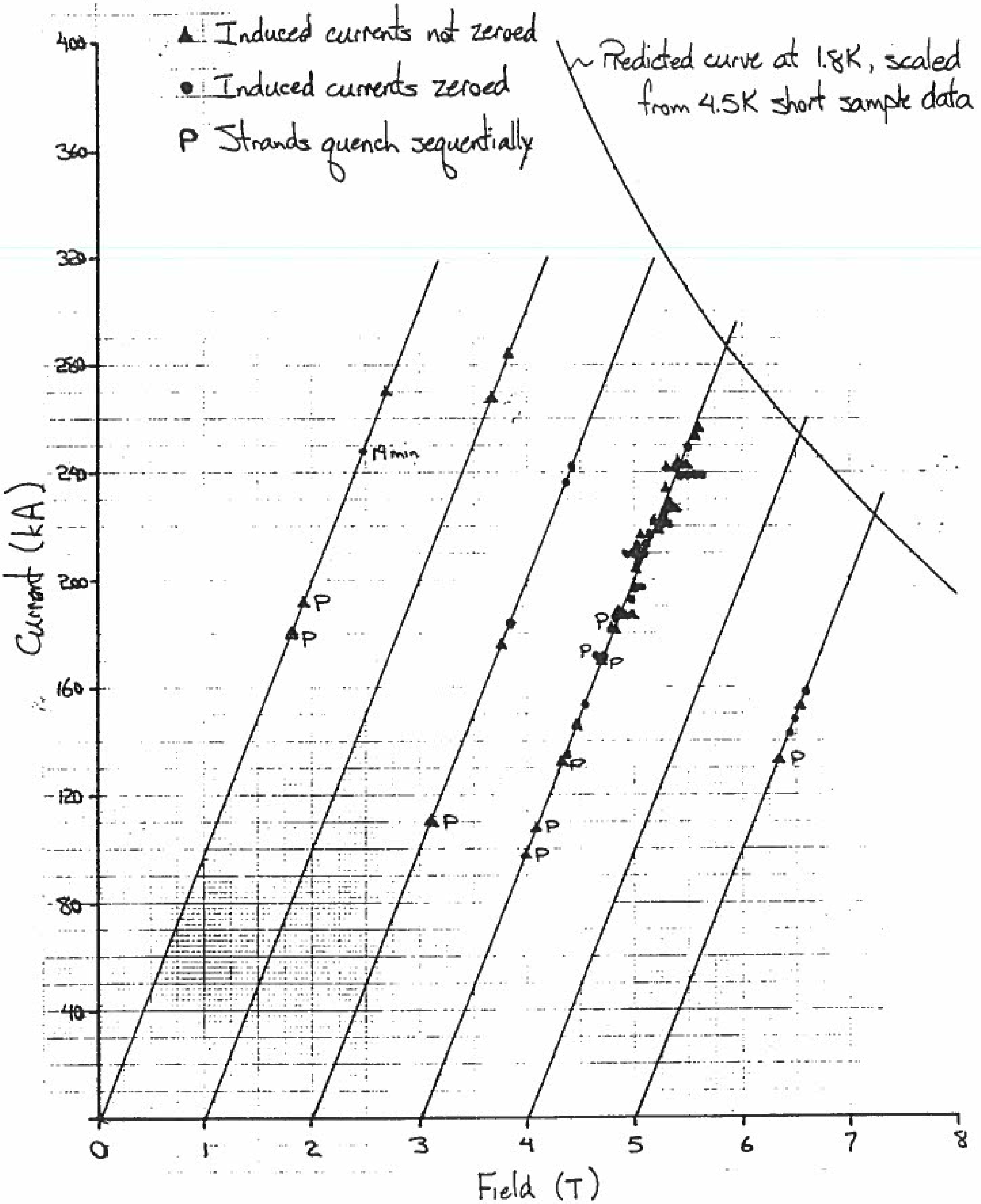
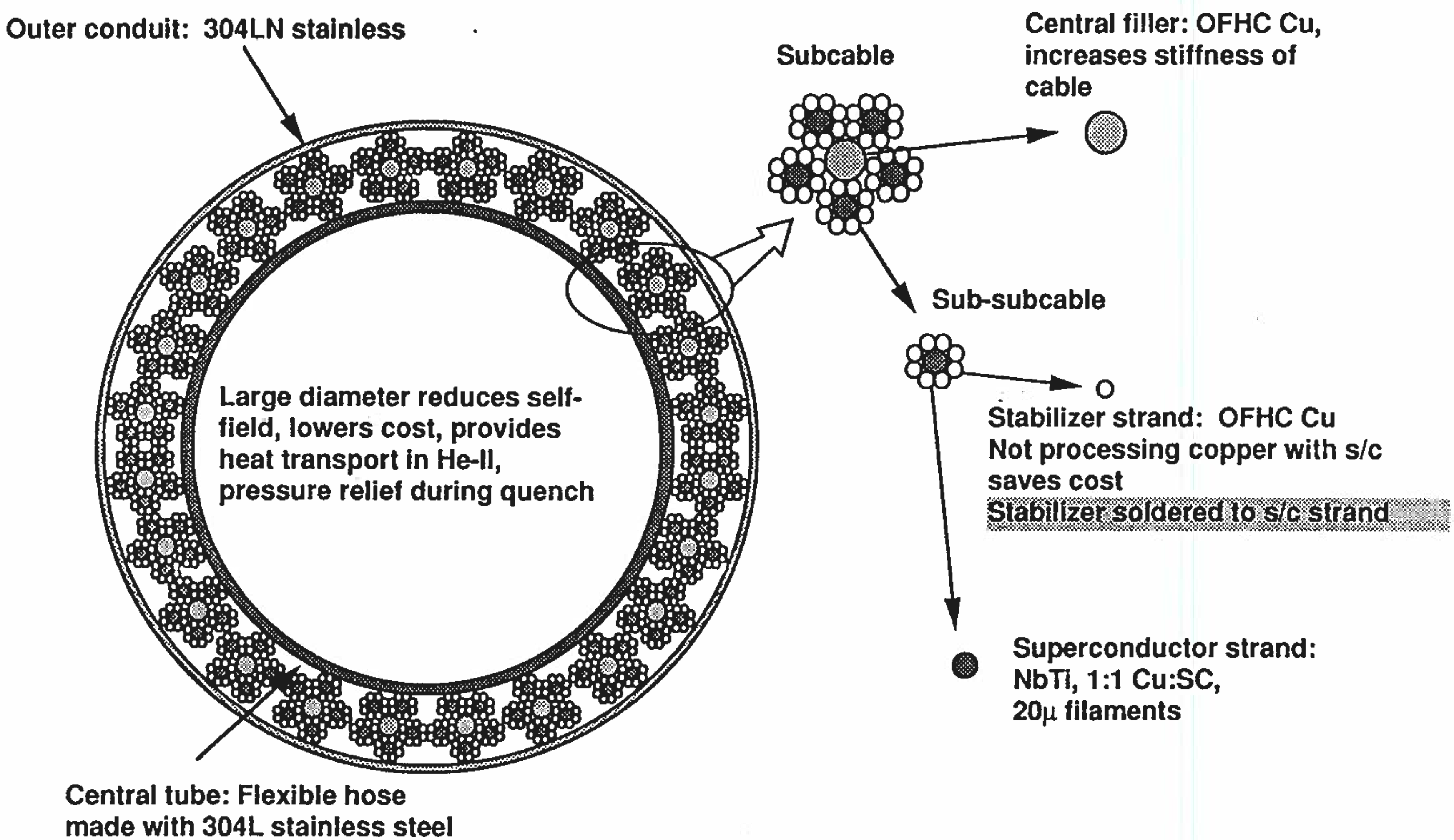


QUENCH DATA FROM FIRST FULLSCALE CONDUCTOR

200 kA Design Solution for SMES: 2nd Iteration



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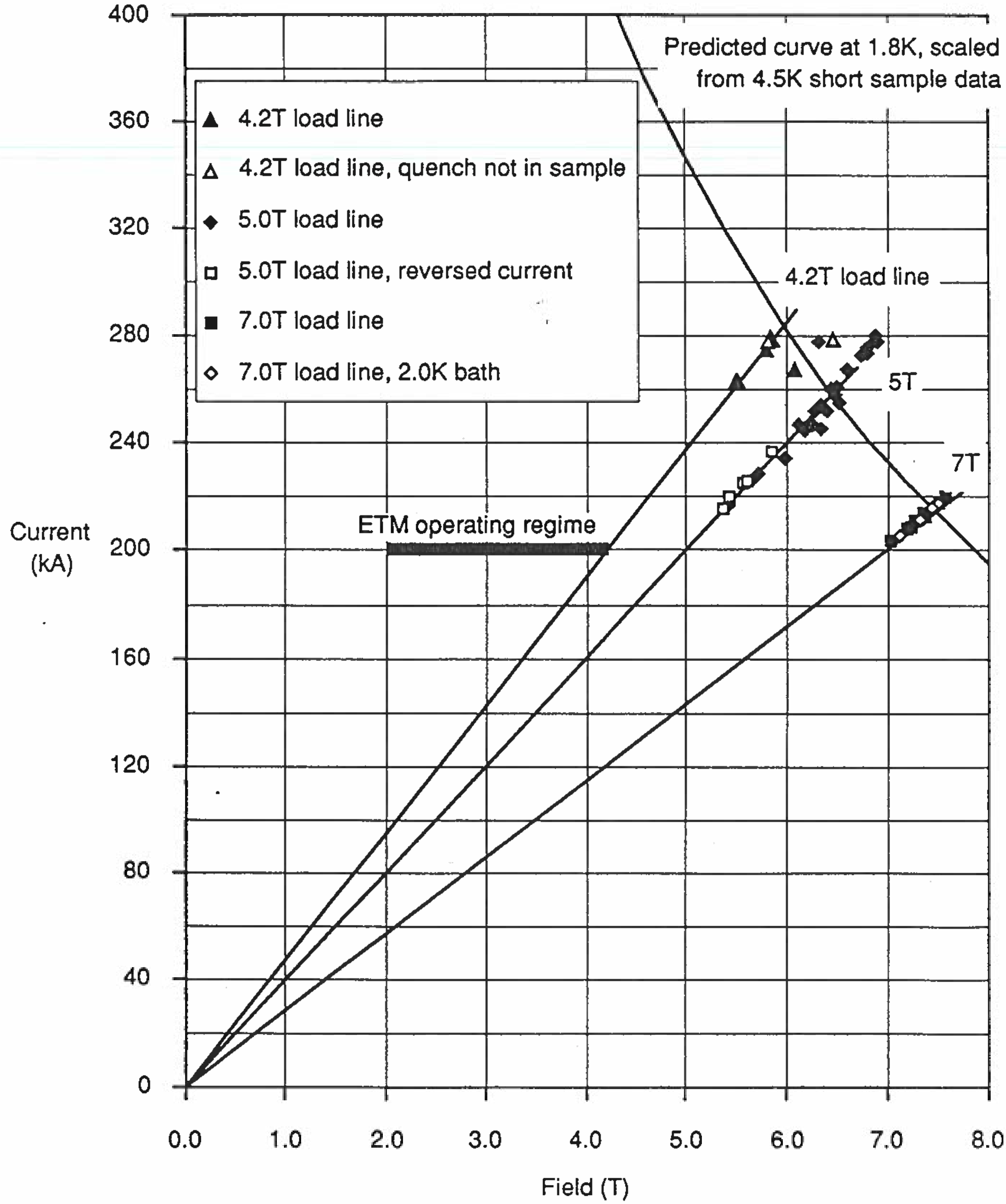
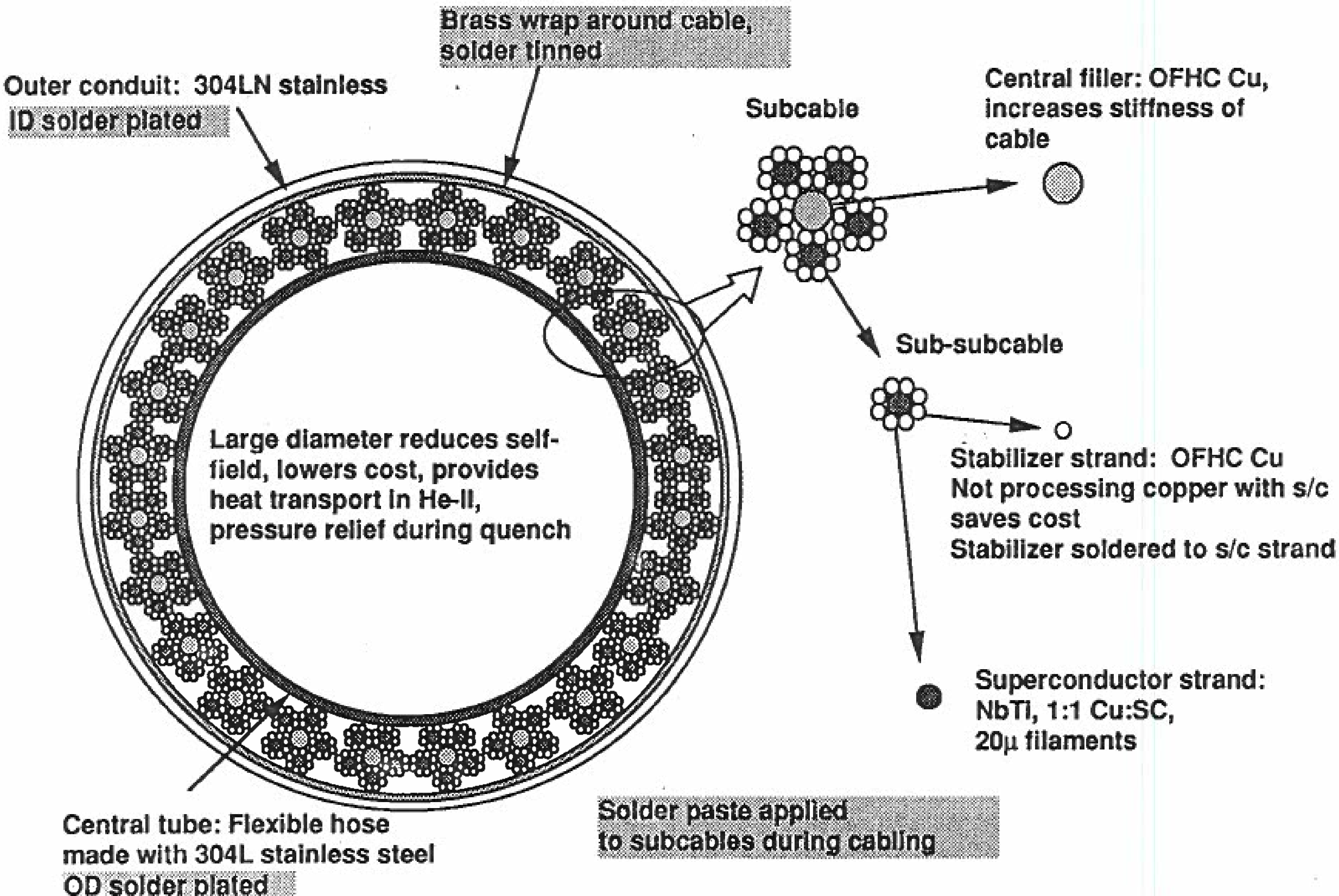
Quench Current Summary (Second 200 kA Test)



200 kA Design Solution for SMES: 3rd Iteration



Entire conductor assembly soldered after conduit compaction

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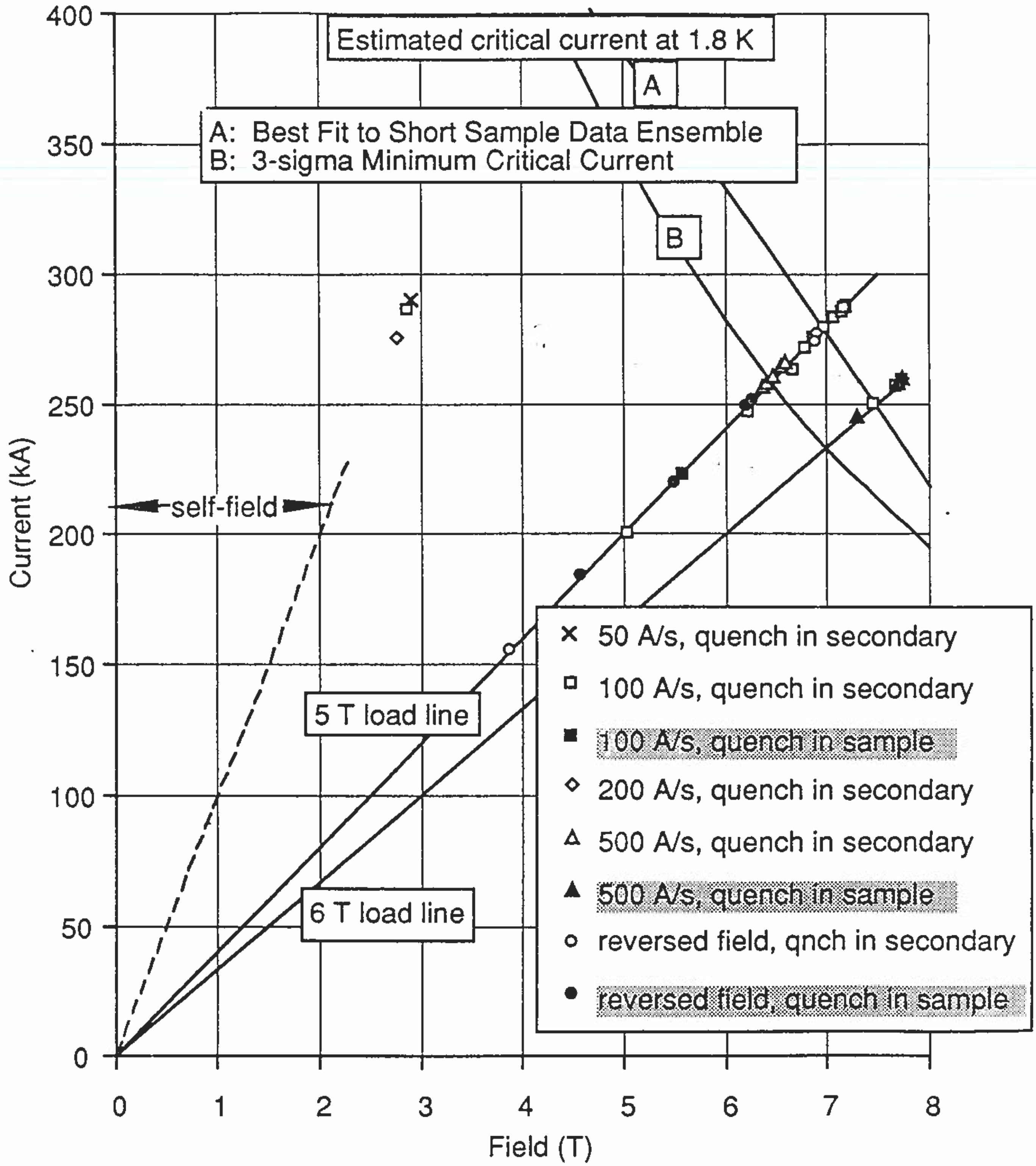
Quench Current Summary (Third 200 kA Test)



Lessons Learned

- Separate copper stabilizer strands must be soldered to s/c strand to be effective at SMES current densities
- Conduit compaction does not provide sufficient pre-stress to secure subcables against Lorentz loads
- Solder is effective in restraining subcables (AC losses?)
- Solder plating ID of steel conduit is straightforward
- Self-field of large, high current conductors creates complex behavior
- 290 kA in 4.35 T background field !

DESIGN OF A 200kA CONDUCTOR FOR SUPERCONDUCTING

MAGNETIC ENERGY STORAGE (SMES)*

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ABSTRACT

This paper reports the status of the design of a 200kA conductor for a Superconducting Magnetic Energy Storage (SMES) system. The reasons for adopting the Cable-In-Conduit-Conductor concept were reported previously. A brief review of these reasons together with the conductor design requirements will precede a description of the method used to establish the detailed design of the conductor. This method utilized manufacturing development test and evaluation techniques to provide discriminators between several CICC configurations. The rationale for selecting the detailed design configuration is given together with a brief overview of conductor testing.

INTRODUCTION

Superconducting Energy Storage Magnet (SMES) Systems are likely to store 4000 MWh of electricity, or more, for full-scale defense and electric utility load leveling applications. Plans exist to build an Engineering Test Model (ETM) approximately 20 MWh in size to demonstrate the feasibility of such systems.

The approach taken by the Bechtel team[1] for the ETM resulted in a requirement for a conductor capable of carrying an operating current of 200kA. This critical component is to be designed, developed, manufactured and tested prior to committing funds to build the ETM.

This paper reports the current status of the conductor development program. A brief review of the previously reported[2] reasons for selecting a cable-in-conduit conductor (CICC) design concept is given followed by a more detailed description of the manufacturing development test results and the rationale used in selecting a detail design configuration. Also, an outline of the tests imposed on the conductor is given.

An in-line conductor splice which is also being developed is briefly referred to in this paper. However, details of the splice and its development will be reported in a future paper when testing of the splice is complete.

* Work performed under subcontract to Bechtel National, Inc.

PROGRAM STATUS AND FUTURE PLANS

The primary tasks associated with development of the conductor are shown in Figure 1.

Cabling trials clearly indicated the most desirable configuration for the detailed design of the conductor. This conductor has been manufactured in configurations suitable for operation in 5 Tesla and 1 Tesla external magnetic fields. Testing is complete on the 35kA subscale and is in progress on the 5 Tesla full scale conductor.

Early in the program both copper and aluminum stabilized CICC's were being pursued. However, results from the testing performed on the preferred copper stabilized subscale conductor have eliminated the need to carry the aluminum stabilized conductor as a back-up.

The in-line conductor splice trade studies and testing to verify the acceptability of the chosen splice concept are complete. A full scale conductor splice is being manufactured and will be tested following completion of the conductor testing.

PERFORMANCE TARGETS

The conductor is required to meet the following criteria:

- 200kA operating current
- 1.8K operating temperature
- Operate at 80% of critical current (I_c)
- High stability margin
- 5.1 Tesla peak external field (ETM is 3.1 Tesla)
- Accommodate cyclic operation and multiple cooldowns without significant degradation.

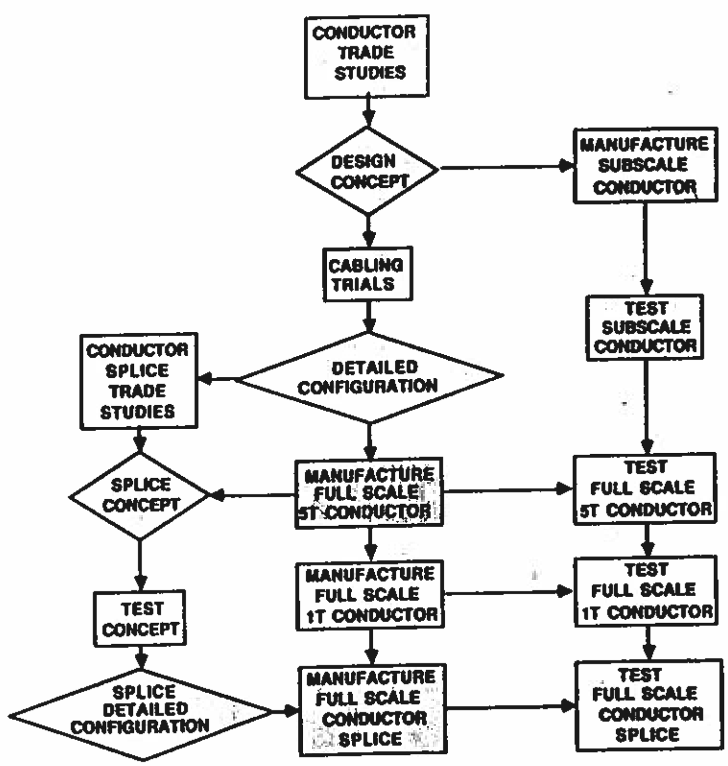


Figure 1. Conductor development program.

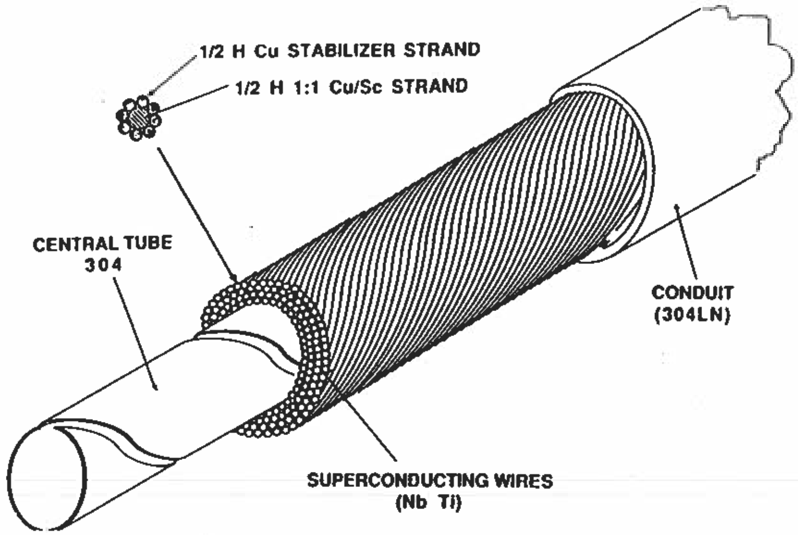


Figure 2. Conductor concept selected.

CONDUCTOR CONCEPT

At the start of the program a number of monolithic and CICC configurations were considered. The large monolithic conductors were rejected because excess heating occurs during a normal zone formation. This is due to slow current diffusion which precludes achieving full cryostability[3]. As a result of this a CICC concept as shown in Figure 2 was selected for its superior technical features and it represents the minimum risk in best achieving the performance targets.

Major benefits of the CICC concept for SMES are; that it eliminates the need for a helium vessel and complex helium dump system; has a low helium inventory; has a high stability margin[2]; utilizes standard manufacturing processes; and grading the conductor for various levels of magnetic field is readily achieved.

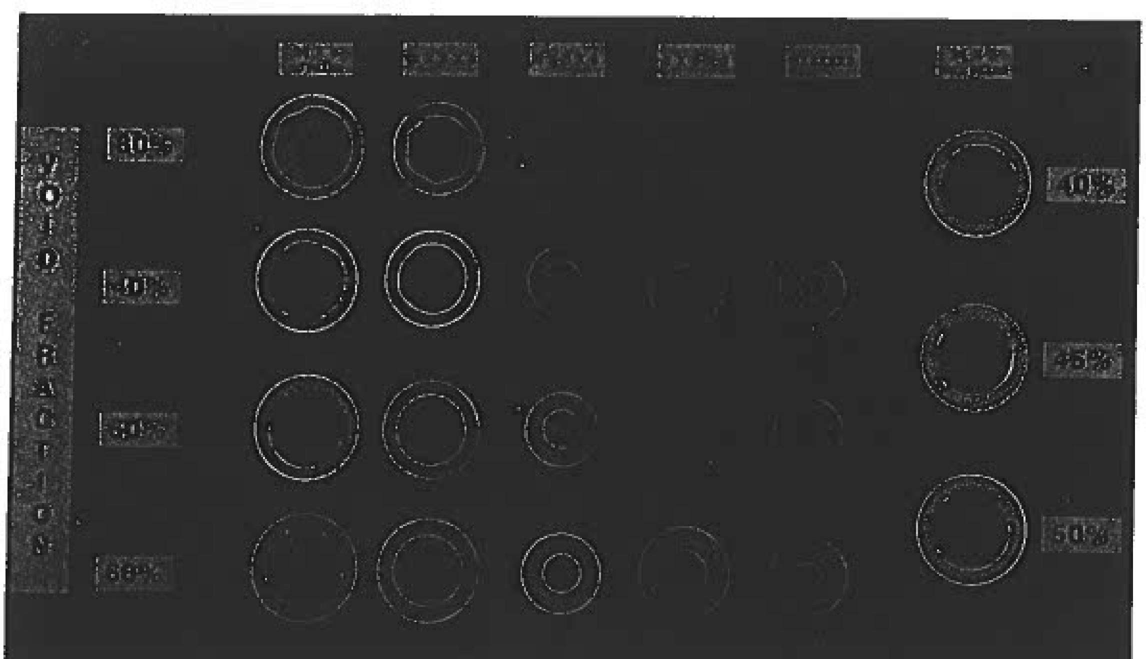


Figure 3. SMES 200kA conductor cabling experiment specimens.

RESULTS OF CABLING TRIALS

Conductor specimens were evaluated by dimensional and visual inspection of polished cross sections and disassembled lengths of conductor. Sections of conductor specimens produced are shown in Figure 3.

A permeable central tube provides a low resistance helium flow path in the event of a quench and reduces self field by increasing its outer diameter. Helically wound superconducting subcables surround and are supported by the central tube. The subcables consist of a number of superconducting strands each of which is surrounded by strands of copper stabilizer. The conduit forms the outer shell of the conductor and is the containment barrier for the helium II. The entire conductor assembly is radially compacted to prevent wire motions causing energy depositions capable of driving the superconductor normal.

CABLING TRIALS

To enable the selection of a detailed conductor configuration a series of manufacturing development tests were made on the cabling configurations shown in Table 1. These configurations were chosen since they encompassed all of the features to be evaluated.

An approximately 5m long specimen of each configuration was produced. Copper was substituted for superconductor and all wires were drawn and heat treated to obtain the required diameter and temper. The final cabling was performed around two types of central tubes; solid seamless tubing and interlocking flexible metal hose. The seamless tubing was only for expediency. A seamless tube was also used for the conduit which was slid over the final cable. The total conductor assembly was compacted to achieve the desired void fraction by sinking on a draw bench. Void fractions in the range of 30% through 60% were produced. Void fraction was calculated as being the area of the annulus between the conduit and the central tube less the cross sectional area of the strands.

Several discriminators were considered to evaluate the different conductor configurations; degradation due to fabrication; ease of conductor splicing; predictability of configuration after compaction; cost; on-site fabrication equipment, complexity, speed, operator training and cost; unsupported length of strands; size and uniformity of voids; distribution of Lorentz loads; helium inventory; and susceptibility to component tolerance variations.

Table 1. 200kA Conductor Configurations Evaluated

	Cable Arrangement				
	24x5	8x5x3	6x3x3x3	18x3x3	8x5x5
No. of SC Strands	120	120	162	162	200
SC Strand Dia. (mm)	1.19	1.25	1.09	1.03	.96
No. of Stabilizer Strands/SC	8	8	9	8	9
Stab. Strand Dia. (mm)	.59	.62	.45	.50	.38
Central Tube O.D. (mm)	42.8	23.4	14.7	36.6	20.3
Outer Conduit I.D. (mm) 40% Void Fraction	51.8	38.4	31.9	47.0	34.0
Conduit Wall Thickness (mm)	1.25	1.25	1.25	1.25	1.25
Conductor Self Field (Tesla)	1.54	2.08	2.51	1.70	2.35
Conductor Cu/SC Ratio	4.93 5.71 (with filler)	4.94	4.07	4.77	3.82

NOTE: All conductors have the same theoretical stability margin.

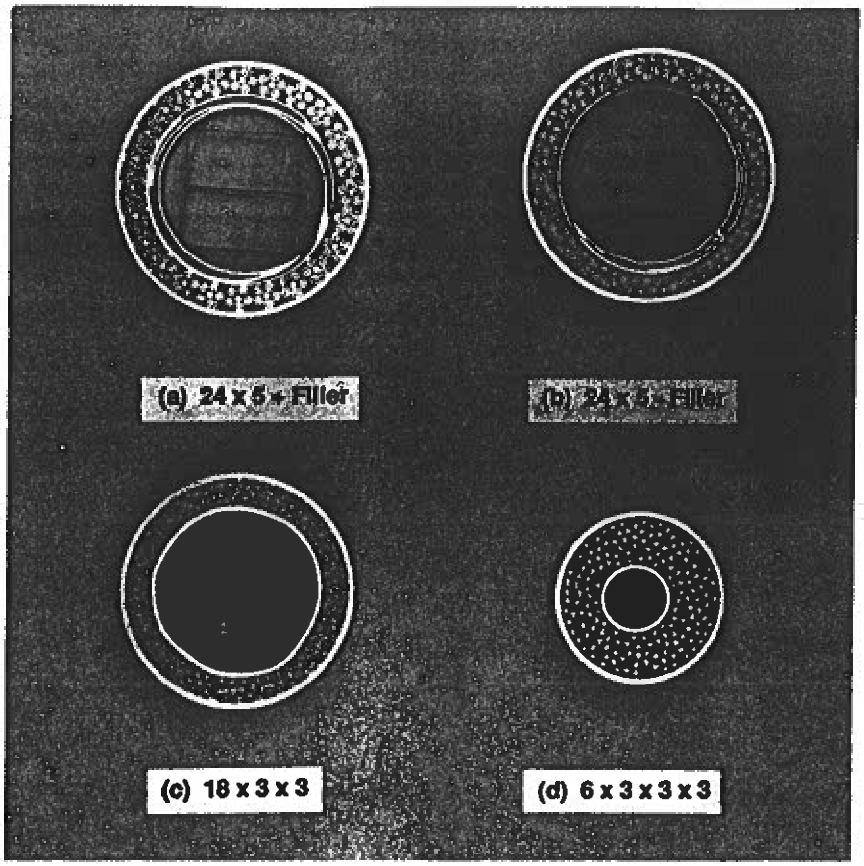


Figure 4. Enlarged examples of manufacturing test conductors.

Examination of the specimens revealed the following:

- The conduit was eccentric to the central tube (e.g., Figure 4b) on all configurations except for the 24 x 5 + filler (see Figure 4a). To ensure that the subcables are circumferentially, as well as radially, compacted an initial clearance between the cables and the central tube is necessary. However, this clearance coupled with the variable distorted shapes of the subcables result in the eccentricity that was found. The central filler wire in the subcable of the 24 x 5 + filler configuration prevented distortion of the subcables which ensured concentricity.

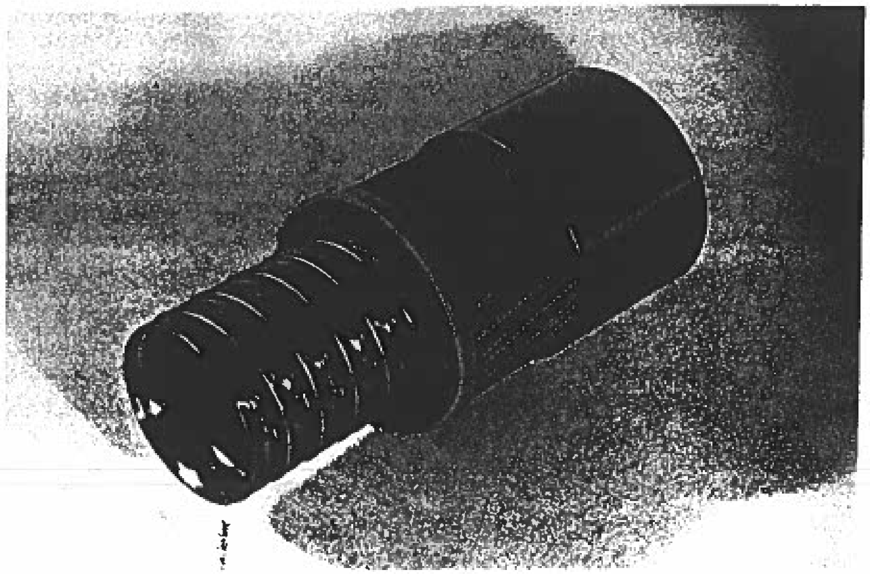
- Configurations that resulted in either an irregular (or lumpy) looking subcable (i.e., 6 x 3 x 3 x 3, 18 x 3 x 3, 6 x 5 x 3) or a small number of subcables (i.e., 8 x 5 x 5, 8 x 5 x 3, 6 x 3 x 3 x 3) tended to buckle the central tube due to poor load distribution during compaction (e.g., Figure 4c).

- Distribution of the voids surrounding the cable strands was random and varied widely in all cases (e.g. Figure 4d) except 24 x 5 + filler (see Figure 4a) where it was the same at all cross sections.

- Significant strand deformation (strands notched halfway through their diameter) was found in configurations that had a small number of subcables (i.e. 8 x 5 x 5, 8 x 5 x 3, 6 x 3 x 3 x 3). Substantial distortion of these subcables was

Table 2. Reduction of Cable O.D. During Drawing

	Configurations with 40% void fractions				
	24x5	18x3x3	8x5x3	6x3x3x3	8x5x5
Reduction in O. D. of cables	8.6%	15.7%	25.7%	27.7%	20.4%



Cabling Configuration	24x5+filler
Conductor	55.1mm
Conductor I.D.	36.4mm
Void Fraction	45%

Figure 5. Selected conductor.

required to achieve the desired compactions. The degree of distortion is evident in Table 2, which shows the reduction in final cable outside diameter to achieve 40% void fraction in the configurations shown. It is interesting to note that significant deformation was only found in the small copper stabilizer strands. It should also be noted that large reductions in diameter during compaction induce high degrees of cold work in the austenitic stainless steel conduit.

In all configurations, except the 24 x 5 + filler configuration, the unsupported length of the strand varied widely and was not predictable. This again was due to the high distortion that the subcables were subjected to during conductor compaction. The 24 x 5 + filler configuration maintains its subcable configuration after compaction and hence the unsupported length is constant and predictable.

SELECTED CONDUCTOR CONFIGURATION

An independent evaluation by a team of engineers from 4 companies resulted in a unanimous decision to adopt the 24 x 5 + filler CICC configuration as shown in Figure 4a and 5.

Cabling trials showed the selected conductor configuration to have a constant predictable cross section; the least potential for strand motion; and minimum deformation of the strands at the strand crossover locations. The 24 x 5 + filler configuration has the lowest current density in the copper. Also, of the configurations evaluated, it has the lowest self field which requires less superconducting material and hence lowers the cost.

SUMMARY

A 200kA CICC conductor with a central tube around which are cabled 24 subcables has been selected by the Bechtel team for their ETM-SMES design. A 35kA subscale conductor has been manufactured and test results have verified the suitability of the conductor concept. Full scale testing is well underway and results will be available in the near future.

ACKNOWLEDGEMENTS

The authors thank William G. Marancik and his team at Oxford Superconducting Technology (OST) for their major contribution to the work covered by this paper. All manufacturing activities were accomplished at OST.

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TEST RESULTS FROM THE 200 kA SMES / ETM CONDUCTOR*

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Abstract

The critical current and stability margin of a 200 kA, copper-stabilized, cable-in-conduit conductor cooled with helium-II has been measured at the Texas Accelerator Center. The test specimen was 3 meters long, inserted in a uniform background dipole field of up to 5 Tesla with an effective length of 0.9 meters. The critical current of the conductor was measured at 1.8 K and found to be 280 kA at a total field of 5.8T, 260 kA at 6.4T, and 215 kA at 7.4T, in good agreement with extrapolations based on 4.2 K short sample data. Normal zones of 2 cm initial length were initiated by inductive heaters, and the voltage and temperature of the conductor in the heated zone was monitored for recovery or propagation. The stability margin is reported as a function of the current density over the cable space at various background fields, bath temperatures, heated length, heater pulse duration, and number of cumulative load cycles. Nominal values of 70 to 80 mJ/cc of metal at 200 kA and 4 to 5 T were measured, again in good agreement with design predictions. The test results demonstrated the conductor will operate at 200 kA in the Engineering Test Model for SMES, where the peak total field is 4.13 Tesla.

Introduction

A full-size superconducting magnetic energy storage (SMES) plant will store thousands of MWh's of energy and deliver hundreds of MW of power. To deliver reasonable fractions of coil energy at high powers and safe voltages requires very large currents. The Bechtel team has decided that, in order to minimize scale-up risk from a 20.4 MWh Engineering Test Model (ETM) to a full-size unit, the current in the ETM should demonstrate full-scale application. It follows, then, that a current on the order of 200 kA is required. This represents an order of magnitude increase in the present state of the art. Therefore, a test program was conceived and carried out to demonstrate that a conductor could be operated at 200 kA with sufficient current and stability margin to be practical in a large SMES device.

There were actually three different tests. The first was a test of a 35 kA sub-scale conductor. This conductor was conceptually similar to the full-size cable-in-conduit design we are proposing for use in the ETM, but was much smaller, had fewer superconducting strands, and a different cabling pattern. The primary purpose of the sub-scale test was to debug the test facility and procedures to be used on the following two tests. This was a successful test in that the conductor performed as expected based on pre-test analyses, and the test rig performed well, although several problems were uncovered and corrected.

The second test was of a prototype full-scale conductor. The results of this test are not reported here, but the lessons learned from this test will be discussed in the text where appropriate. Briefly, the performance of the prototype conductor was very poor. It would quench at seemingly random current levels well below the predicted maximum. The stability margin also was lower than desired. Careful analysis of the data showed that the quench currents were limited by the Lorentz force on the conductor, suggesting that the cable was vulnerable to excessive motion. At the time it was unclear whether the motion was an intrinsic property of the cable or a result of the way the conductor was supported in the test rig. It was also determined that the problem was aggravated by certain features of the test rig configuration and the way the background field was adjusted relative to the level of current in the test specimen.

Demonstrating the adage that the third time is a charm, the next conductor, with modifications to correct deficiencies in the cable, test rig, and operating procedures, achieved the performance goals required for use in the ETM. The critical current of the conductor was found to be 280 kA at a total field of 5.8T, 260 kA at 6.4T, and 215 kA at 7.4T, in good agreement with extrapolations based on 4.2 K short sample data. The conductor did require a few training quenches to reach critical current the first time, but even the first quench current was sufficiently above the ETM operating current to provide a large design margin, and the randomness disappeared from the data. Details of the quench current and training behavior are described below. The stability margin was measured at nominal values of 70 to 80 mJ/cc of metal at 200 kA and 4 to 5 T total field, again in good qualitative agreement with design predictions. Difficulties in calibrating the energy deposition of the inductive heater introduce uncertainty in the absolute magnitude of the stability margin. This is discussed in more detail below.

Test Set-Up and Procedures

The conductor test specimen was a copper stabilized cable-in-conduit,[1] consisting of twenty-four subcables twisted around a 5.5 cm diameter porous-walled central tube with a twist pitch length of 50 cm. Each subcable is made up of five sub-subcables twisted around a central copper filler wire. The sub-subcables are made by twisting and soldering eight copper stabilizer wires around a multi-filamentary superconducting strand. The strand has a diameter of 1.19 mm and has a nominal copper to superconductor ratio of 1.0. Figure 1 shows a cross section of the conductor.

The change to the conductor based on the prototype test results was the soldering of the stabilizer wires to the superconducting strand. This was done for two reasons: first, to eliminate one potential source of relative motion between strands, and second, to reduce the contact resistance between the s/c strand and copper stabilizer. By locking the stabilizer wires to the s/c strand, no slip motion can occur directly against the superconductor. The surrounding copper wires also act as a thermal buffer against energy generated by slips between other elements of the cable. In addition, the presence of solder reduces the contact resistance between strand and stabilizer. It can be shown that

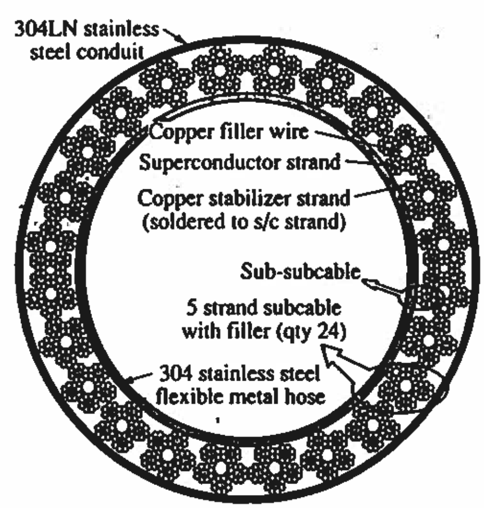

Figure 1. Cross-Section of the 200 kA SMES Conductor.

* Work performed under contract to Bechtel National, Inc.
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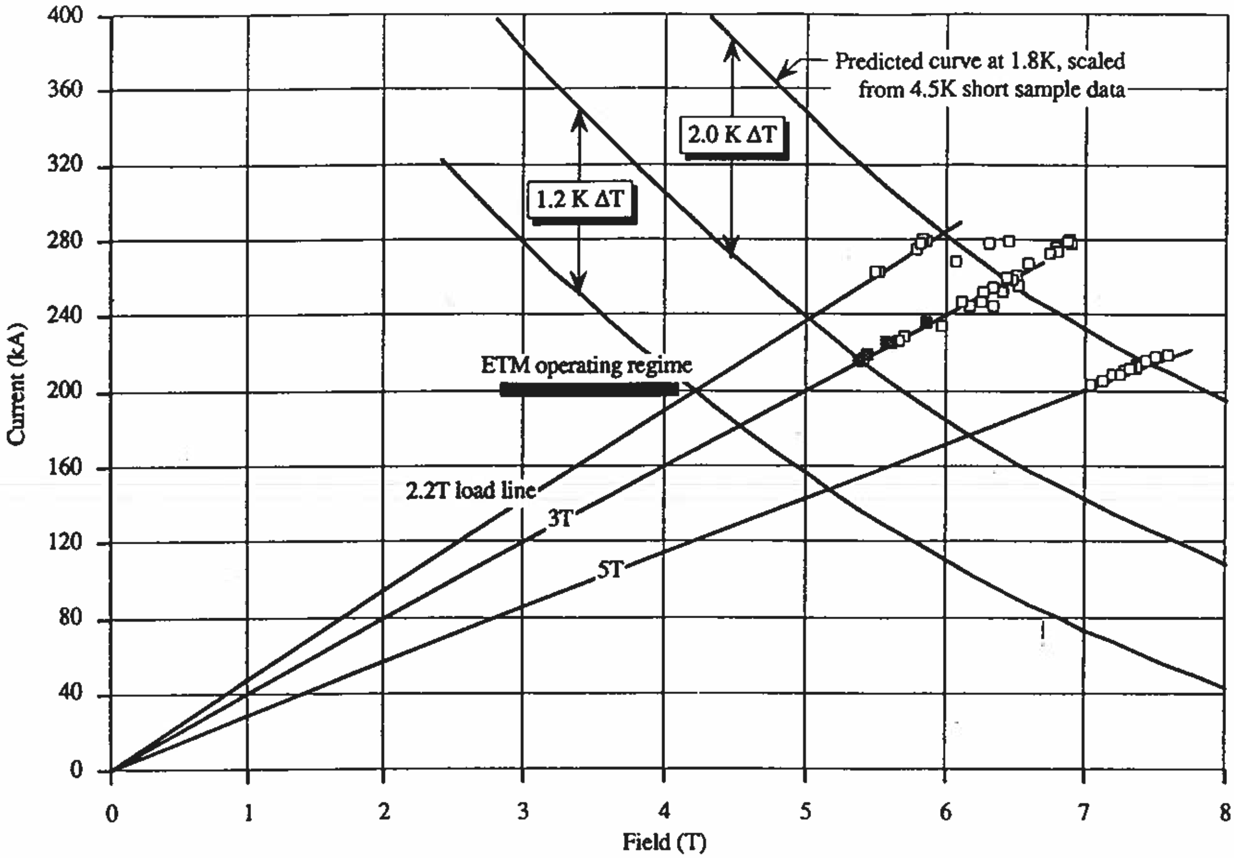

Figure 2. Quench Current Summary for the 200 kA Conductor.

a high contact resistance traps the current in the s/c strand if the normal zone is 'short'. Without solder, 'short' meant roughly the same length as the inductive heater, and so the current was trapped. With solder, 'short' means only a millimeter or so, and thus normal zones longer than this become effectively stabilized by the copper wires wrapped around the s/c strand. These benefits were judged to outweigh the loss of cooled surface within the cable due to the solder, and so in the final cable configuration the stabilizer wires are soldered to the superconducting strand.

The test specimen was approximately 3 meters long, and was spliced into the secondary loop of a superconducting transformer. The sample formed part of a coaxial hairpin, which was immersed in 1.8 K superfluid helium and inserted into the bore of a 5 T dipole magnet. Solenoidal inductive heaters 2 cm long were wound around the outside of the test conductor for stability tests. Details of the test rig and instrumentation are reported elsewhere at this conference.[2]

The test was designed to measure several aspects of the conductor performance. We were interested mainly in the quench current and stability margin, and the amount of degradation that might occur due to cyclic loading. The sequence of testing was to measure the resistivity of the stabilizer before and after cooldown, measure the quench current at different background fields, measure stability margin at several fields and currents, load cycle the conductor to the design condition 500 times while measuring stability margin at regular intervals, doing a final measurement of quench current, and finally measuring resistivity before and after warmup.

The resistivity of the conductor was measured to monitor the amount of work hardening that was done to the copper throughout the testing. Those results are not reported here, except to say that the initial RRR of the stabilizer indicated a 1/4 hard condition, and testing reduced the RRR by about 10%. The final RRR was still higher than the design value, however. Work hardening of the copper does not seem to be an issue for this conductor.

The first measurement of quench current was done as a part of a process we called load conditioning, whereby the current in the sample was ramped up and down in increasing step sizes, in tandem with the background field. This process 'worked' the strands in the cable, releasing pent-up strain energy and work-hardening the strands at the cross-over points for greater load carrying capacity. Once the conductor was conditioned, several measurements of quench current along simulated magnet load lines were done. Performing the tests along simulated load lines was one change made to the procedure from the prototype test. In that test the background field was held constant, independent of the current in the sample. Because the self-field of the conductor is so large at 200 kA (~ 2 Tesla), this had the effect in the prototype test of constantly changing the direction of the force vector on the individual strands. We feel that this constantly changing force direction contributed to the excessive motion problem in that test.

Quench Current Results

Figure 2 shows a summary of the quench current data from the conductor test. The data is plotted along load lines that give the total field on the conductor as a function of current just the same as would occur in a magnet. The load line identifier in the figure represents the background field when the conductor current is 200 kA. Since the self-field at 200 kA is 2 T, the 3 T load line passes through 5 T at 200 kA. Some of the quench points occur off of a load line. This is because the current measurement at TAC is limited to a maximum of 280 kA. In some tests, when this limit was reached, the conductor current was held constant while the background field was increased until a quench occurred.

The initial tests were done along the 3 T load line. The lowest data points on the line, represented by open squares, were also the earliest. As will be seen shortly, the quench current 'walked' up the load line until the values reached the short sample predicted critical current. The conductor trained, with an initial quench current of about 216 kA. The reason that some of the data points lie above the

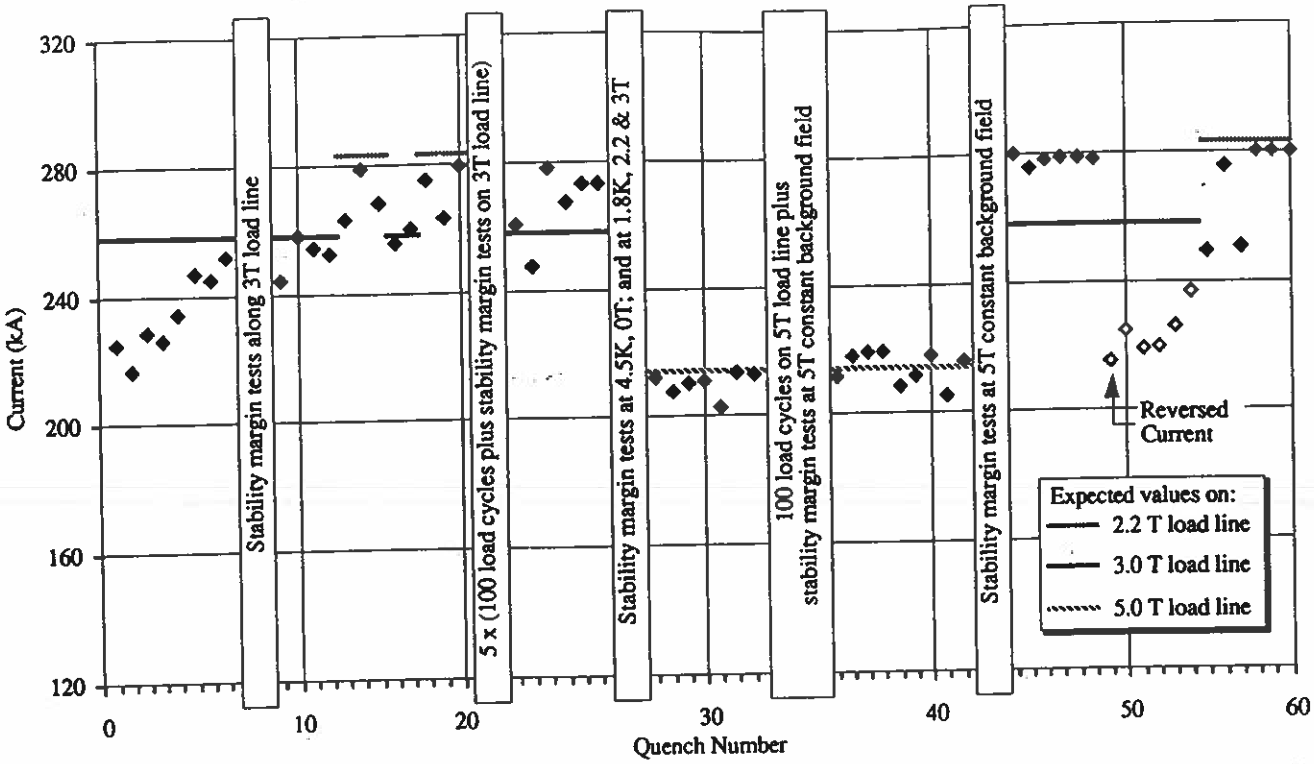

Figure 3. The 200 kA Conductor Exhibits Training Behavior.

predicted value is that the short sample data had some scatter in it, and the prediction analysis allowed for the scatter and took a worst case approach.

One important issue concerning ETM is the temperature margin of the conductor. A measure of this can be obtained from the quench current data by finding the temperature difference necessary to move the critical current curve from the lowest quench point to the most severe ETM operating point. This has been done in Figure 2. If the effective critical current curve is assumed to pass through the lowest quench point, a temperature rise of 1.2 K is required to lower that curve such that it passes through the worst case ETM operating point. A temperature margin of 1.2 K is rather large for a superconducting magnet. By comparison, a similar analysis done for SSC coils shows a margin of about 0.5 K.

The training history of the conductor is shown in Figure 3, where the quench currents are plotted in sequence. The critical current testing was interrupted periodically to do stability margin testing and load cycling, which also resulted in quenches which are not shown and are not counted in the sequence of quenches. As can be seen, the quench current steadily increases during the first eight or nine quenches, and then stays fairly close to the expected critical current. One interesting feature of the conductor behavior can be seen from the filled-in square data along the 3 T load line in Figure 2. On the 43rd quench, the current was reversed. This effectively untrained the conductor since the forces on the strands were acting in a new direction. The quench current displayed the same training behavior on subsequent runs as it did on the first few. It is very interesting to note that the first quench occurred at the same current for each version of the untrained conductor. In particular, the force level at which the initial quenches occurred was the same, 700 kN/m. The maximum force the conductor will see in ETM is only 440 kN/m. While the fact that the currents were identical is probably coincidence, the data should be very representative of what can be expected of the conductor in the ETM. It is important to note that the value of IxB on the conductor at the initial quench point is almost twice the maximum value of IxB that the ETM would ever experience. Based on the test data, then, there is a 60% margin on the force level that could cause a quench of ETM.

Another interesting aspect of the conductor performance is the higher than expected quench currents following the 5 T runs. Following quench numbers 27 to 42, which occurred along the 5 T load line, the next six quenches (after the stability margin quenches at a 5 T background field) were significantly higher than previous results along the 3 T load line. The fifteen previous quenches occurred at the highest values of IxB, and probably 'packed' the cable to the point where there was no motion during the next series of quenches at a lower field. Thus quenches 43 through 48 probably are caused by a true critical current limit, while all the others are caused by motion (aided by the fact that the stability margin vanishes as the critical current is approached).

Stability Margin Results

The stability margin was measured by setting the background field, ramping the conductor to a pre-determined current level, and then discharging a capacitor through an inductive heater wound around the conductor. The addition of solder to the conductor improved the stability margin over that obtained in the prototype test, although it was difficult to quantify exactly how much improvement there was. That is because of a difficulty in calibrating the short (2 cm long) inductive heaters used for the stability tests.[3] In the following stability charts, the absolute magnitudes of the data must be interpreted cautiously, but relative comparisons are valid.

Figure 4 shows the stability margin data obtained at 2.2, 3, and 5 T constant background fields. The trend of the data agrees well with the analytical prediction[1] based on a method of calculating the stability margin of conductors stabilized with a limited volume of sub-cooled He-II.[4] This is especially true in the 2 to 3 Tesla range. We have no explanation for the apparently low margin at 5 Tesla at this time. If the absolute magnitude of stability is a reasonable estimate, we can expect about 70 to 90 mJ/cc margin at the peak field operating point of the ETM.

The data shown was taken with a heater pulse length of one millisecond. There was an attempt made to vary the length of the heater pulse to see if there were any effects. The heater was energized from a capacitor, and the pulse length was varied by allowing the

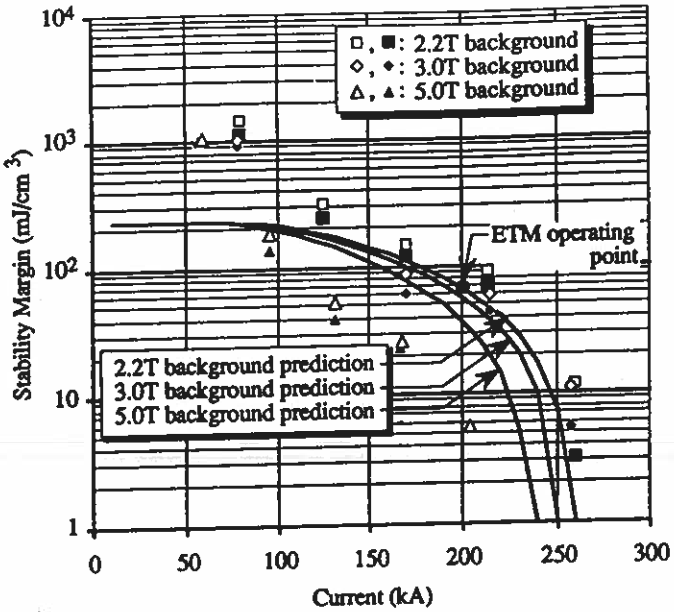

Figure 4. Stability margin of the 200 kA conductor at constant background field. Open markers indicate a quench, filled markers indicate no quench.

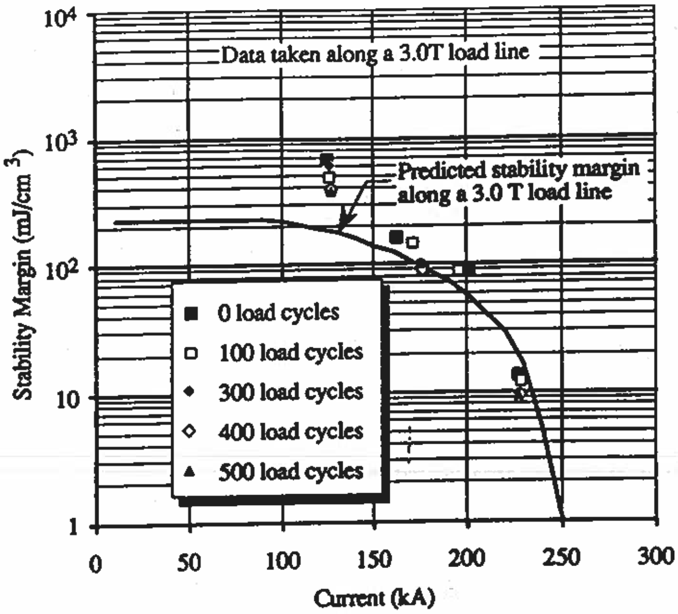

Figure 5. Effect of Load Cycles on Stability.

heater current to ring for an arbitrary number of cycles. It turned out that most of the energy stored in the capacitor was deposited in the conductor in the first half-cycle regardless of the total number of cycles in the pulse waveform. Thus the conductor did not see a large difference in energy deposition, and the stability margin results reflected that. There was not a large effect of pulse length on the stability margin, with longer pulses being slightly better than shorter pulses.

Figure 5 shows the effect of accumulated load cycles on the stability margin. There seems to be a slight degradation in margin during the first two or three hundred cycles, after which no change occurs. The degradation is attributed to work hardening of the copper stabilizer.

Finally, a series of stability margin tests were made at zero background field and 4.5 K to test the conductor for use as the 1.8 K to 4.5 K transition. For currents up to 200 kA, the stability margin at 4.5 K and 0 T appears high enough to use the basic conductor as the transition.

Conclusions / Lessons Learned

The second full size conductor test showed that the conductor with stabilizer strands soldered to the superconducting strands meets the ETM service requirements, and has a substantial margin in doing so. For an ETM with a worst case design point of 2.2 T external field, 1.8 K, and 200 kA, the conductor has:

- 59% margin on initial quench IxB
- 70 - 80 mJ/cc of stability margin
- 1.2 K temperature margin to initial quench critical current curve
- 45% margin to initial quench critical current curve at constant field
- 20% margin to initial quench critical current curve along the load line
- 36% margin to initial quench critical current curve at constant current

These margins would be even larger if the conductor did not train, thereby reducing the effective critical current curve. (Note: the latest iteration of the Bechtel ETM design has a maximum external field of 2.13 T, meaning the conductor would have slightly larger margins than quoted above.)

The stability data indicates that the method used to predict stability captures the relevant phenomena, i.e., the shape of the curves agree well with the data. Our best estimate of the absolute magnitude of the stability margin indicates a value in the range 70 to 90 mJ/cm^3. If the heater calibration for the energy deposition is correct, the stability results agree quite well with analytic predictions. Load cycling of the conductor does not appear to degrade stability margin.

The RRR of the conductor was higher than expected for half-hard OFHC copper, perhaps closer to a quarter hard condition on the stabilizer. The mechanical performance of the conductor did not seem to suffer from the softer copper. The residual resistance of the stabilizer appeared to increase by about 10% after 500 load cycles, but was still less than the value used in the design analysis of the ETM.

Acknowledgements

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Test Results for a Subscale (100 kA) SMES Splice

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Abstract—The design for the 20 MW-hr SMES-ETM for the Bechtel concept calls for two splices per turn of conductor, and over 100 turns. The design value of resistance for the splices is on the order of 10^{-11} ohms (0.4 W/splice @ 200 kA), which is an order of magnitude less than the state of the art for high current devices. The splice design utilizes a superconducting braid wrapped around lapped subcables for an extremely low resistance joint. A history of the manufacturing development for the splice is presented. The performance of a sub-scale version of the splice joint has been measured at Texas Accelerator Center. Values of splice resistance at 1.8 K and background fields up to 5 T are reported. Performance of a 100 kA conductor is also reported.

INTRODUCTION

The Bechtel team SMES - ETM concept features a 200 kA cable in conduit conductor [1] consisting of twenty four subcables wrapped around a central tube with a porous wall. In order to remove the conductor fabrication from the critical path of the coil pack assembly, the conductor is manufactured in lengths and then spliced together at periodic intervals as the coil pack is assembled. Previous tests of early conductor [2] and splice concepts revealed elements of risk in the designs. These were the restraint of the subcables in the conductor and transition to the splice overlap, the resistance of the splice, and the manufacturability of the splice.

The conductor design has evolved to include a brass wrap around the cable and inclusion of solder as a structural restraining material to help support the superconducting strands against movement caused by Lorentz forces. Instead of the Phase I concept of segmented copper wedges carrying individual superconducting strands, the splice now provides a brass support structure for subcables from each length of conductor to be overlapped and wrapped with superconducting braid. This creates a low resistance joint which securely holds the superconductor in place while maintaining a continuous path to carry hoop loads. The subcables are continuous through the transition from conductor to overlap, and so are more securely held in place. The splicing of subcables instead of individual strands is much easier to accomplish as well.

A test of this design concept has been carried out at half scale (100 kA) at the Texas Accelerator Center test facility. It was done at half scale since the bore of the test magnet cannot accommodate a splice with the diameter required for twenty four subcables (full scale). The objectives of the test were to

a) measure the resistance of a prototypical splice;
b) demonstrate the stability of the conductor / splice transition;
c) demonstrate the non-training behavior of the soldered conductor

The splice design, test setup, test procedure, and results are discussed in the following sections.

SPLICE DESIGN / FABRICATION

Splice

The splice configuration is shown in Fig. 1. The splice is made by overlapping individual subcables, enclosing the lapped joint in a braid made of superconducting wire, and embedding this sub-assembly in a channel machined in a brass body. To have room for twenty four pairs of subcables around the periphery of the brass body, it must have a larger diameter than the conductor itself. Transition cones at each end of the brass body provide a means of holding the subcables securely as they transition from the cable structure in the conductor to the overlap joint. The subcables are laid in grooves cut in the cones. These grooves carry the subcables in a transition from the helix angle of the conductor to the straight length of overlap, and change the circumferential subcable spacing to accommodate a row of vent holes in the body. The holes are manifolded to the cryogenic distribution system and provide pressure relief for the conductor in the event of a quench.

Key to the splice concept is the overlap of the subcables and enclosure in a superconducting braid. This approach is the result of development work done for the SMES program by Advanced CryoMagnetics, Inc. of San Diego, Ca. An earlier design for a SMES splice called for a direct overlap between individual strands in mating subcables. It was thought this was necessary to achieve the required value of resistance of 10^{-11} ohms. While this approach worked in principle, it required that the conductor be uncabled over some transition length. It was difficult to stabilize and support the individual superconducting strands in this region, and it was determined that there was a high risk of premature quenches there. With the present design, no uncabling is required, and the superconducting braid in effect creates the strand to strand contact that was sought in the initial concept.

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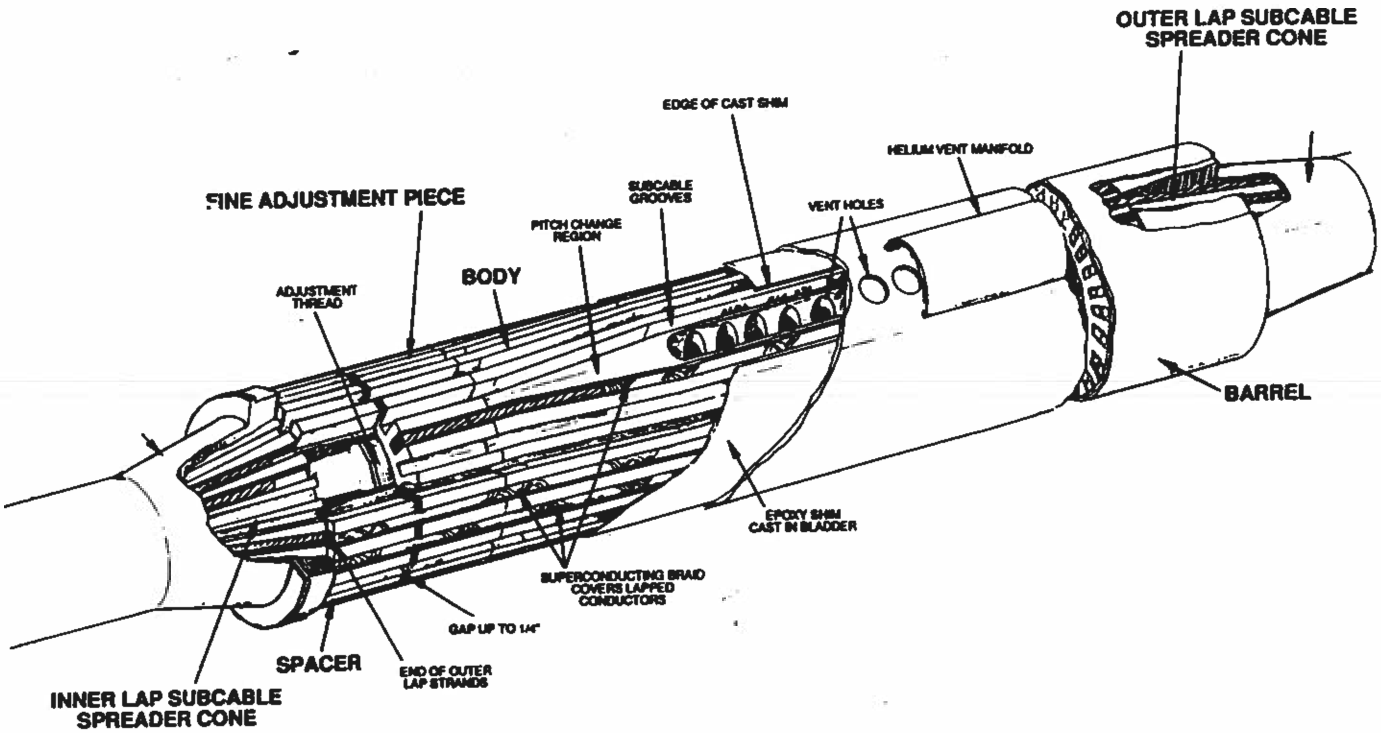

Fig. 1. Schematic of SMES Conductor Splice.

The braid also helps to wick solder into and around the subcables. The solder is applied as pre-sized slugs laid in the grooves on top of the braid, and held in place with aluminum clamps. An induction heater is used to melt the solder. The heater consists of a three turn coil placed around the brass body. The coil is the secondary of a 15 kW, 10 kHz transformer.

The splice is soldered using 96%Sn-4%Ag solder. This solder is selected because it has a lower resistivity than Sn-Pb solder. This compensates in part for the presence in the splice current path of the copper stabilizer that surrounds the superconducting strands. The earlier design did not have the stabilizer wires in the current path, and so Sn-Pb solder was acceptable.

Conductor

The conductor cross-section is shown in Fig. 2. For this 100 kA subscale test, only twelve subcables are employed, instead of twenty four in the 200 kA conductor. The cable is wrapped with a brass strip. The strip is soldered to both the subcables and outer conduit to provide support against magnetic forces. During cabling, 50%Sn-50%Pb solder paste is applied to the subcables, which is flowed in an induction heater after conduit compaction. The soldering provides additional restraint against conductor motion.

TEST SETUP / PROCEDURE

The test was carried out on a 100 kA splice and conductor which were inserted into the secondary of a superconducting transformer and operated in a 1 atm, 1.8 K helium bath in the presence of a background dipole magnetic field. The test facility at Texas Accelerator Center has been described elsewhere [3].

Instrumentation on the sample included eight voltage taps, four Hall probes, two temperature sensors, and a pressure sensor. The current and voltage across a quench heater mounted on the conductor were measured. In addition, the transformer primary current and voltage, secondary current and dI/dt, background field magnet current and terminal voltage, and bath temperature and pressure were monitored during

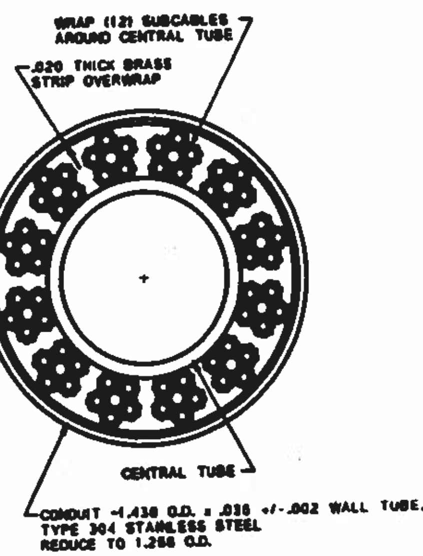

Fig. 2. 100 kA Conductor Cross-Section.

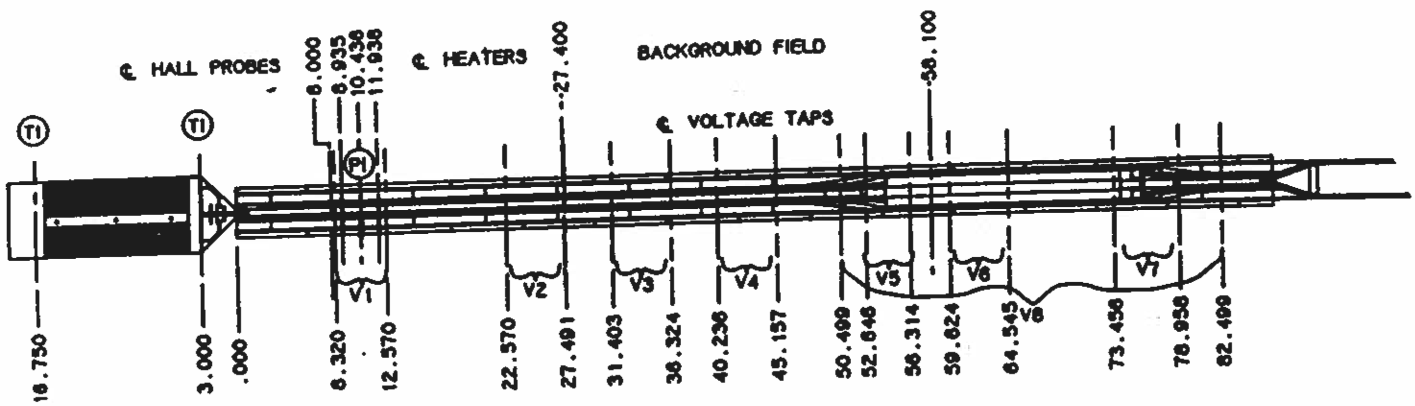

Fig. 3. Schematic of Test Sample and Instrumentation Location.

testing. The test sample and instrumentation are shown in Fig. 3. Measurements of splice resistance were made by recording the voltage across the splice (tap V8 in Fig. 3) with a Keithley model 181 nanovoltmeter. This meter has a noise floor on the order of 30 nV. The signal being measured at 40 kA was on the order of 30 µV.

During testing, the sample current and background are ramped simultaneously. This accurately simulates the forces on the conductor that would be seen in an actual winding. The Bechtel ETM design calls for a background field of 3 T at the design current of 200 kA (8333 A/subcable). The self field of the 100 kA conductor at 8333 A/subcable is approximately 1.8 T. Thus the total peak field on the conductor at 100 kA in the test facility should be nominally 4.8 T to simulate the ETM load line.

The test was conducted to measure the splice resistance at currents ranging from 40 to 120 kA along the self-field, 2 T, 5 T, and 6 T load lines. The sample was repeatedly ramped to quench along the self-field, 2 T, 5 T, and 6 T load lines. The sample was ramped at rates ranging from 50 A/sec to 1000 A/sec. The degree of training was measured by noting the number of quenches required to reach a plateau. In addition, the residual resistivity of the copper stabilizer was measured in zero background field before and after testing.

RESULTS

Splice Resistance

A series of runs were made to measure the splice resistance. A summary of all data is shown in Fig. 4, which is a plot

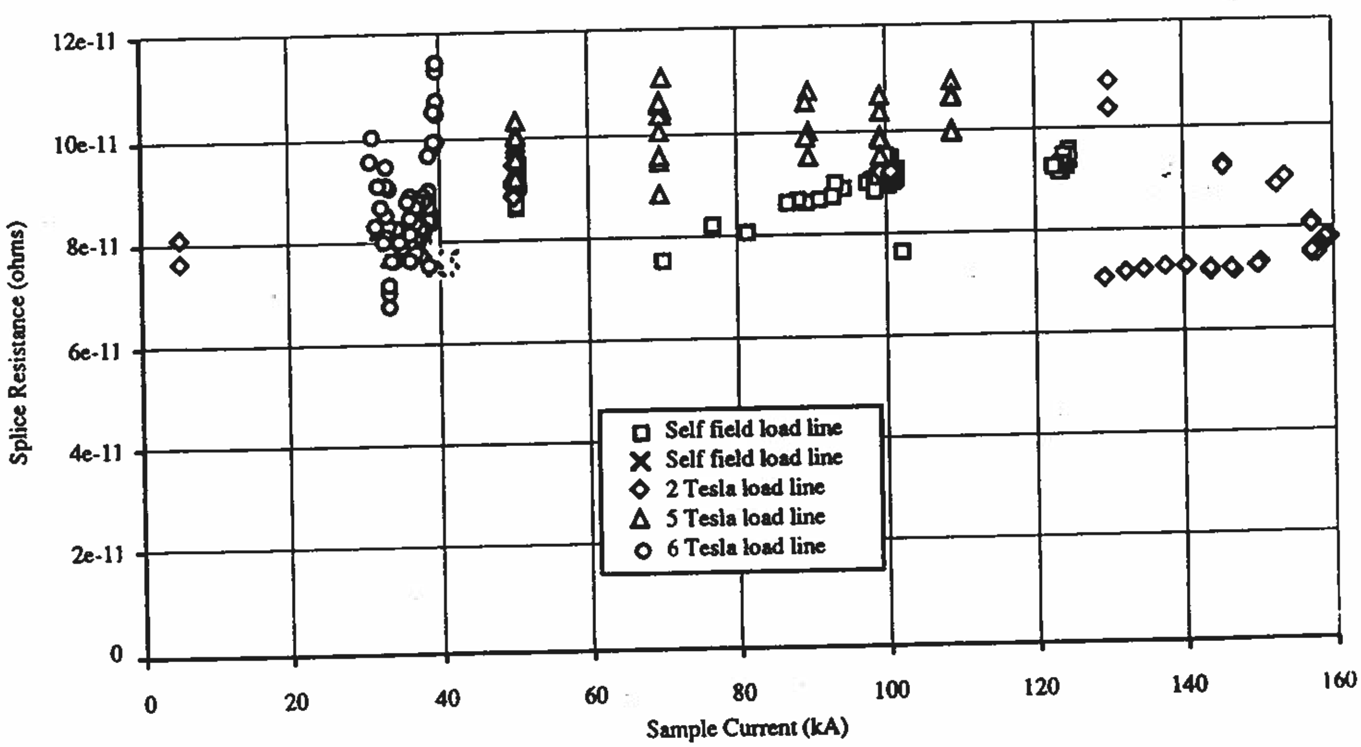

Fig. 4. Summary of Splice Resistance Measurements Plotted Against Sample Current.

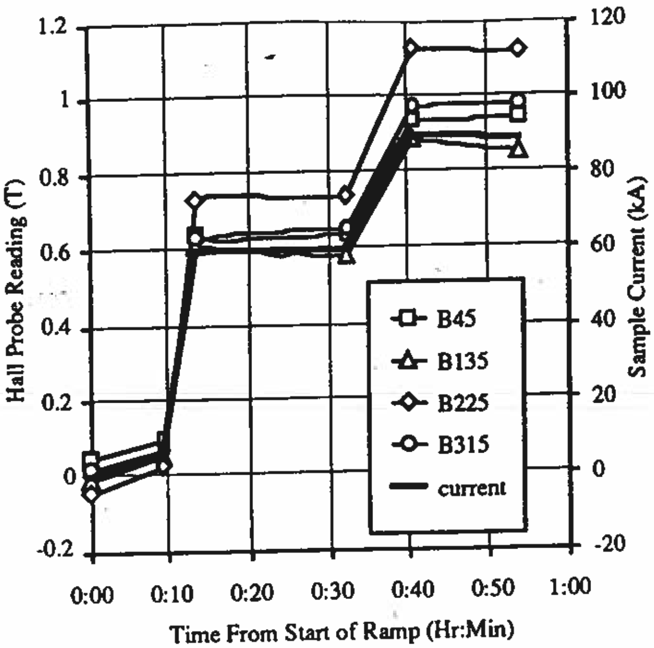

Fig. 5. Typical Hall Probe Data Show a Non-Uniform Current Distribution in the Subcables.

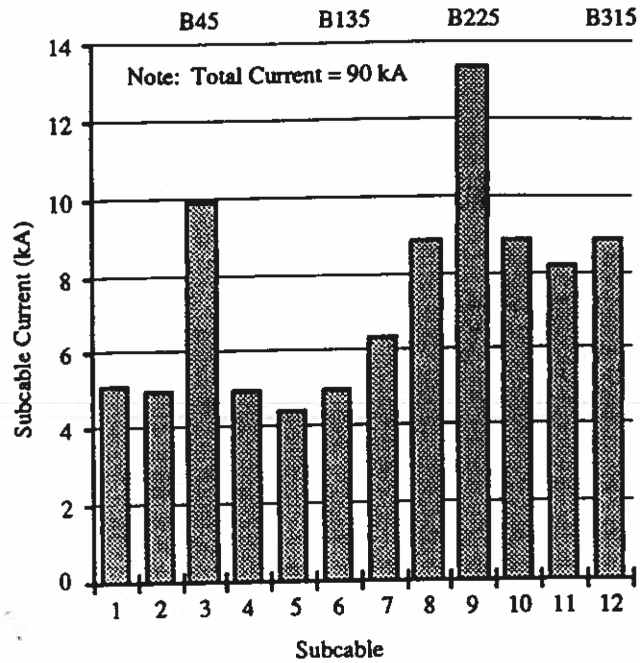

Fig. 6. Typical Subcable Current Distribution Corresponding to Hall Probe Data.

of splice resistance as a function of sample current. There is a large amount of scatter in the data, which masks any apparent dependency on current or background field. The majority of the data fall within a range between 7 and 11 x 10^{-11} ohms. The expected value for this splice prototype was 5 x 10^{-11} ohms. There is a trend toward higher resistance with increased background field, but the noise in the data is greater as well. The increase in scatter is due to inductive coupling between the voltage tap measuring splice resistance and the background field current.

The increase in resistance over the design value could be due either to a greater resistivity in the solder than anticipated, or due to geometric effects such as non-uniform spacing between subcables. An increase in solder resistivity would be expected to be uniform for each subcable splice, while geometric effects (presumably due to assembly variables) would be random from subcable to subcable and tend to produce a non-uniform current distribution around the conductor. Typical Hall probe data which is shown in Fig. 5 support the second hypothesis. A current distribution similar to that shown in Fig. 6 would produce the field around the conductor typical of that measured by the Hall probes. If the individual subcable splice resistances are estimated from this current distribution (provided the assumption can be made that the lowest subcable splice resistance is equal to the design value), then the ratio of measured value to design value for the conductor splice resistance ought to be approximately 1.8. This factor applied to the design value of 5 x 10^{-11} ohms gives a value of 9 x 10^{-11} ohms, which is in very good agreement with the measured value.

The higher than expected value of splice resistance is most likely due to variability in the spacing between subcables that occurred during assembly. This can be accounted for in the design of an ETM type machine by extending the length of the overlap, and by fine tuning the design and assembly procedure to minimize the variability that can occur. In the TAC test rig, the subcable to subcable resistance distribution determines the current distribution in the conductor. In a larger device, the self and mutual inductances of the subcables will play a much larger role in determining the current distribution, which as a result should be much more uniform. However, during a detailed design phase, an analysis of the subcable current distribution should be done to verify that this will indeed be the case. The test data do demonstrate that the splice concept is a viable, low risk approach for ETM and large scale SMES.

Quench Behavior

The conductor / splice did not approach the short sample limit of the superconductor during the test. Quenches occurred at various current levels, depending on the load line, as shown in Fig. 7. There was no apparent training behavior, and there was no typical quench origin location. A summary of the quench history is shown in Fig. 8. Several reasons for a low quench current were postulated, including excessive eddy current heating, degradation of the superconductor J_c during soldering of the splice and conductor, motion of the subcables under Lorentz load, mal-distribution of current in the subcables due to non-uniform resistance in the subcable overlap joints, and temperature rise of the splice caused by overheating. Several quench runs were made under controlled conditions designed to test these hypotheses. It was determined that the reason for the low quench current behavior was a thermal limit peculiar to the testing of a 100 kA splice in the TAC test rig. There was one quench, following a warmup / cooldown cycle, for which the most likely explanation is conductor motion.

The temperature sensors on the return and lead end splices joining the conductor sample to the secondary loop of the transformer indicated temperature rises of varying degrees during testing. This was due to the heat generated at the splices at the ends as well as the test splice. The inability of the test setup to remove the heat generated at the splice is the primary reason for the premature quenches. The principal heat transfer path from the return end splice to the 1.8 K heat exchanger in the test chamber is through the superfluid helium in the central tube of the conductor (see Fig. 3). A simple calculation shows that the critical heat flux for superfluid is reached in the central tube when the conductor current is approximately 150 kA. This result depends on many conditions in the test setup which can only be approximately modeled, and should only be interpreted as an indication that there is a heat transfer limit to the current that can be achieved in the rig. What seems to have happened is that the helium inside the conductor was slowly heated as the current increased, since the refrigerator could not keep up. At some point superfluidity was lost, and the central helium became even more isolated from the refrigerator. Heat from the splice then raised the helium temperature rapidly to the current sharing temperature of the conductor, and a quench occurred.

RRR

The resistance of the sample between voltage taps was measured prior to cooldown, and at 15 K before and after testing. The RRR of the conductor was about 56 before testing, and decreased slightly to 52 after testing. The RRR of the conductor in the splice body was approximately 100 both before and after testing.

The small decrease in RRR of the conductor stabilizer is most likely due to work hardening caused by Lorentz loading during testing. A similar decrease of roughly 10% has been seen in past testing of this conductor concept. The expected RRR for the conductor is about 50, so it is apparent that the copper stabilizer did not anneal during any soldering operations.

On the other hand, it is likely that the stabilizer in the splice region did anneal during soldering. This would explain the increase in RRR to 100. The softer copper is not considered a problem, since the strands and subcables are mechanically held by the solder in this region. The rigidity of the subcables and strands do not depend on the hardness of the copper in the splice.

The measured RRR of the conductor and the splice overlap is consistent with the design requirements for the ETM.

CONCLUSIONS

The objectives of the test were achieved during testing at Texas Accelerator Center:

- The splice resistance was measured to be approximately 9×10^{-11} ohms, compared to a design target of 5×10^{-11} ohms.
- The quenches did not originate in the transition regions between conductor and splice.
- The quenches did not demonstrate training behavior.

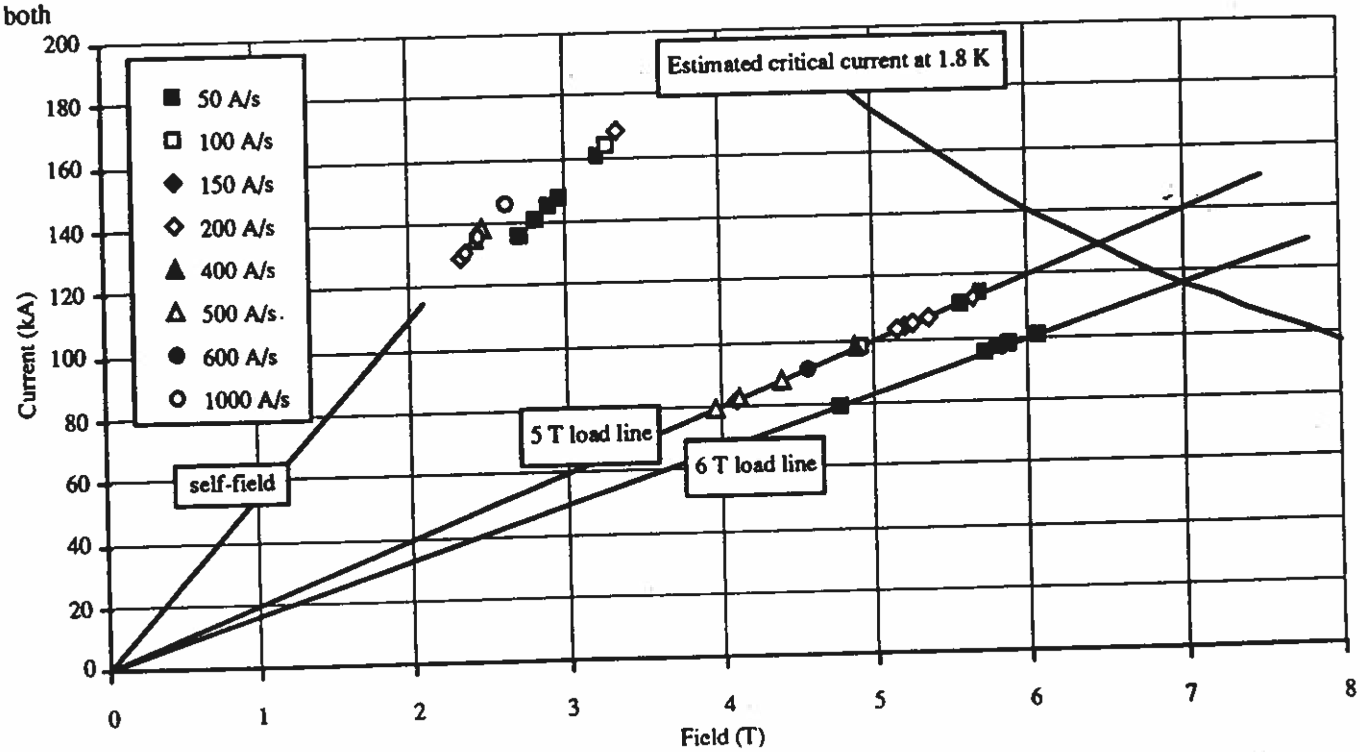

Fig. 7. Summary of Quench Current Behavior by Load Line.

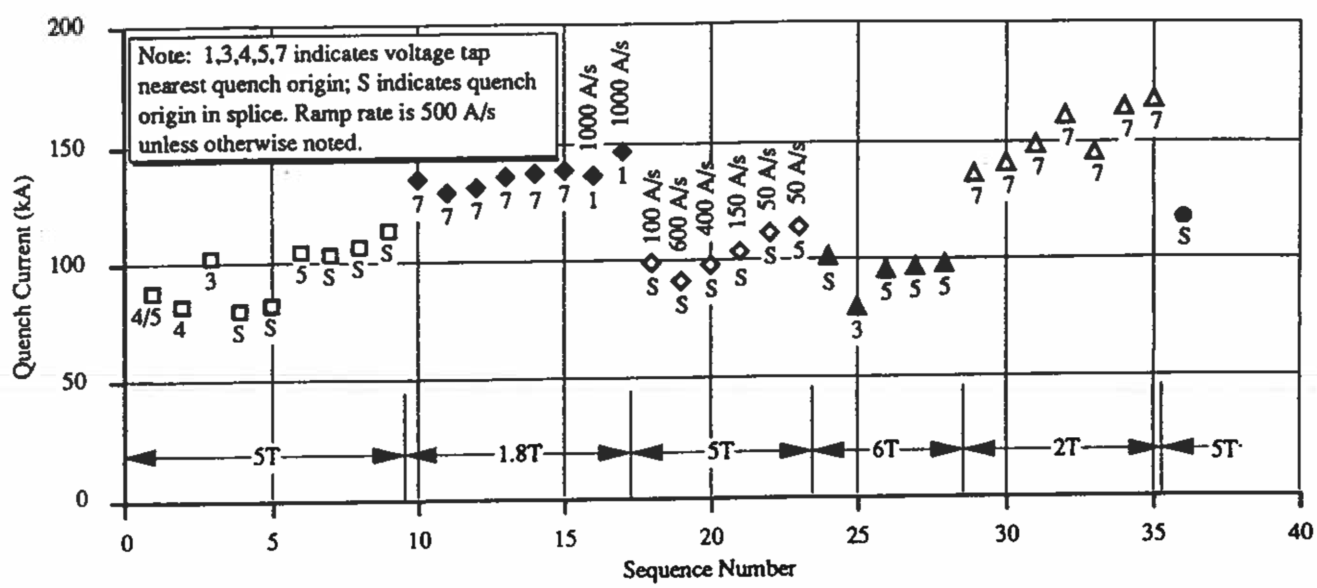

Fig. 8. Sequential History of Quench Data

The higher than expected value of splice resistance is due to unequal subcable-to-subcable splice resistances, which can be prevented in the design of an ETM type machine by extending the length of the overlap, and by fine tuning the design and assembly procedure to minimize the variability that can occur. In the TAC test rig, the subcable to subcable resistance distribution determines the current distribution in the conductor. In a larger device, the self and mutual inductances of the subcables will play a dominant role in determining the current distribution, which as a result will be much more uniform. However, during a detailed design phase, an analysis of the subcable current distribution should be done to verify that this will indeed be the case. The test data do demonstrate that the splice concept is a viable, low risk approach for ETM and large scale SMES.

The conductor did not reach short sample critical current during testing, due to a thermal limitation on the test rig when testing a 100 kA splice, and due to the unequal subcable-to-subcable splice resistances. The thermal limit is not present in the ETM design, since each splice is connected directly to a manifold connected to the 1.8 K refrigerator, and the manifold is sized to carry the heat generated by the splices. Soldering the subcables eliminated the training observed in a previous test of a 200 kA conductor, and definitely improved the stability of the conductor in the transition region between cable and splice. This greatly reduces the risk of premature quenching at the splices in the ETM.

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