Lawrence Berkeley National Laboratory

Title

MEASURED MECHANICAL PROPERTIES OF SUPERCONDUCTING COIL MATERIALS AND THEIR INFLUENCE ON COIL PRESTRESS

Author

Meuser, R.B.

Publication Date

1981-03-01

Peer reviewed

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

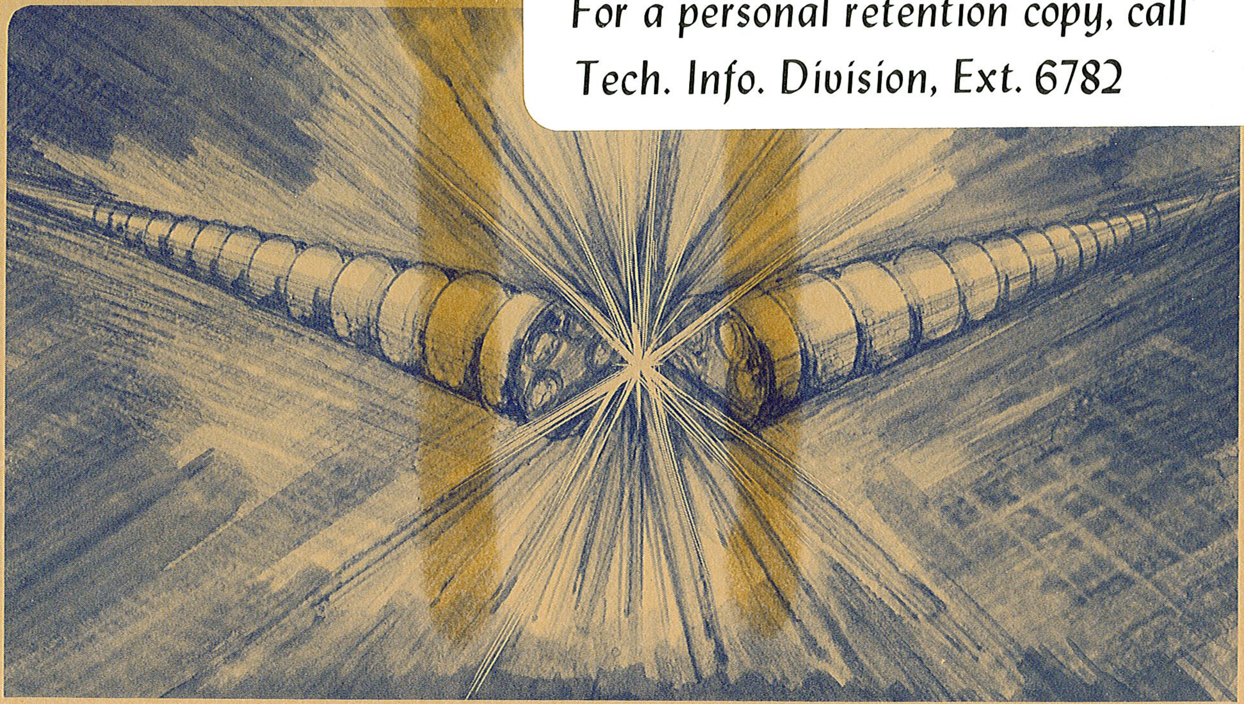
Accelerator & Fusion Research Division

Presented at the VIIth International Conference on Magnet Technology, Karlsruhe, Germany, March 30-April 3, 1981

MEASURED MECHANICAL PROPERTIES OF SUPERCONDUCTING COIL MATERIALS AND THEIR INFLUENCE ON COIL PRESTRESS

Robert B. Meuser, Shlomo Caspi, and William S. Gilbert

March 1981



Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

LBL-12438

MEASURED MECHANICAL PROPERTIES OF SUPERCONDUCTING COIL MATERIALS AND THEIR INFLUENCE ON COIL PRESTRESS*

Robert B. Meuser, Shlomo Caspi, William S. Gilbert

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

March 1981

*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division of the U.S. Department of Energy under Contact No. W-7405-ENG-48.

MEASURED MECHANICAL PROPERTIES OF SUPERCONDUCTING COIL MATERIALS AND THEIR INFLUENCE ON COIL PRESTRESS

Robert B. Meuser, Shlomo Caspi, William S. Gilbert

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

Abstract. Some measured thermal-mechanical characteristics of a film-insulated, superconducting, Rutherford-type flat cable are presented. Loads are applied, and strains measured, perpendicular to the wide face of the conductor, corresponding to the circumferential direction in a dipole magnet. Stress-strain-time behavior at room temperature, during cooldown, and at 77 K, with some data at 4 K, are presented. Properties were greatly improved by holding the insulated conductor at 100C for 4 hr. while under a compressive stress of 15 kpsi.

INTRODUCTION

One kind of superconducting magnet currently under development at the Lawrence Berkeley Laboratory employs Nb-Ti, Rutherford-type, flat cable wrapped with plastic film insulation; no epoxy or other resins are used in the winding [1] (Fig. 1).

Figure 2 shows a cross section of a representative dipole magnet. The winding is compressed radially by the external structure, resulting in circumferential compressive "pre-stresses" within the coil. Because the coil components and the surrounding structure have different mechanical and thermal properties, the pre-stress changes when the magnet is cooled to 4 K. When the magnet is energized, the compressive circumferential stress increases near the horizontal mid-plane and decreases near the poles, resulting in circumferential motion of the conductors toward the midplane. If the pre-stress is too small, the conductors near the pole may separate from each other or from the pole spacer, causing additional motion of all the conductors, which results in aberrations in the magnetic field in the aperture, and a release of energy which can contribute to premature quenching.

In order to predict the mechanical behavior of the magnet during cooldown and operation, we need to know the mechanical and thermal characteristics of the insulated conductor. We report the results of a series of tests designed to determine some of those characteristics. Such a "poorly behaved" material, having mechanical characteristics that are non-linear, orthotropic, inelastic, and temperature dependent, is difficult to characterize in a way that relates meaningfully to coil design. Nevertheless, some order appears in the data.

In the work presented here, we focus on only the strain and stress perpendicular to the face of the conductor, corresponding to the circumferential direction in the magnet, with no constraints or loads in the other directions. These are the principal properties affecting the thermal-mechanical behavior of a magnet.

Part way through the testing program, it was discovered that the mechanical properties could be greatly improved by "heat treating" the conductor: heating it for a few hours at 100 C while it is under a compressive load of 15 kpsi. Most of the results presented here are for the non-heat-treated material. Most of the "cold" tests were done in liquid nitrogen; one in liquid helium.

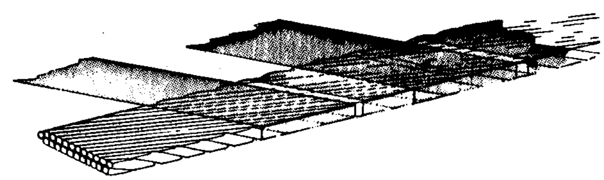


Fig. 1. Rutherford-type cable insulated with plastic film.

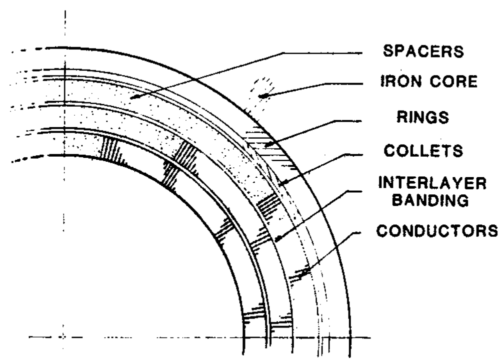


Fig. 2. Cross-section of representative dipole magnet.

CONDUCTOR

The non-insulated cable is nearly identical to that of the Fermilab Doubler/Saver magnets, consisting of 23 strands of 0.027-in. (0.69 mm) diameter having a copper-to-superconductor ratio of 1.8. The conductor is passed between rollers to compact it and to give it a keystone-shape cross-section. The final dimensions are: width, 0.312 in. (7.9 mm); thickness at thick edge, 0.053 in. (1.3 mm); taper angle, 1.5 deg.

The insulation consists of a spiral wrapping of Kapton 0.001 in. (0.025 mm) thick by 0.5 in. (13 mm) wide followed by a wrapping of Mylar .002 in. (0.05 mm) by 0.5 in. (13 mm) wide. There is a gap of .050 in. (1.3 mm) between adjacent turns. The gap in the second layer coincides with the middle of the tape in the first layer.

APPARATUS, PROCEDURES

Test Samples

A test sample consists of a stack of 16 pieces of the keystoned conductor 3 in. long, with adjacent pieces having the wide edge on alternate sides to give a parallel-sided stack. The compressive load is applied perpendicular to the wide face of the conductor, corresponding to the circumferential

*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division of the U. S. Department of Energy under Contract No. W-7405-ENG-48.

direction in the magnet, over a 1-in. (25 mm) length. All samples were made from the same piece of conductor; all tests were performed on specimens that had not previously been tested.

Apparatus

The sample is inserted into a loose-fitting, U-shape, stainless steel block. The load is applied with a stainless steel plunger. Quartz rods transmit the positions of the block and plunger to the body and piston, respectively, of a linear variable differential transformer (LVDT), which is at room temperature.

Testing is performed in a dewar installed in an Instron universal testing machine having a capacity of 5000 lb. (22 kN). Signals from the LVDT and load cell are recorded and processed by either an HP9845B or HP85A desktop computer. Displacements of the apparatus, determined by tests using a steel specimen, are subtracted out by the computer.

Procedures

We standardized, for convenience, on a crosshead speed of 0.1 in/s; during the first loading at room temperature, loading from 2 to 15 kpsi* took about a minute. After loading, usually to 15 kpsi, the samples were maintained at that stress for 2 hr before cooling. A longer "hold" - several weeks - would better simulate conditions in a magnet, but was impractical. A two-week hold was used in one test. The load-temperature sequences for the various tests are outlined in Table 1 and Fig. 3.

RESULTS, DISCUSSION

Space does not permit showing σ-ε graphs for all the tests. (More complete results are presented in [2]). The main results are presented in Tables 2

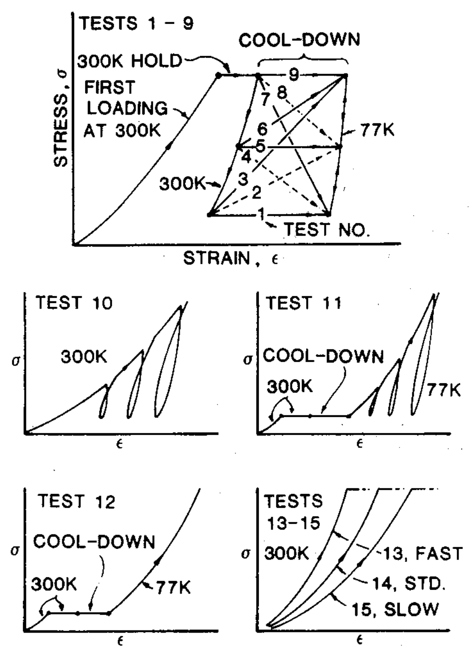


Fig. 3. Test procedures.

* 1 kpsi = 1000 psi = 1000 lb_f/in^2 = 68.046 atm = 68.948 bar = 6.8948×10^7 $dyne/cm^2$ = 70.307 kg_f/cm^2

TABLE 1

Test Conditions

Tests 1-9, 16, 18, 20: 2nd run at 300 K was after cold test.

Tests 11, 12: Both runs at 300 K were after cold test. Sample held at 2 kpsi before cooling.

Test 13: 2nd run at 300 K after 26 hr creep at 300K.

Test 14: 2nd run at 300 K after 22 hr creep at 300K.

Test 15: 2nd run at 300 K after 40 hr creep at 300K.

Test 17: 2nd run at 300 K after 40 hr creep at 340K.

Test 18: Heat treated for 4 hr at 100 C, stress 15. to 12 kpsi.

Test 19: Two-week creep at 300K, 15 kpsi.

Test 20: Bare, uninsulated conductor.

through 4. A representative σ-ε graph is presented (Fig. 4). Throughout, we use "stress" to indicate the average stress over the loaded region of the sample, and "strain" based on a standarized initial specimen height corresponding to a stress of about 200 psi.

In Table 3, the elastic modulus, $\partial\sigma/\partial\varepsilon$, is the slope of a straight line fitted to the part of the σ-ε curve between 2 and 15 kpsi for increasing load. (For decreasing load, the non-linearity gives local values of $\partial\sigma/\partial\varepsilon$ varing from zero to nearly infinity, and average values that aren't expecially enlightening.) The "offset" is the intercept of the fitted straight lines with the strain axis.

With such an ill-behaved material, a direct measurement of the thermal-contraction integral, essentially

$$K = \int \alpha \, dT,$$

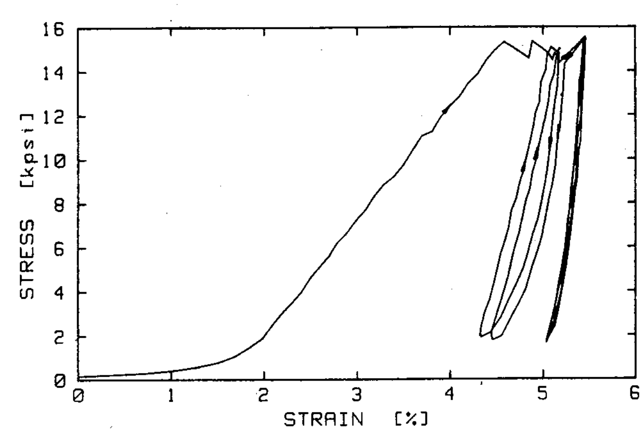


Fig. 4. Typical stress-strain curve. Cold testing was in liquid helium. Saw-tooth pattern at top occured during 2-hr. hold, with last tooth representing cooling to 4 K. Open loops are for 300 K, closed loops for 4 K.

at zero stress, is not very meaningful. A more useful thermal-contraction integral can be inferred from the formula

$$K = \epsilon_2 - \epsilon_1 - \sigma_2/E_2 + \sigma_1/E_1$$

This is derived on the basis of linear σ-ϵ behavior (Fig. 5), the only kind of behavior that yields a thermal contraction integral having any utility. The thermal contraction values presented are rather imprecise; nevertheless we present them for what they may be worth.

The behavior of the composite structure is of course, related in a complex way to the properties of the constituent materials, but the behavior is also strongly dependent on the configuration. High local stresses are probably developed, within both the metal and the plastics, that are many times greater than the nominal stresses. The wiggles in the conductor, resulting from the manufacturing processes, probably do not intermesh perfectly at all stages of the stress history, and some sliding into position probably occurs. The plastic undergoes severe permanent local deformation, being squeezed into the voids between the metal strands.

Different samples showed a wide variation in initial unloaded height. However with the strain based on a standardized height, the total spread in strain at 15 kpsi was only about 0.25 percent for the first loading at 300 K.

One set of tests, Nos. 1 through 9, was to determine whether, or to what extent, the cold stress-strain characteristics are a function of the stress-temperature history during cooling down, that is, whether an "equation of state" applies. If an equation of state does not apply, then one must model the stress-strain history during cooldown in order to predict the state of stress in the magnet coil after cooldown; a tedious, iterative process. If an equation of state applies, then the cold state of stress of the magnet coil can be predicted more easily, particularly if the σ-ϵ behavior is linear. Of the nine tests planned, six were performed.

The "equation of state" tests, indicate that the final strain at 77 K is indeed dependent on the stress-temperature path during cooldown. The shift of the σ-ϵ curve at 77 K for various paths is of the order of the elastic strain at 77 K, for a stress range from 2000 to 15000 psi. Perhaps this was too severe a test; it seems likely that the final state would be sufficiently path-independent for practical purposes for a smaller stress range, but one still large enough to bracket possible cool-down paths for conductors in a magnet.

Three characteristics dominate the behavior of the conductor: permanent set, or yielding under short-time loading with no creep; hysteresis during a complete loading-unloading cycle; and creep. We discuss these characteristics in that order.

Upon the first loading at room temperature there is a long "tail" to the σ-ϵ curve of 2 percent in strain, followed by a linear region with a slope of 0.5 x 10^6psi. If the loading is stopped at some point, and the load is cycled between the load at that point and some value near zero, there is a shift in the σ-ϵ loops between the first and second cycles, but virtually no shift - no additional permanent set - upon subsequent cycles; the σ-ϵ curve follows that of a sample that has been continuously loaded without the intermediate load cycling.

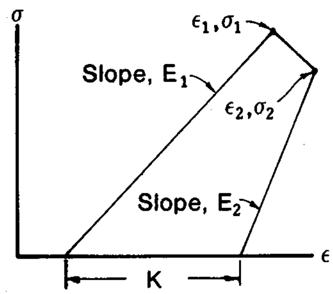


Fig. 5. Basis for formula for thermal-expansion integral K.

TABLE 2

Results: Elastic modulus, plastic deformation, thermal-contraction integrals

Test No.	Lower test temp K	Loading rate psi/s	300 K First Run $\partial\sigma/\partial\epsilon$ 10^6psi	300 K First Run Offset %	300 K Second Run $\partial\sigma/\partial\epsilon$ 10^6psi	300 K Second Run Offset %	77 K $\partial\sigma/\partial\epsilon$ 10^6psi	77 K Offset %	K, 300 to 77 or 4 Cooling %	K, 300 to 77 or 4 Warming %
1	77	258	.48	1.55	1.12	3.77	2.22	4.44	.347	.475
3	77	258	.52	1.48	1.20	3.60	3.10	4.38	.477	.461
5	77	253	.51	1.46	1.25	3.77	3.17	4.80	.699	.692
6	77	254	.50	1.43	1.24	3.78	3.16	4.78	.623	.715
7	77	257	.51	1.55	1.18	3.72	3.39	4.90	1.361	.921
9	77	263	.53	1.53	1.22	3.80	3.03	4.85	1.119	.892
11	77	-	.49	1.44	1.05	3.50	1.85	2.58	.426	.410
12	77	-	.52	1.48	1.10	3.40	1.88	2.60	.435	.441
13	300	51	.48	1.50	1.20	4.00	-	-	-	-
14	300	260	.53	1.44	1.18	3.62	-	-	-	-
15	300	1275	.54	1.46	1.21	3.80	-	-	-	-
16	4	260	.52	1.60	1.7	4.20	3.8	5.1	.772	.693
17	300	257	.50	1.37	1.35	4.20	-	-	-	-
18	77	260	.54	1.54	3.00	5.70	6.25	6.23	.543	.494
19	300	266	.51	1.57	2.00	4.50	-	-	-	-
20	77	326	1.81	-	4.70	-	4.80	-	-	-

When the specimen is loaded to 2 kpsi at room temperature, cooled to 77 K, loaded to 15 kpsi, unloaded to 2 kpsi, and returned to room temperature, the behavior at room temperature is nearly the same as that of a sample that had remained at room temperature; no significant permanent effect takes place during loading at 77 K.

Hysteresis in σ-ϵ loops is clearly evident in all the tests at all temperatures except in the test of a heat-treated sample tested at 77 K, where it was less than the resolution of the apparatus, about 0.02 percent in strain. For a standard test at room temperature the loop has a width of about 0.5 percent in strain for a stress range of 0 to 15 kpsi. At 77 K, the loop width is about 0.1 percent. Under no conditions does the width of the loop change significantly upon repeated load cycling. It is interesting to note that the loop width for insulated conductor at 77 K is less than that of uninsulated conductor; possibly the observed squeezing of the plastic into the voids between strands of conductor prevents relative motion of the strands, which contributes to the hysteresis. The width of the σ-ϵ loop decreases, of course, with decreasing stress range.

Creep is associated primarily with the insulation; an uninsulated sample exhibits little creep. Reducing the temperature from 300 K to 77 K decreases the rate of creep by a factor of 10; during the "heat treatment" at 100 C, the creep rate increases by a large factor.

No attempt was made to fit the creep data to a conventional model. It was found, though, that the σ-t characteristic appears, roughly, as a straight line on a σ-log t graph. Straight-line behavior is represented by an equation of the form:

$$e^{(\epsilon-\epsilon_0)} = (t/t_0)^n$$

where the coordinates t_0, σ_0 represent an arbitrary point on the curve, which we take soon after the load has been applied. The exponent, n, was found to be 7.5×10^{-4} for a stress of 15 kpsi, for strain expressed in mm/mm, not percent.

After heat treating the sample to 100 C for about 4 hr, the total creep strain was 1.8 percent. If we extrapolate the creep data for non-heat-treated samples using the above formula (admittedly stretching the data beyond all reason) the time required to reach 1.8 percent creep would be about 100 years. After the specimen was returned to 300 K,

TABLE 3

Results: Load Cycling

Test No.	Temp. K	Stress kpsi	$\partial\sigma/\partial\epsilon$ 10^6psi	Offset %
		2 - 5.5	1.07	2.10
10	300	2 - 10	1.23	2.73
		2 - 15	1.47	3.50
		2 - 15(1)	1.88	4.28
		2 - 5	1.63	2.36
11	77	2 - 10	1.76	2.47
		2 - 15	1.85	2.58
12	77	2-15(2)	1.45	2.30
		1-15(3)	1.88	2.60

(1) After 24 hr creep.
(2), (3) Successive runs.

TABLE 4

Results: Creep data

Test No.	Stress kpsi	Temp K	10^4n	Strain % at 60s
1	15	300	7.12	.25
3	15	300	7.94	.25
7	15	300	7.06	.32
9	15	300	7.13	.34
10	15	300	6.67	.13
	15	300	7.95	.29
12	15	77	0.88	.02
	2	300	0.60	.03
13	15	300	8.75	.18
14	15	300	7.54	.32
15	15	300	6.57	.48
17	15	340	14.3	.29

$e^{\epsilon-\epsilon_0} = (t/t_0)^n$ for ϵ in (mm/mm)

no further creep was evident. However, using the same formula and data, an additional 0.1 percent creep would require about a year.

APPLICATION TO MAGNET PRESTRESS AFTER COOLDOWN

A minicomputer program [3] is used to predict the stresses in a magnet after cooldown. Equations were derived for a thick cylinder of a linear orthotropic material under plane-stress conditions, with internal and external applied radial pressures. The conductor layers, Nylon banding between layers, and the outer aluminum clamping rings are treated as cylinders. There can be interferences between the cylinders. The program solves the resulting set of compatibility and equilibrium equations to give the pre-load stresses at room temperature, and the final stresses after cooldown.

CONCLUSIONS

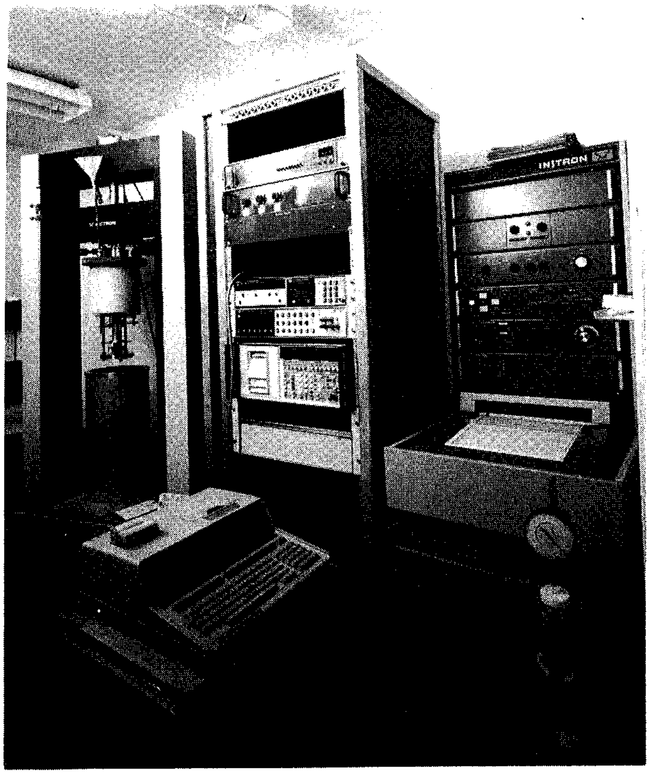
Some properties of the insulated cable at room temperature, 77 K, 4 K, and during cooldown are presented.

"Heat treating" the insulated conductor - soaking at 100 C for 4 hours at a stress decreasing from 15 to 12 kpsi during the baking - greatly improves its mechanical properties. The elastic modulus at 77 K is increased from 3×10^6 to 6×10^6 psi; creep rate and hysteresis are greatly reduced.

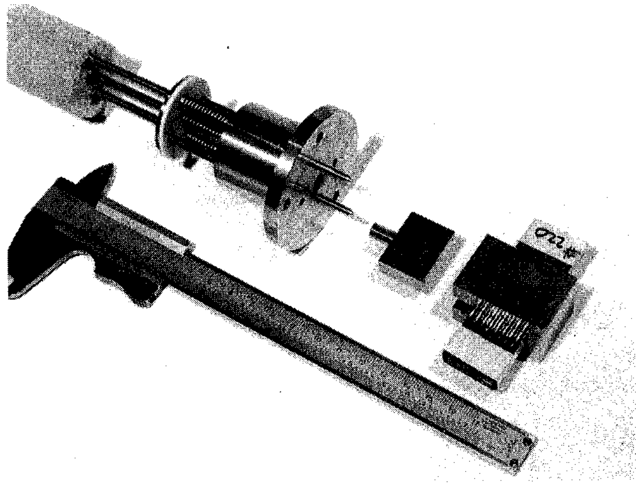
Considerably more work will be necessary to fully characterize the thermal-mechanical properties of the composite material.

REFERENCES

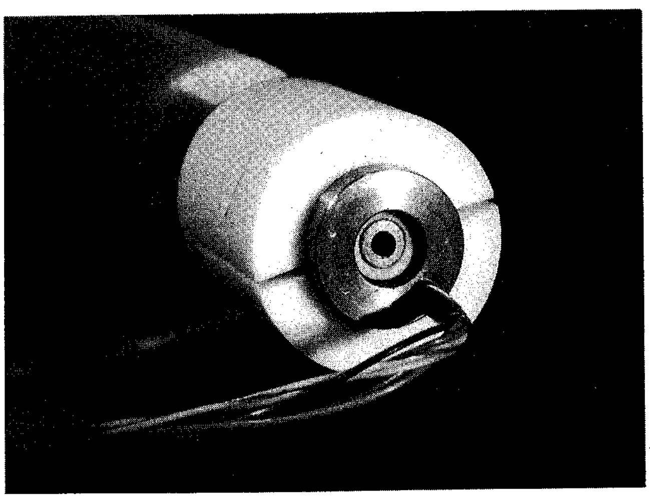
1. C. Taylor, et.al., "Design of Epoxy-Free Superconducting Dipole Magnets and Performance in Both Helium I and Pressurized Helium II", VII International Conference on Magnet Technology, Lawrence Berkeley Laboratory Report LBL-12455.
2. R.B. Meuser, S. Caspi, W.S. Gilbert, "Some Thermal-Mechanical Properties of a Film Insulated Superconducting Cable", LBL-12438, March 1981.
3. R. Meuser, S. Caspi, a series of reports relating to thermal stresses in orthotropic cylinders with interference fits, Lawrence Berkeley Laboratory Engineering Notes, M5698 M5543, M5537, M5153, M5104.



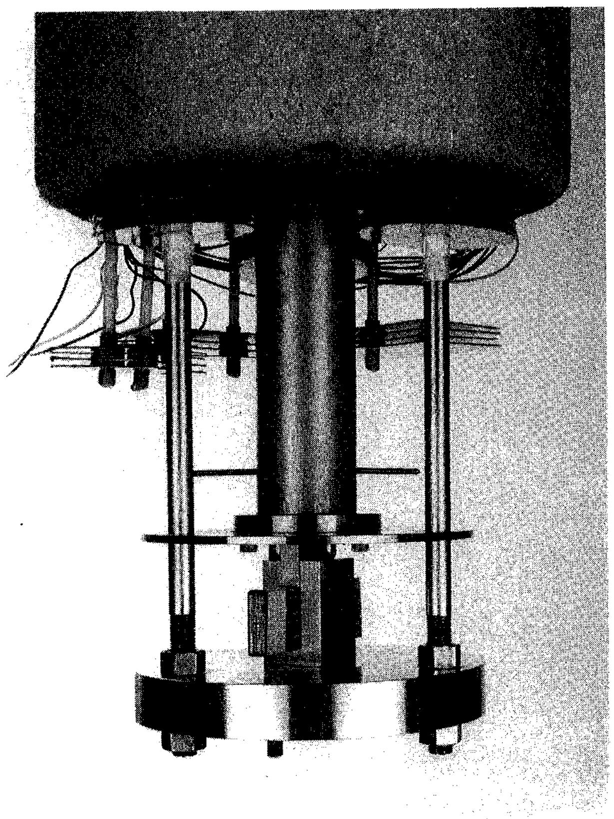
Mechanical facility for compression and thermal tests (400 to 4 K).



Sample, compression plunger, and strain measuring rods.



LVDT - transformer and core at upper end of strain measuring rods.



Closeup of sample in compression apparatus.