SSC CENTRAL DESIGN GROUP
LAWRENCE BERKELEY LABORATORY
BLDG. 90 • ROOM 4040 • EXT. 4772

October 30, 1987

TO: V. N. Karpenko

FROM: M. Zaslawsky

SUBJECT: Material Tests Required to Perform Analysis

Attached is a proposal, SSC-N-414, from C. A. Tatro of the Materials Test and Evaluation Section, LLNL, which I request be approved.

A Proposal

TO EXPERIMENTALLY DETERMINE THE PHYSICAL PROPERTIES OF SUPERCONDUCTING SUPER COLLIDER MAGNET MATERIALS

Proposed Sponsor: SSC Central Design Group, Berkeley, CA 94720

Principal Investigator: C. A. Tatro, MTE Section, Engineering Sciences Division, LLNL, Livermore, CA.

INTRODUCTION

This proposal is to test materials to be used in the Superconducting Super Collider (SSC) for the purpose of experimentally determining the physical properties of these materials. Emphasis will be placed on obtaining those properties needed for the Finite Element Codes NIKE3D and NIKE2D with emphasis on the former. The materials in this study will be limited to the SSC magnet windings. Conditions of testing will be chosen to assure that sufficient knowledge of the material properties of these materials will be available for all operating phases anticipated in SSC operation. They will include assembly, cool-down, normal operation at 4.35 Kelvin (K), and quench.

The SSC Magnet Coil is a highly complex composite from the mechanics/ materials point of view. It might be described as a composite within a composite, within a composite — etc. The subject finite element codes give only a limited number of choices for a material description, and none of the choices admit a description as complicated as would be needed to describe the SSC coil in detail. Thus a significant part of the proposed testing effort must be directed toward choosing test specimens that represent a reasonable "average" behavior of the coil under all of the mechanical loading conditions expected in service. It is known that the principal parameters to be considered are differential thermal expansion (DTE) during cool-down and quench, Lorentz forces during operation and quench, and helium pressure during quench. A mechanical preload is imposed during assembly by a collar that surrounds the coil. This preloading is part of the strategy used to assure that the collar and coil do not separate under energization and operation.

APPROACH

Measurements for this endeavor must be taken over a wide range of temperature (300 K to 4.35 K) and represent average properties. It is recognized that testing below 77 K is very expensive. Liquid helium cost for a single test at or near 4.35 K is approximately $500. Test designs will emphasize minimizing testing below 77 K, consistent with supplying reliable data for SSC operating temperatures. Some analysis (curve fitting) and measurements at several temperatures above 77 K are implied by this approach.

From the mechanical testing viewpoint, a critical task is to select a reasonably representative sample and volume of the magnet material. While there are general guidelines for making this choice, iteration of the test specimen results with finite element calculations is probably the only way to assure that a proper choice has been made. Experimental data needs to be transmitted to the CDG Magnet Division as soon as it is available, and specimen design corrections should be made on the basis of mutual agreements between the Test Group and the CDG Magnet Division.

The current concept for producing an economical (and reproducible) test specimen is to start with a length of cable, section it in approximately one inch pieces, and stack it into a frame producing side deflections. The specimens are to be provided by the SSC Magnet Division (John Zabasnik). The individual insulated cables would be stacked alternately with a thick edge next to a thin edge, perhaps six cable segments high. Using this same epoxy and insulation as in the actual assembly to adhere the segments together would add realism (Fig. 1). The stack would be cured under pressure and time conditions similar to actual coil fabrication. The material would be tested in compression mode. Cycling tests would be performed to assess changes suspected to occur in the early load cycles of actual use. Simple fixturing would be built so that compressive behavior could be studied in the three "natural" directions of this most important material: through-the-thickness, edge-on, and axial. These tests should provide useful results that could steer us to variations of the basic test configuration, if necessary, or dictate a different approach. Certainly, it should indicate the degree of anisotropy inherent in the coil, and thus it should lead us to a firm assessment of the testing needed to complete the program.

A brief mathematical summary, based on a generalized material law, i.e., a constitutive relationship, and tailored to emphasize input requirements for NIKE 3D work, is contained in Appendix I. This Appendix was supplied by the CDG Magnet Division and supports the test program being described herein.

SAMPLE

The coil consists of superconducting cable helically wrapped double layer of Kapton with 50% overlap and helically wrapped single layer of pre-impregnated epoxy woven fiberglass. The three principle directions are r, θ, and z ,where the z axis is normal to the paper. In the example cited, there are 16 turns and 3 wedges or spacers per quarter in the inner coil and 21 turns and one wedge in the outer coil (Fig. 1). A cross-section is illustrated in Fig. 2, where 2 turns or 2 cable cross-sections are demonstrated. Again z would be direction normal to paper. While we are measuring average values and using average values in the analysis, we need to determine the variation in properties, especially in the θ direction. It can be observed that not only are there additional cables at one end, but they have been greatly deformed compared to cables away from the end. If there is only a slight difference, then the cables can be alternately stacked, i.e., alternating thick/thin stacks of n cables, when n = 2, 4, 6, 14.

In order to determine the variation E_θ, it is proposed to cut several turns in thirds where the first third would represent the wider end and the last third represent the thin end, alternate the cables in each third, and then test. The central third should correspond to average values, and the test at each end will give us the variation. If the variation is > 10%, then we will apply different material properties to the coil depending on the location of the element. If we obtain different results for $n \geq 2$, 4, 6, 14 (which we do not anticipate), then the analysis will incorporate different material properties per element accordingly.

Therefore, the first series of tests would be compression tests of coil and Cu wedges at R.T. and several temperatures down to 77° K and 4.35° K. (See Fig. 1.) Modulus would be measured in each direction coupled with extensions in the other directions. Load is applied in one direction and measurements of contraction/ extension are made in all three principal directions. Both loading and unloading data will be obtained. A second series of tests at temperature would measure the bulk properties on loading and unloading. Thermal contraction/expansion for the coil will also be obtained for the three principal directions. These results will be compared to existing data provided by CDG where available. There is limited circumferential moduli at R.T., loading and unloading, and circumferential coefficient at thermal contraction (Zabasnik, Peters, and Caspi respectively).

Tests have already been performed using sections of the entire magnet together with collar. A finite element analysis on the test set-up evaluates the model. The test results of the system essentially give modulus in one direction, ignores friction. Strain gages, inserted in the collar subject to pressure or displacement at some point in the system, will read a response. If the predicted response agrees with the recorded responses based on a specific model, then there is a basis of validity to the material model. There are, of course, more complex tests being run on whole systems at LBL, FNAL, and BNL, and the output of these tests should match a FEA of these experiments. If results are not comparable, then a more complex model is required.

Comparing a finite element analysis of the LBL/BNL test set up, (CDG to perform FEA) and material properties and model defined by the LLNL tests, a comparison of the validity of model can be evaluated. Should the model be inadequate, a more complex model will be required but will not necessarily require additional test data. Working together with the CDG, models available in the codes will be utilizes first. That is, currently available models will be evaluated using the material properties data as inputs.

A second problem of primary importance in performing a finite element calculation of the coil performance has to do with the treatment of slidelines. Here, the important unknown number is the value of friction to assign to the slidelines. We will start immediately to design a fixture that will permit us to measure the friction of the surfaces where slidelines are inserted in the NIKE code, as a function of temperature.

Coefficient of friction will be obtained between:

Kapton and coil
G-10 and Kapton
Kapton and copper

The coefficient of friction will be obtained as a function of both temperature and pressure. An attempt will be made to distinguish between static and dynamic friction.

CAPABILITY

LLNL has a number of closed-loop, servo-controlled testing machines, as well as several new machines of the screw driven variety with modern precision load measuring capability. It also has intensive capability for digital data acquisition, and a wide variety of tools for measuring material deformation under load. The strain gage technology proven for temperatures down to 4.35 K was developed for our MFTF program. However, application of strain gages to the subject material are not planned at this time.

The Materials Test and Evaluation (MTE) Laboratory has two liquid helium cryostats that were designed for use with testing machines. One is currently configured for fracture mechanics testing and has a comparatively small test volume. The other, currently configured for tensile testing, has a large test volume. MTE personnel are familiar with the operation of these devices. In addition, a variety of environmental chambers are owned by the section, and would permit measurements down to 77 K relatively economically. The larger of the helium cryostats is capable of maintaining temperature between 77 K and 4.35 K.

To perform the subject tasks, new fixturing would certainly have to be made. Skilled personnel are available for producing this fixturing. Most have had extensive experience with low temperature.

Skilled engineers are available on a part-time basis to perform the necessary test designs and evaluation. They include Robert Brady, Robert Engle, William Feng, and Donald Lesuer, in addition to the principal investigator.

The most serious short-fall in capability is with the low temperature measurement of CTE. As stated above, the devices to produce precision measurement over our temperature range is approximately two man-months away from realization.

TEST PROGRAM ELEMENTS

For "BASIC" specimens (built up from cables):

Kinds of specimens — four
Test temperatures above and at 77 K — four
Replications of tests — three
Number of cycles per test — one to ten

Temperatures below 77 K:

Kinds of specimens — four
Replications of test — four
Test temperatures — two

For "FRICTION" Measurements: (see list in text)

Kinds of specimens — four
Replications of test — three
Temperatures below 77 K — one
Replications — three

For "BULK MODULUS" Measurements

Kinds of specimens — two
Replications — three
Temperatures above 77 K — two

FEA will be provided by CDG, in support at the Test Program.

COST ESTIMATE

Mechanical Tests:

The mechanical test effort is estimated on a per test basis. Assembly, check out, etc., are included in the per test estimate.

Room temperature tests:		
49 tests at $+ per day. Days required	12	
Cold tests at Liquid nitrogen (LN) and above:		
107 tests at 2+ per day. Days required	52	
Cold tests below LN (requires helium chamber):		
26 tests at 1 per day. Days required	26	
Report, discussions, analysis. Days required	10	
Total estimated manpower for mechanical testing	100 days	
Total cost of manpower (128 days)		48 K$
Supplies and expenses:		
Fixturing design and fab., sensors	25 K$	
Liquid helium for 28 tests below LN	13 K$	
Total estimated cost for supplied and expense		38 K$
Total estimated project cost		86 K$

Specimens will be prepared by CDG

This cost estimate has been written in a form that indicates how the costs are distributed, recognizing that several of the items listed may be modified, extended, or deleted. It also assumes that this work will be undertaken on a best-effort basis, recognizing that some of the tests required are not routine and some features require innovative engineering approaches.

10/29/87

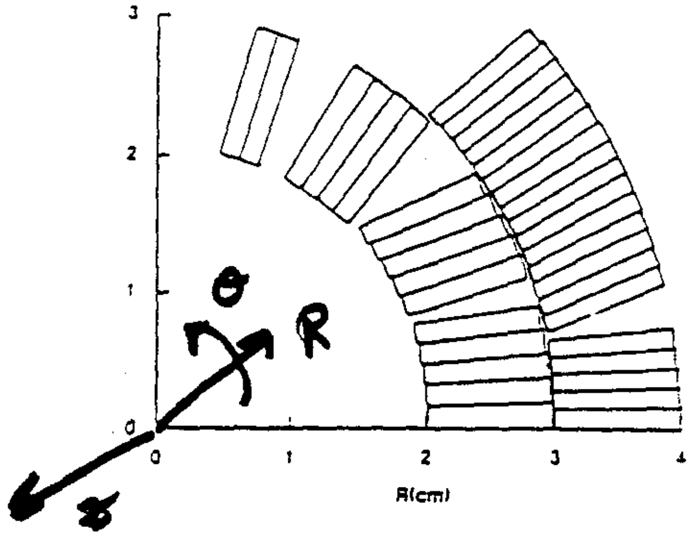


Fig. 1a. A quadrant cross section of NC515, a 4-wedge solution.

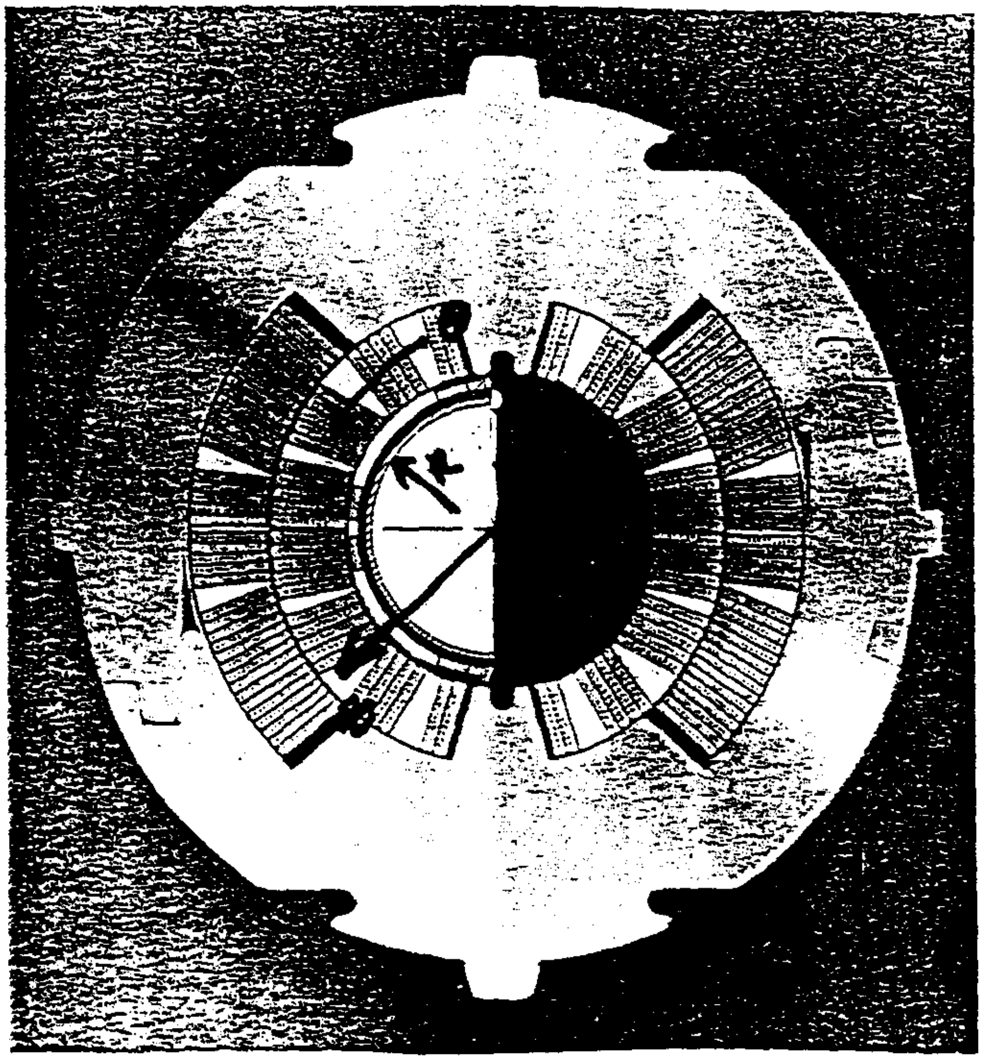
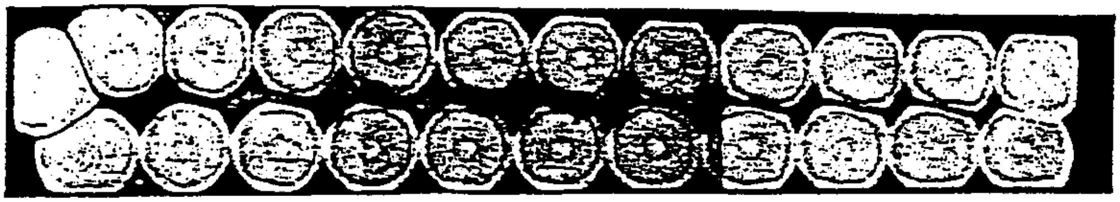


Fig. 1b. A model cross section of NC515.

23 STRAND KEYSTONED CABLE



30 STRAND KEYSTONED CABLE

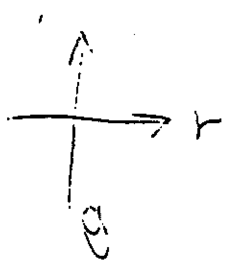


Fig. 2. 23 strand and 30 strand keystoned cable cross sections.

APPENDIX I

Tests at BNL and LBL have shown that $E_z \simeq 9\,E_\theta$. Limited acoustic emission data have shown that $E_R \simeq E_\theta$ From observation of the geometry, it is possible that $E_\theta = E_R$. Then the orthotropic thermo-elastic-plastic model can be used.

The material law, constitutive relationship can be defined as

$$\tilde{C} = \tilde{T}^t \, \tilde{C}_L \, T$$

where $\tilde{T}$ is a transformation matrix, and $\tilde{C}_L$ is the constitutive matrix defined in terms of the material constants of the orthogonal <u>material</u> axes a, b, and c.

In this case, a, b, c $\equiv$ r, θ, z

$$\tilde{C}_L^{-1} = \begin{bmatrix} \frac{1}{E_a} & \frac{-\upsilon ba}{E_b} & \frac{-\upsilon ca}{E_c} & \phi & \phi & \phi \\ \frac{-\upsilon ab}{E_a} & \frac{1}{E_b} & \frac{-\upsilon cb}{E_c} & \phi & \phi & \phi \\ \frac{-\upsilon ac}{E_a} & \frac{-\upsilon bc}{E_b} & \frac{1}{E_c} & \phi & \phi & \phi \\ \phi & \phi & \phi & \frac{1}{G_{ab}} & \phi & \phi \\ \phi & \phi & \phi & \phi & \frac{1}{G_{bc}} & \phi \\ \phi & \phi & \phi & \phi & \phi & \frac{1}{G_{ca}} \end{bmatrix}$$

$\frac{-\upsilon ab}{Ea} = \frac{-\upsilon ba}{Eb}$, $\frac{-\upsilon a}{Ec} = \frac{-\upsilon ac}{E_a}$, $\frac{-\upsilon cb}{E_c} = \frac{-\upsilon bc}{E_b}$ as shown above. Therefore, what is required E_a, E_b, E_c, $-\upsilon ba$, $-\upsilon ca$, $-\upsilon cb$, G_{ab}, G_{bc}, G_{ca}, or E_θ, E_r, E_z, $-\upsilon r\theta$, $-\upsilon z\theta$, $-\upsilon zr$, $G_{r\theta}$, $G_{z\theta}$, G_{zr}.

It is anticipated to change the NIKE3D to input the above as functions of temperature for loading:

For each T_i we provide:

$$\underbrace{E_\theta, E_r, E_z, -\upsilon r\theta, -\upsilon z\theta, -\upsilon zr, G_{r\theta}, G_{z\theta}, G_{zr}}_{\text{9 constants}}, \alpha_q, \alpha_r, \alpha_z \tag{1}$$

For unloading T_i we provide

$$K_u, \underline{\text{bulk}} \text{ unloading modulus.} \tag{2}$$

To use these models for the entire range of temperatures requires some minor modifications to the source code. To use these results at one temperature requires no change to the source code. Therefore, for each temperature, we need (1) and (2) above.