STRESS RELAXATION STUDIES OF CBA AND SSC COIL SECTIONS*

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M. Anerella, A. Hoffman, R. Jackimowicz, W. Lenz, J. Skaritka and L. Tuttle
Brookhaven National Laboratory
Upton, NY 11973

DE85 012265

Abstract

Instrumented fixtures were built to measure coil assembly stress and relaxation rates in samples of CBA and SSC coil sections. The effects of constant temperature and thermal cycling on short and long term relaxation are presented. Conclusions and suggestions are presented to achieve minimum long term stress relaxation during the assembly and installation of the SSC rings.

Introduction

Over the past 3 years investigations into the properties of superconductor coil composites have been carried out. This involved the measurement of coil stress in assemblies of CBA quarter coil creep fixtures, straight stack fixtures, and 1 ft. long full coil cross sections of CBA and SSC magnets.

Calibrated stress transducers consisting of strain gaged bars apply assembly stress to cable sections. In quarter coil creep fixtures, transducers were mounted on the top and bottom of the sample coils. In the full coil cross sections, transducers were placed in the top and bottom pole spacers for the inner and outer coils to assure redundancy in the stress measurement.

Coil creep relaxation is the reduction of stress in a coil assembly at constant overall strain. At high stress >10 KPSI, the elastic modulus of the CBA coil is 2×10^6 PSI. At these stresses very small displacements in conductor volume can produce large stress changes. Cable motion is distributed throughout the conductor stack. Relaxation occurs as interstitial voids between the cables fill with plastically displaced material.

Kapton becomes embossed by the conductor pattern as material is slowly extruded. Voids are filled with flowing plastic and the coil stack relaxation rate decays as further extrusion is resisted by the coil stack's own internal pressure.

Relaxation is not limited to the plastic components of the cable, since the conductors within the

The glass epoxy constituent of the cable aids in the distribution of the internal coil prestress as it cradles and protects the Kapton during cure and coil assembly. The contact stresses between the cables are decreased by the increased distributed contact area. It has been seen in cable stacks without glass that kapton extrudes into the crevices of the cable depleting the insulation thickness.

Procedures are available to reduce the initial relaxation. In studies where coils were assembled at initially high prestress, allowed to relax, and then reassembled at a lower prestress, it was found that short term relaxation rates decreased. This precreep-creeping procedure might be used in the coil assembly process to reduce long term relaxation in the magnet.

In large accelerators such as the SSC thousands of magnets will be built. Years will be required to install the magnets. Each of the magnets may have slightly different coil stresses due to long term creep relaxation. Generally, it is believed that a minimum prestress in the dipole of 9 KPSI on the inner coil and 6.5 KPSI on the outer coil is required to prevent the coil package from pulling away from the pole spacer at high fields. This is necessary to prevent magnet training as well as losing field quality.²

Experiments were devised to find what factors in the environment have the greatest effects on long term coil stress relaxation. Quarter coil creep fixtures were assembled with sections of CBA coils with Hexcel or Acme epoxy-impregnated glass.

Figure 1 shows samples placed at two temperatures. It was found that samples placed at 5°C had very little relaxation where samples placed at 35°C showed increased initial relaxation. When sample environments were switched, it was found that the initially warm sample with a high relaxation rate decreased its rate to a negligible amount. However samples which were initially cold showed a sizeable increase in relaxation rate even though the sample had been relaxing for about two weeks.³

Hexcel epoxy seems to be less susceptible to temperature changes than Acme epoxy although sizeable

rate decays as further extrusion is resisted by the coil stack's own internal pressure.

Relaxation is not limited to the plastic components of the cable, since the conductors within the cable have point to point contacts which will induce stress concentrations at the points where adjacent wires in the cable cross over each other.

As the stress increases during coil assembly, the conductors in the cable deform as individual yield points are reached. Progressive yielding occurs until the average stress in the coil stack is below the yield point of any of the individual cable constituents.

The amount of stress reduction is a function of the constituent yield points, the applied coil stress at constant strain, and the contact area of adjacent conductor surfaces. At constant temperature it has been seen that in CBA cross sections at prestresses >5 KPSI the percent relaxation is independent of the initial coil assembly stress.

The rate of stress relaxation is a function of the internal energy of the cable stack. As the temperature of a cable stack increases the viscosity of its components decrease. The yield points of the various cable components generally decrease.

This can easily be seen in any high temperature curing coil stack where an initially high curing stress in a closed mold is rapidly lost. Inspection of the coil after curing show conductor impressions in the Kapton and glass coil constitutes.¹

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increase in relaxation rate even though the sample had been relaxing for about two weeks.³

Hexcel epoxy seems to be less susceptible to temperature changes than Acme epoxy although sizeable effects did occur.⁴

A summary of these results is shown in Table 1. The results indicate that the magnets should not be exposed to temperatures above 30°C .

Samples were also stationed at LN_2 temperature. After initial relaxation due to differential thermal contraction between the coil and fixture no relaxation was detected.

Various tests have been performed involving straight stacks of different types of superconductor and insulations. Internally flattened cable sections show that conductor creepage as well as insulation creepage must be considered in stress relaxation. Since the internal flat increases the internal surface contact area of the cable, lower initial relaxation rates are achieved. Table 2 is a summary of the short term straight stack relaxation properties.

Sections of 1 ft. magnets were assembled. The coil sections were allowed to relax for several months at room and LN_2 temperatures. Calculations were made to determine how much prestress would be lost due to cool down: predicted values were $\sqrt{2}$ KPSI for inner coils and $\sqrt{4}$ KPSI for outer coils.⁵ It was found that typically $\sqrt{3}$ KPSI was lost in the inner coil and $\sqrt{4}$ KPSI in the outer coil upon cooldown.

The one ft. CBA coil sections were repeatedly cycled between -196°C and 20°C . It was found that an

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average of 300 PSI in prestress was lost after each temperature cycle. Figure 2 shows typical results of a CBA inner coil. Table 3 summarizes the results for several of the first CBA coil assemblies.

After reviewing the data of the 1 ft. assemblies and 1/4 coil creep results it was felt a new series of 1 ft. assemblies were required to determine the optimal environment to store CBA or SSC magnets for long periods of time. One foot CBA and SSC cross sections were placed at different temperatures after initial relaxation at room temperature. Figure 3 shows the typical initial assembly and long term relaxation characteristics of the CBA coil sections. Most coils had initial inner coil stresses of 12 KPSI and outer coil stresses of 6 KPSI.

Figure 4 shows in greater detail the typical long term relaxation of the above coil sections. It was found that the majority of the relaxation had occurred after 5 months with an 25-30% reduction in prestress. It was found that the stress in some sections would actually increase for several months and then decrease. This cycle effect seemed the most prevalent in coil sections stationed at room temperature and least with samples stationed at -28°C and -62°C. Coil sections which were stationed at -196°C did not have any long term relaxation.

It was observed after a year of data taking that higher stresses were recorded in the summer at constant temperature but highest humidity. The winter samples had as much as 1000 PSI less prestress than the summer samples. We found that by placing these samples into a vacuum vessel, possibly because the moisture was removed, the coil stress would decrease. Table 4 shows a summary of long term relaxation in CBA and SSC cross sections.

Figure 5 shows the relaxation characteristics of a typical SSC cross section that was enclosed in a vacuum after 6 months of room temperature relaxation. It can be seen that SSC stress relaxation is similar to CBA and that a drop in moisture content did decrease the coil stress.

Conclusions

It has been found that temperature greatly influences the relaxation characters of coil assemblies. High temperature thermal shocks may drastically increase the relaxation rate. Thermal cycling between -196°C and 20°C will in general decrease the coil prestress.

At cryogenic temperatures coil sections can be

perature should be kept to the absolute minimum to reduce random stress variations inside the accelerator magnets.

References

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Table I

1/4 Creep Fixture Weekly Percent Relaxation

Cured Coil Sections	1 Wk	2 Wks	3 Wks	4 Wks
Acme Coil 32°C	49.0	2.6	--	--
Acme Coil 20°C	33.0	1.9	--	--
Acme Coil 5°C	14.0	0.8	--	--
Hexcel Coil 32°C	22.0	4.0	--	--
Hexcel Coil 20°C	19.3	3.1	1.6	0.0
Hexcel Coil 5°C	14.1	0.0	0.5	0.5
Hexcel Coil -15°C	12.0	1.5	0.4	0.0
Hexcel Coil -196°C	0.0	0.0	0.0	0.0
Precreeep Hexcel Coil at 22°C	0.0	0.0	0.0	0.0

Table II

Straight Stack Weekly Percent Relaxation

Coil Sample At 20°C	1 Wk %	2 Wks %	3 Wks %
Uncured Glass & Kapton Wrapped Cable	56.0	13.6	5.3
Uncured Kapton Wrapped Cable	15.9	5.6	2.0
Uncured Coil Stack Interleaved With .008" Kapton	11.6	2.5	1.1
Cured Kapton Wrapped Cable Stack	9.6	2.3	1.4

ences the relaxation characters of coil assemblies. High temperature thermal shocks may drastically increase the relaxation rate. Thermal cycling between -196°C and 20°C will in general decrease the coil prestress.

At cryogenic temperatures coil sections can be held for years without stress relaxation.

Procedures can be used to reduce initial room temperature relaxation by precreeping the coil assemblies or by using initially flattened cable.

The majority of coil sections indicate that the exponential decay in coil stress will end after 5 months with an average of <30% stress reduction.

Humidity will effect long term coil stress by as much as 10% annually.

If the SSC magnet coils must have a long term minimum coil prestress of 9 and 6.5 KPSI prior to cool down magnets must have an initial assembly stress of 13 and 9.5 KPSI to compensate for long term relaxation.

Ideally coils should be stored at cryogenic temperature, but this may be impractical. However adequate coil stress could be maintained if the collared coil assembly would be stored in a refrigerated warehouse with controlled humidity. Throughout the storage and installation period a cool, dry environment should be provided avoiding any momentary high temperature thermal shocking such as a failure in warehouse air conditioning. This type of storage will assure greater uniformity in coil prestress throughout the accelerator. Once the accelerator is operating, thermal cycling to room tem-

Cable	56.0	13.6	5.3
Uncured Kapton Wrapped Cable	15.9	5.6	2.0
Uncured Coil Stack Interleaved With .008" Kapton	11.6	2.5	1.1
Cured Kapton Wrapped Cable Stack	9.6	2.3	1.4
Cured Glass & Kapton Wrapped Cable Stack	8.3	2.0	1.2
Cured Glass & Kapton Wrapped Nb ₃ SN Cable Stack	8.2	1.1	0.0
Bare Stack of NbTi Cable	9.9	0.7	0.0
Glass & Kapton Wrapped Cured NbTi Cable of Cables	8.6	1.5	0.7
Bare Stack of NbTi Cable of Cables	6.7	1.0	1.0
Glass & Kapton Wrapped Cured Internal Flat NbTi Cable	3.8	1.0	0.0
Bare NbTi Internal Flat Cable	1.0	0.9	0.8

Table III

Weekly % Relaxation of 1 Ft. CBA Cross Sections

1 Ft. Section	1 Wk	2 Wks	3 Wks	4 Wks	5 Wks
CBA LM 23 20°C	16.9	1.9	1.3	<0.5	<0.5
CBA LM 23 20°C	18.4	1.5	0.8	1.5	0.4
CBA LM 23 -196°C	1.5	0.0	0.0	0.0	0.0
CBA LM 23 -196°C	2.1	0.0	0.0	0.0	0.0

Table IV

% Relaxation of 1 Ft. CBA & SSC Cross Sections

Inner Coil Average Stress	$\bar{\sigma}_1$ Day	1 Wk	4 Wks	12 Wks	24 Wks	52 Wks
SSC 22°C	14.4*	14.4	16.1	20.4	25.2	--
CBA 22°C	11.2*	17.5	20.2	26.4	29.6	26.5
CBA 5°C	12.5	16.7*	18.1	18.8	21	22.4
CBA -28°C	12.0	17.7*	23.1	22.6	23.3	23.9
CBA -62°C	16.4	22.1*	28.2	26.4	26.4	25.2
CBA -196°C	10.2	16.4*	39.4	39.4†	54.9	54.0
Non-Cryo- Average	12.8	17.4	21.1	22.9	25.1	24.5
Seasonal Fluctuation ± 5 KPSI						
*Stationed at constant long term temperature.						
†Warmed up and cooled down again.

Fig. 1. Effects of temperature reversal on CBA 1/4 coil sections.

Fig. 2. Effects of repeated cooldown on CBA inner coil stress.

Fig. 3. Initial relaxation of CBA coil sections.

Fig. 4. Long term relaxation of CBA coil sections.

Fig. 5. Relaxation of SSC coil section.