Fermi National Accelerator Laboratory

FERMILAB-Conf-99/052

Investigation of Cable Insulation and Mechanical Properties of Niobium-Tin Composite

D.R. Chichili, T.T. Arkan and I. Terechkine

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

April 1999

Presented at the *Particle Accelerator Conference*,
New York, New York, March 29-April 3, 1999

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy

Investigation of Cable Insulation and Mechanical Properties of Niobium-Tin Composite*

D.R. Chichili+, T.T. Arkan, I. Terechkine, Fermilab, Batavia, IL, USA

Abstract

As a part of the Fermilab high field Nb_3Sn dipole development program, various issues of magnet technology are being investigated. In cable insulation development, S-2 fiber glass sleeve and a new ceramic insulation developed by Composite Technology Development Inc. (CTD) were studied as a possible candidates. For each type of insulation, Nb_3Sn ten-stack samples were reacted and then vacuum impregnated with epoxy. Measurements of modulus of elasticity and Poisson's ratio under compression were made at room temperature and at 4.2 K. For comparison, an epoxy impregnated NbTi composite was also tested.

1.0 INTRODUCTION

Fermilab, in collaboration with LBNL and KEK, is developing a high field Nb_3Sn dipole for use in the next generation Hadron Collider. The conceptual design for the first magnet, detailed elsewhere [1], is based on a 2-layer $\cos\theta$ coil structure and cold iron yoke. As a part of this program, various issues of the magnet technology such as cable insulation, epoxy impregnation and thermo-mechanical properties of the composite are being investigated.

2.0 SAMPLE PREPARATION

2.1 Cable Parameters

A summary of Nb_3Sn and NbTi cable parameters used in the present study are given on Table 1. The variation of Nb_3Sn cable mid-thickness with pressure before and after reaction is shown in Fig. 1. The cable mid-thickness increased with reaction and decreased with pressure [2]. On the other hand, the cable length contracted by about 4.5 μm/mm and the cable width increased from 14.232 mm to 14.669 mm due to reaction. Note that these later measurements are taken on a free standing cable.

Table 1: *Cable Parameters*

	Nb_3Sn	NbTi
Number of Strands	28	38
Strand diameter	1.012 mm	0.808 mm
Cable Thickness	1.7852 mm	1.4573 mm
Cable Width	14.232 mm	15.3943 mm
Keystone angle	0.91 deg.	1.038 deg.

* Work supported by the U.S. Department of Energy

+ Email: chichili@fnal.gov

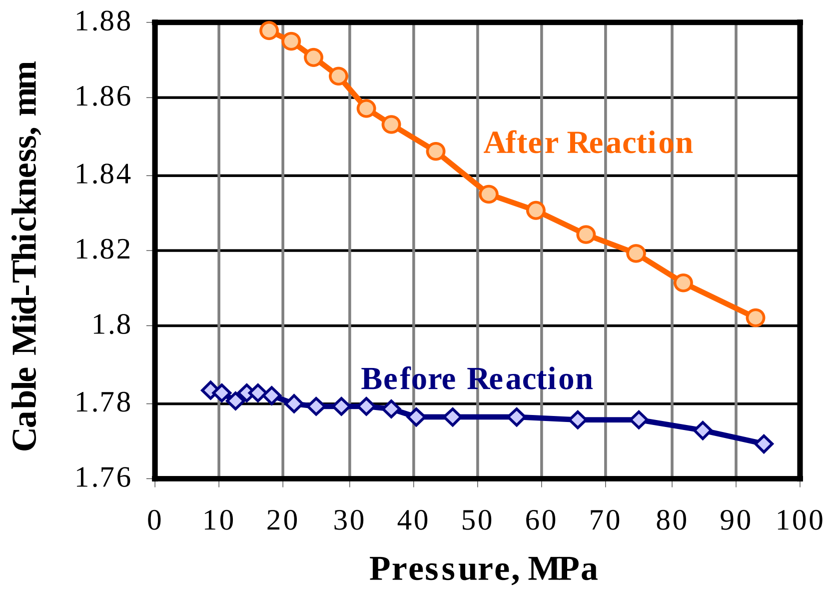

Figure 1: *Variation of cable mid-thickness with pressure before and after reaction.*

2.2 Cable Insulation

The most common insulation material used for Nb_3Sn cables is S-2 fiber glass either in tape form or sleeve [3,4]. In the present work, we investigated S-2 fiber glass sleeve and a new ceramic insulation.

The organic binder used on the S-2 fiber glass sleeve which provides protection/lubrication for the glass strands during processing left a carbon residue during reaction under argon atmosphere. This could create turn to turn shorts in the coil. So the sleeve was first heat-treated at 450 °C in air to remove the binder and a different binder was applied that would not leave much carbon residue during reaction [4,5].

Ceramic tape on the other hand does not have any organic sizing. The binder (CTD-1002x) which is applied to the tape is also inorganic and can be used to preform the coils in shape before reaction by curing at 120 °C for 30 min. Hence with the binder we can have a insulated and cured coil before reaction which helps to define the coil shape. This also makes the coils easier to handle. We tested two processes of using ceramic tape, the first process consists of insulating the cable with pre-pag tape and then curing. Note that in pre-pag form, ceramic fiber comes with binder. In the second process the cables were insulated with dry ceramic tape and then vacuum impregnated with binder and finally cured. In the first method we do not require the impregnation process, however it is difficult to insulate the cable with pre-pag tape as it is wet. After reaction the ten-stack samples for both processes remain bonded together, however the binder became porous and formed crystals due to shrinkage (see Fig. 2). Note that the amount of crystals formed with the pre-pag tape is much less than for the sample which was impregnated with binder. The process that will be adopted for the first model dipole will be to use the dry tape and to paint and/or spray the binder after winding each turn. This will not only allow us to use the existing tooling for cable insulation but also eliminate the process of vacuum impregnation of binder which leads to formation of large amounts of crystals. Further the micrographs in Fig. 2 show that the crystals are black in color; this is because the cables were not cleaned prior to the reaction and the lubrication oil on the cables formed carbon residue during the heat-treatment cycle in argon atmosphere. Hence we need to clean the cable before insulating it to remove any residue left on it during cabling process. Finally the formation of porous crystals is infact useful as it allows the epoxy to penetrate during impregnation.

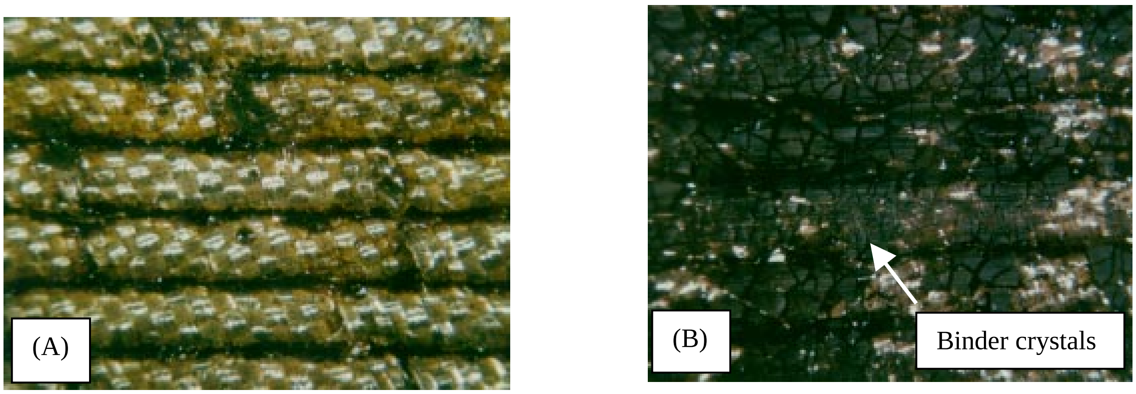

Figure 2: *Micrographs showing the edge view of the ten-stack samples (a) with pre-pag tape and (b) with dry tape and then vacuum impregnated with binder.*

The variation of the insulated cable thickness with pressure before and after the reaction is shown in Fig. 3. Cured four stack samples were used to make these measurements. Comparing with Fig. 1, it is clear that there is no observable variation in the insulation thickness with pressure as it is primarily due to the cable itself.

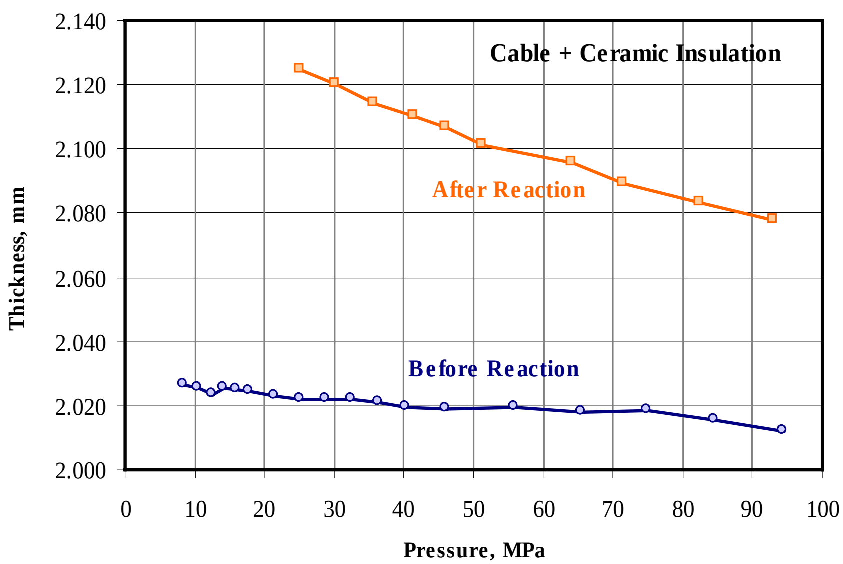

Figure 3: *Variation of insulated cable thickness with pressure before and after reaction.*

2.3 Epoxy Impregnation

Insulated ten-stack samples were first reacted and then vacuum impregnated with epoxy. Note that the samples were compressed with a pusher block during impregnation and the effect of this impregnation pressure on the mechanical behavior was also investigated. For epoxy impregnation, we investigated two epoxy systems, DMP-30 and CTD-101K. The mechanical properties of the composite with both the epoxies were found to be similar, however CTD-101K has higher pot life than DMP-30. All the results presented in this paper are with the samples impregnated with CTD-101K. Readers are referred to [6,7] for more detailed description on epoxy impregnation procedure and comparison's between two epoxies. Fig. 4 shows an epoxy impregnated composite with direction convention used in this paper.

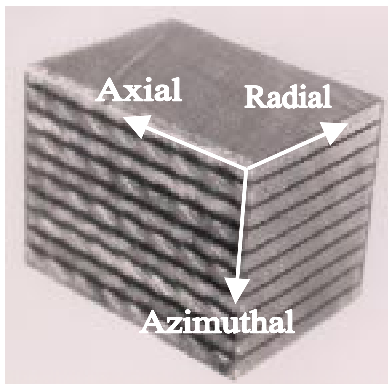

Figure 4: *Epoxy impregnated composite.*

3.0 MECHANICAL PROPERTIES

Strain gauges were mounted to measure strains both in the direction of load and transverse to the direction of the load to obtain modulus of elasticity and Poisson's ratio. A calibrated load cell was used to record the force applied on the sample. To validate the testing fixture and strain gauge mounting technique, elasticity modulus of 6061-T651 aluminum and ULTEM 2300 were measured and compared with published literature. Table 2 lists these values. Note that the measured values compare well with the published data.

Table 2: *Modulus data for 6061-T651 and ULTEM 2300*

MATERIAL	MEASURED	PUBLISHED DATA
6061-T651	68.5 GPa	70.0 GPa
ULTEM 2300	6.7 GPa	6.5 GPa

Mechanical properties of the Nb_3Sn and NbTi composite were measured along all the three directions; azimuthal, axial and radial. Identical tests were done on more than one sample to check the repeatability. Fig. 5 shows the repeatability test results for an epoxy impregnated

Nb_3Sn composite with S-2 fiber glass insulation. The data shows that the results are quite repeatable.

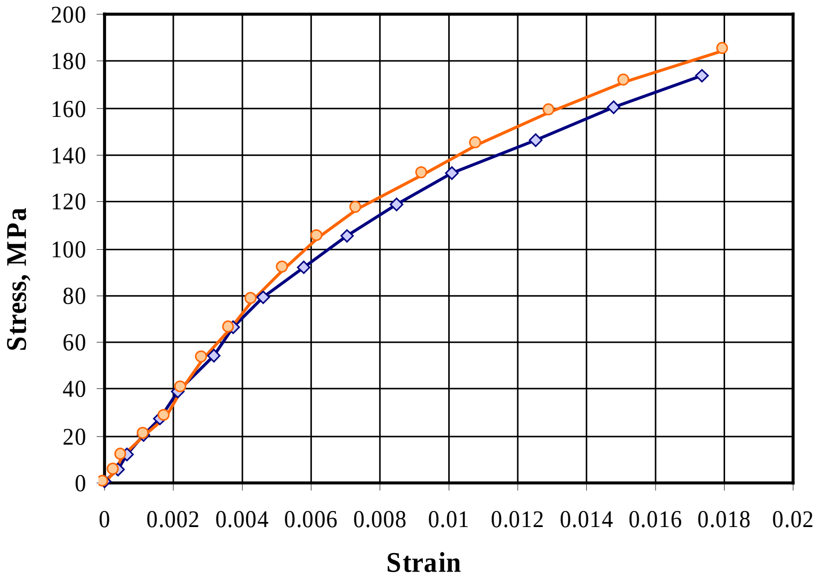

Figure 5: *Repeatability tests*.

Both monotonic and load-unload-reload tests were performed at 300 K and at 4.2 K and the test results are discussed below.

3.1 Azimuthal Direction: Monotonic Loading

Fig. 6 shows the test results at room temperature. Note that the Nb_3Sn composite exhibits non-linear behavior in contrast to the linear behavior observed for NbTi composite. This behavior of Nb_3Sn composite was first thought to be due to low impregnation pressure (10 MPa) compared to NbTi composite (45 MPa). To test this hypothesis, another Nb_3Sn composite was fabricated at higher impregnation pressure (45 MPa) and tested. The results shown in Fig. 7 show that the mechanical response in azimuthal direction does not depend on impregnation pressure. Note that this pressure is the mechanical pressure applied on the sample, not on the epoxy.

Fig. 6 also shows the behavior of the Nb_3Sn stack with ceramic insulation which was cured, reacted but not impregnated. The modulus of this composite is about 3.5 GPa. The initial idea was not to impregnate the coils because with ceramic insulation and binder we could cure the sample, which would form a solid coil. This idea was abandoned as the modulus of the composite is too low.

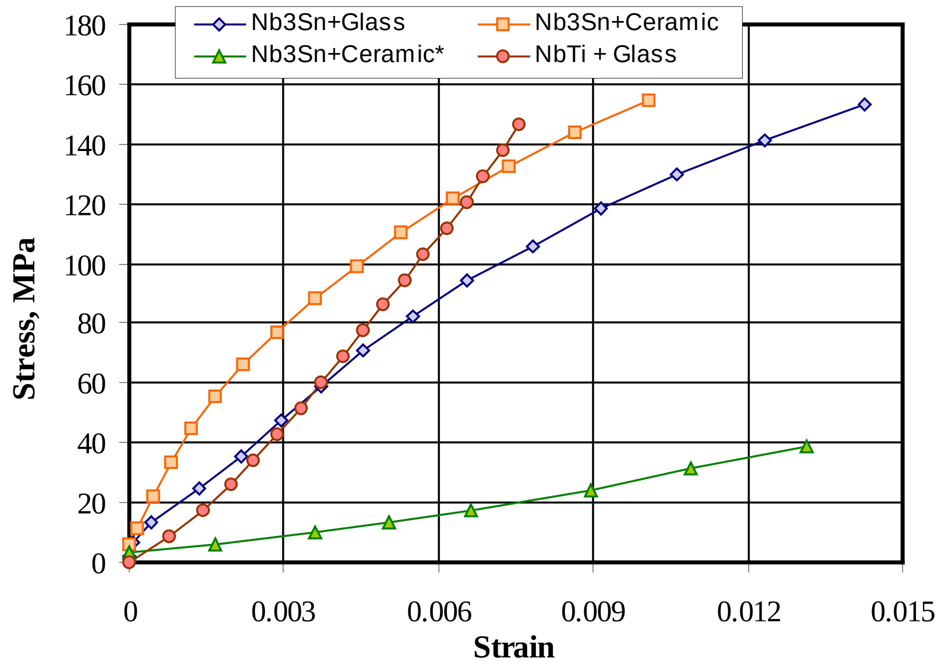

Figure 6: *Mechanical behavior at room temperature.(*Nb_3Sn stack with ceramic insulation cured and reacted; but not impregnated).*

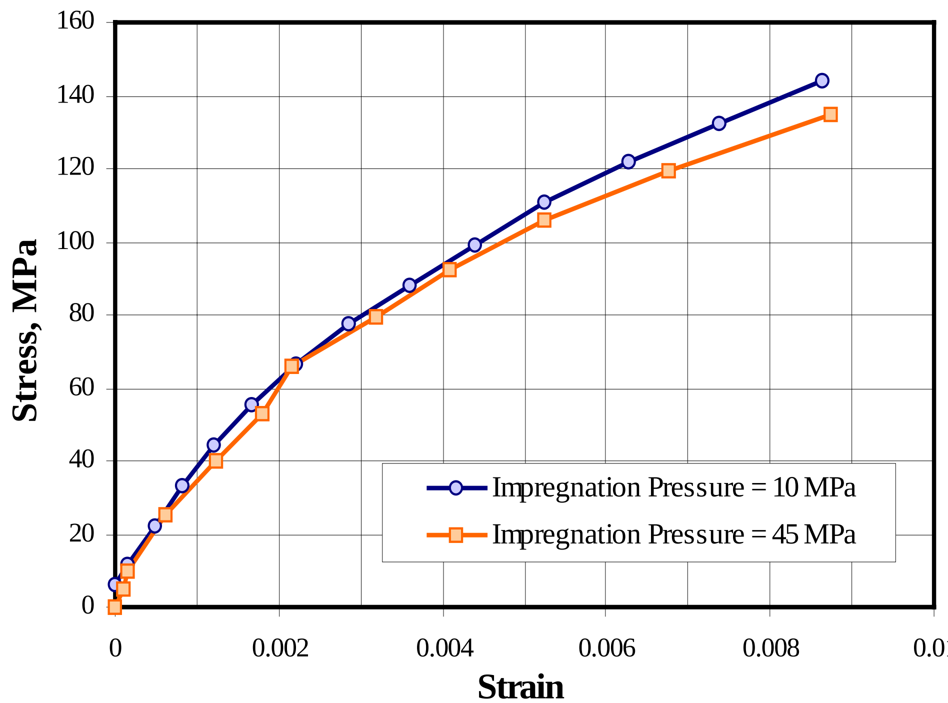

Figure 7: *Effect of impregnation pressure on the mechanical behavior of the Nb_3Sn composite with ceramic insulation.*

Figs. 8 and 9 show the Poisson's ratio measurements for Nb_3Sn composite with ceramic insulation and S-2 Fiber Glass insulation. The loading direction azimuthal direction, and strain in all the three directions were measured using strain gauges. Note that the Poisson's ratio in azimuthal-axial direction is smaller than azimuthal-radial direction.

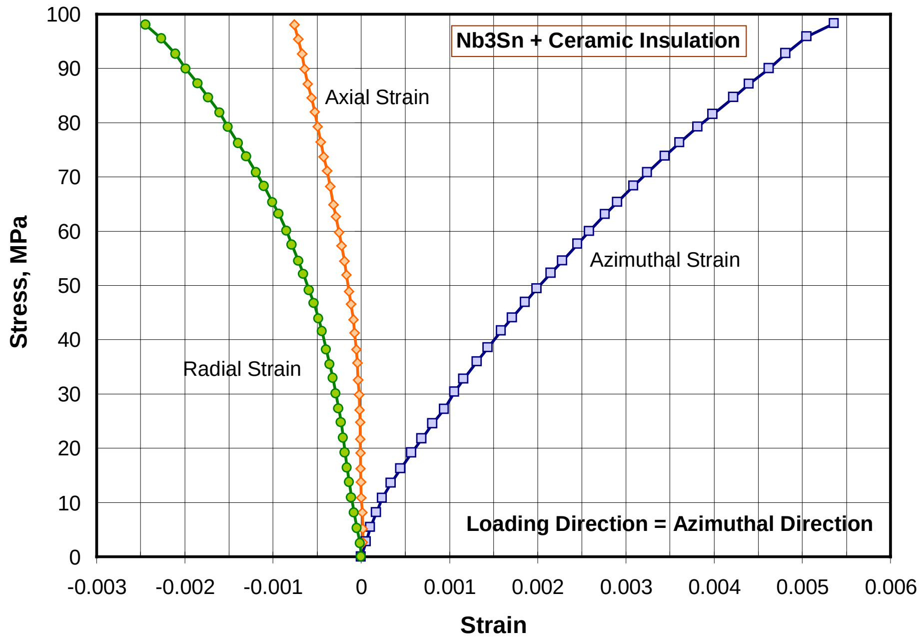

Figure 8: *Poisson's ratio measurements for Nb_3Sn composite at room temperature.*

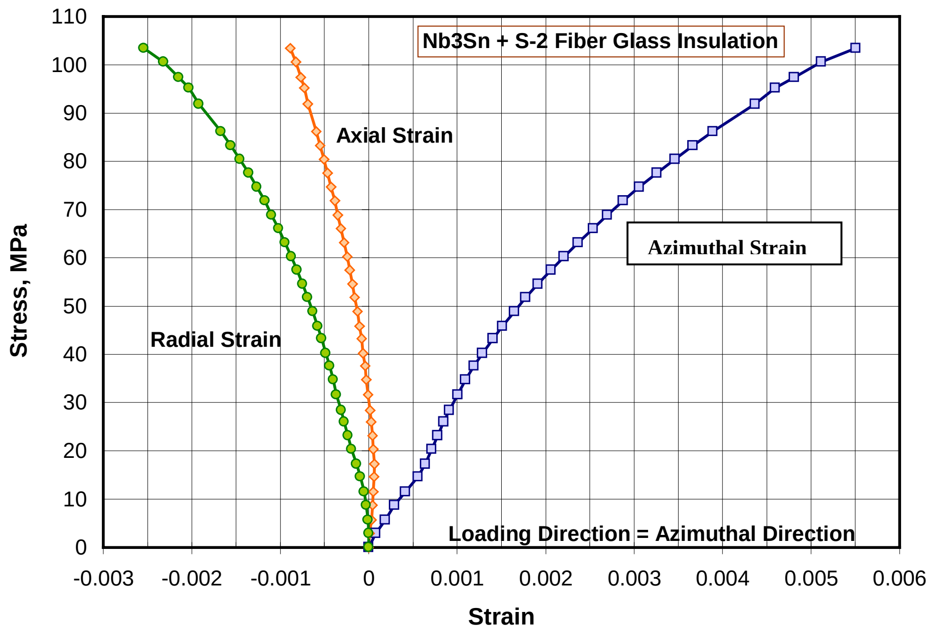

Figure 9: *Poisson's ratio measurements for Nb_3Sn composite at room temperature*

The effect of temperature on the mechanical response of Nb_3Sn composite is shown in Figs. 10 and 11. There is significant increase in the modulus for Nb_3Sn composite with S-2 glass. However with ceramic insulation, the modulus did not change with temperature except that the composite behavior is more linear at 4.2K than at 300K. This behavior was very repeatable and even the load-unload-reload tests (see next section) show this behavior.

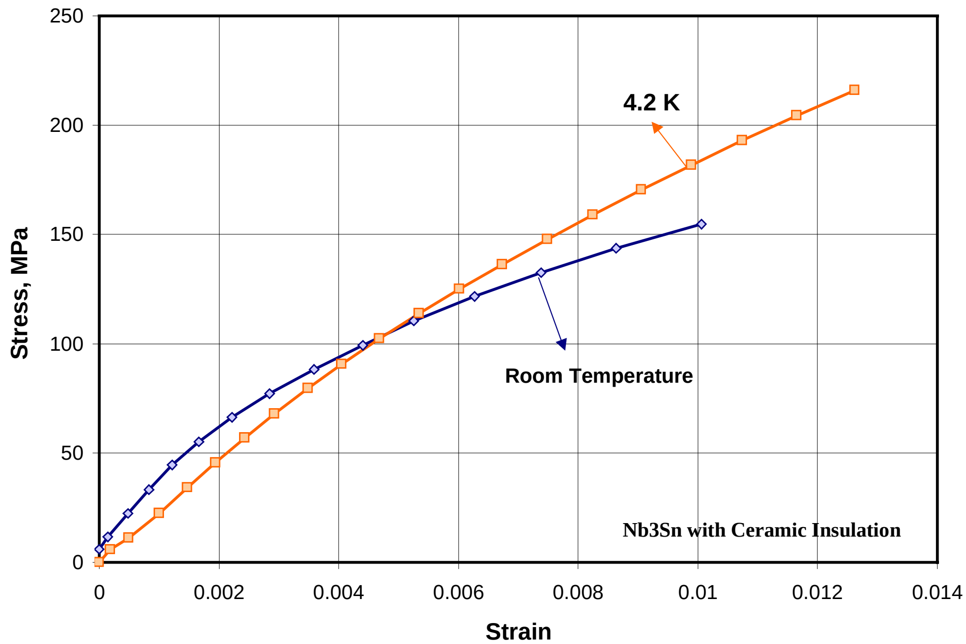

Figure 10: *Effect of temperature on the behavior of Nb_3Sn composite with ceramic insulation.*

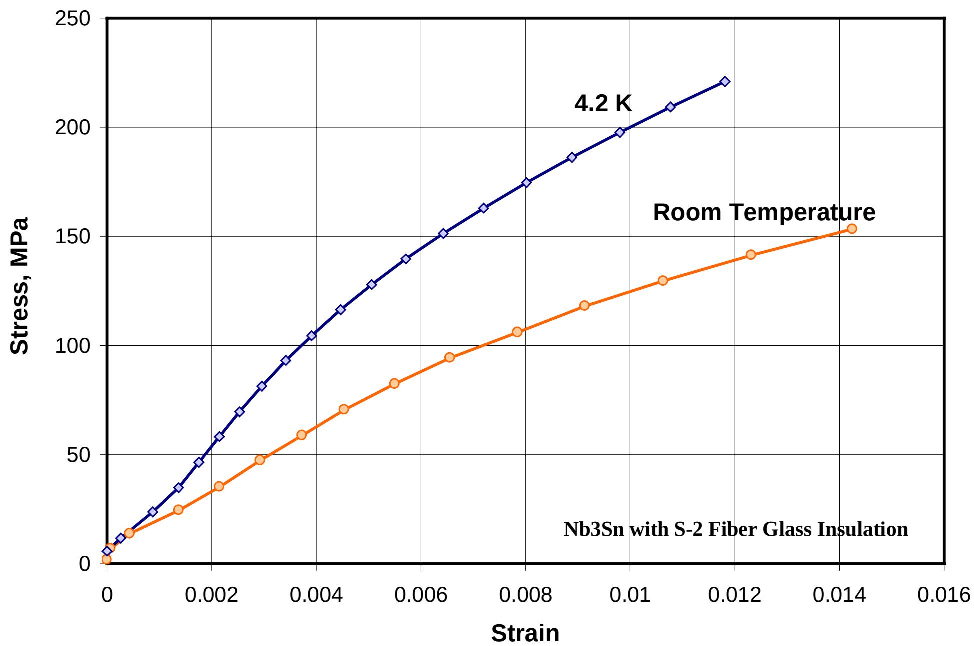

Figure 11: *Effect of temperature on the behavior of Nb_3Sn composite with S-2 Glass.*

3.2 Azimuthal Direction: Load-Unload-Reload Tests

The coils in a magnet are subjected to loading, unloading and reloading repeatedly during assembly, cool-down and excitation. Hence it is very important to understand the mechanical behavior of the composite under these loading conditions. Fig. 12 shows load-unload-reload test results for Nb_3Sn composite with ceramic insulation both at 300K and at 4.2K. The following observations can be inferred from these results (i) the overall behavior of the composite under loading is similar to that under monotonic loading, (ii) there is no apparent change in modulus by decreasing temperature.

Similar load-unload-reload experiments were conducted for the Nb_3Sn composite with S-2 glass insulation. The mechanical behavior was found to be similar to that with ceramic insulation except that the modulus increased with decreasing temperature.

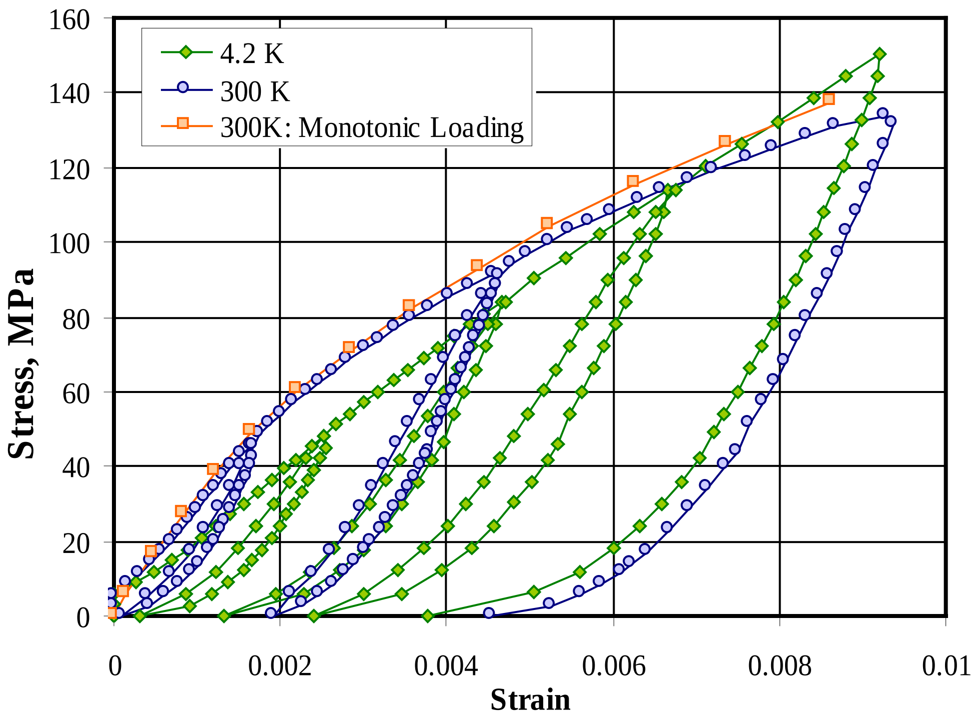

Figure 12: *Load-unload-reload tests for impregnated Nb_3Sn composite with ceramic insulation.*

Figs. 13 and 14 shows the behavior of the Nb_3Sn composite with ceramic insulation and S-2 glass insulation under cyclic loading after initial "massaging" to 100 MPa. These results show that we could massage the coils up to a peak stress before assembly, which would then result in a composite with higher modulus and a linear mechanical behavior. However this massaging leads to a plastic deformation of 0.3% in the composite which should be taken into account while designing the magnet cross-section.

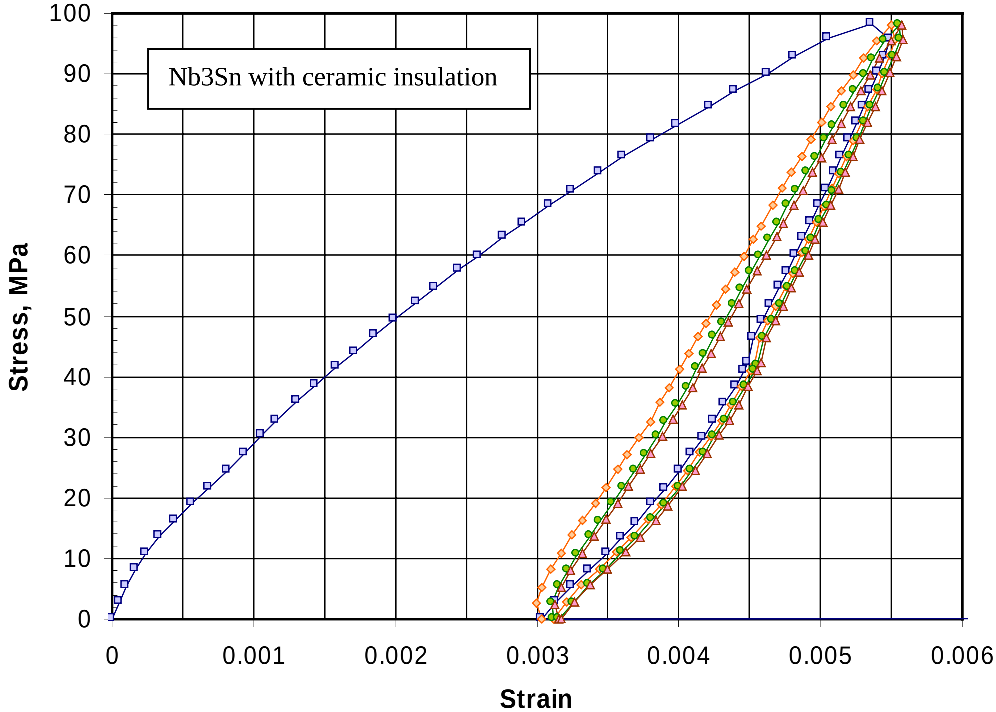

Figure 13: *Cyclic loading tests after initial massaging up to a certain stress.*

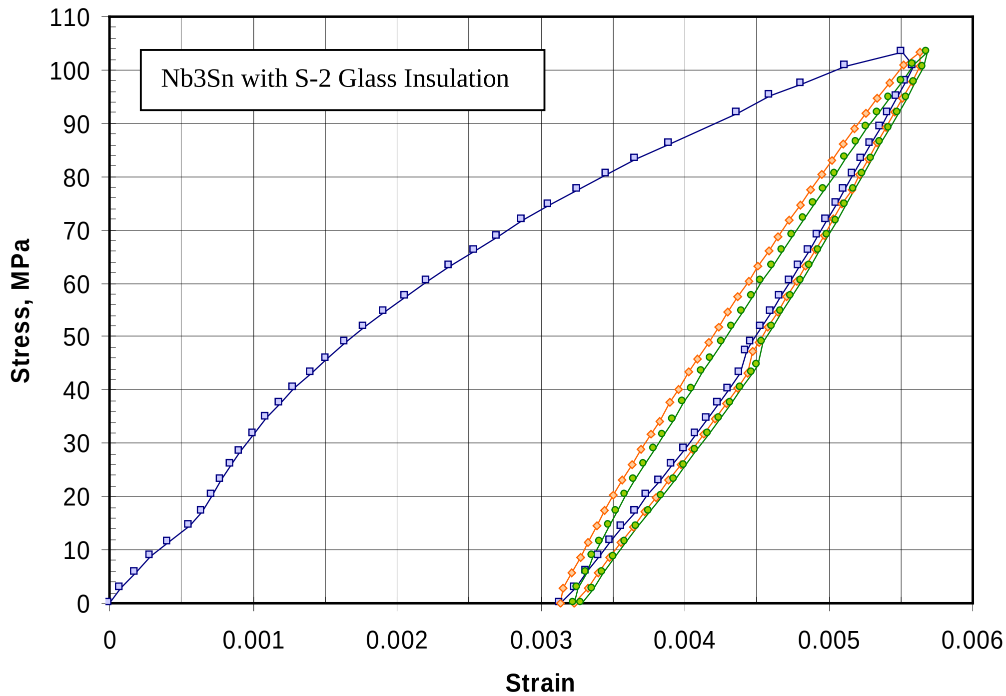

Figure 14: *Cyclic loading tests after initial massaging up to a certain stress*

The Poisson's ratio measurements for the second loading cycle is shown in Fig. 15. Note that the Poisson's ratio remained constant in the axial direction from the first cycle to the second cycle at 0.14, however in the radial direction it decreased from 0.45 to 0.33.

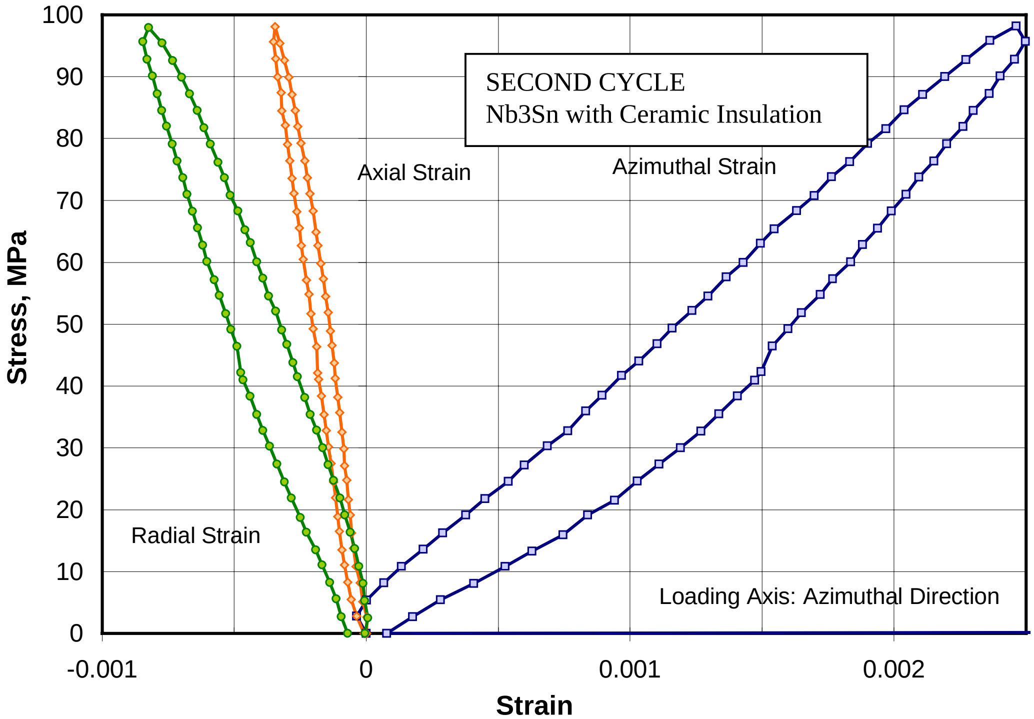

Figure 15: *Poisson's ratio measurements for the second cycle.*

The results from the previous tests show that for the first short model we should massage the coils upto a peak stress before assembly which would then increase the modulus with linear mechanical behavior. If we had to follow the loading, unloading history of the coils in a magnet, the coils would be initially massaged to certain peak stress at room temperature, then reloaded at room temperature during magnet assembly, further loaded during cool down, unloaded during excitation at 4.2 K and then reloaded during warm up. To duplicate these conditions, a ten-stack sample was put through four cycles under different loading and unloading conditions; the first cycle was initial massaging at room temperature to 100 MPa, the second cycle was re-loading and unloading at room temperature, third cycle at 4.2 K and fourth cycle back at room temperature. Figs. 16 and 17 show these test results. The behavior is quite linear after initial massaging with some hysteresis both at 300K and at 4.2K. Further the reloading moduli at 300 K and at 4.2 k are identical. However, during the third cycle both the samples underwent plastic deformation on the order of 0.06%. This deformation should be included during analysis as it reduces the stress in the coil at 4.2 K. One way to take this into account is to increase the thermal contraction coefficient of the composite by 0.06%.

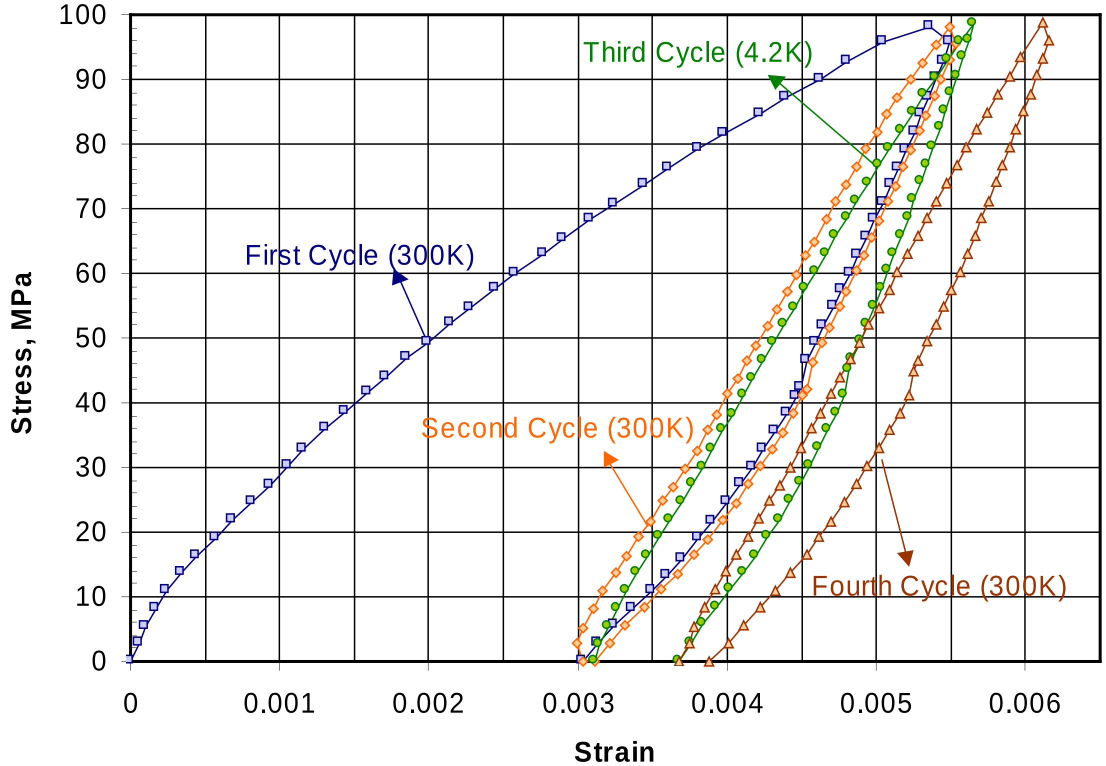

Figure 16: *Mechanical behavior of Nb_3Sn composite with ceramic insulation under various loading conditions.*

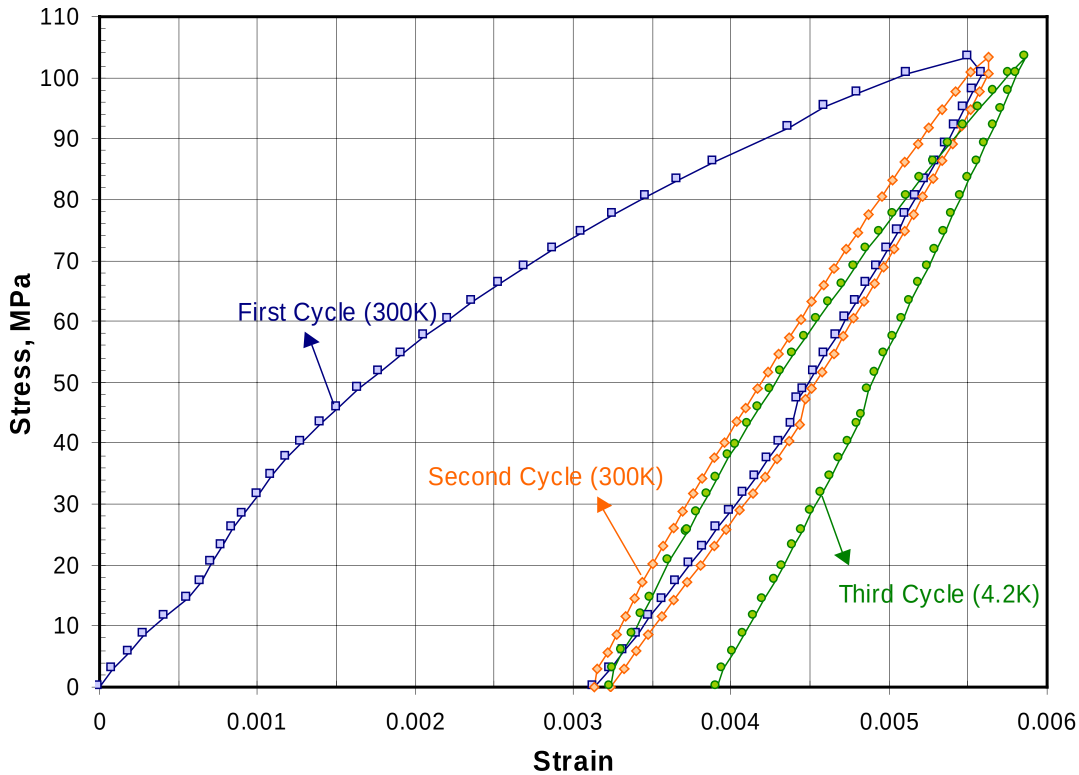

Figure 17: *Mechanical behavior of Nb_3Sn composite with S-2 glass insulation under various loading conditions*

3.3 Axial Direction

Fig. 18 shows the mechanical response of Nb_3Sn composite with ceramic and S-2 fiber glass insulation along axial direction at room temperature. The behavior is quite linear unlike in the azimutal direction and is similar with both insulation materials.

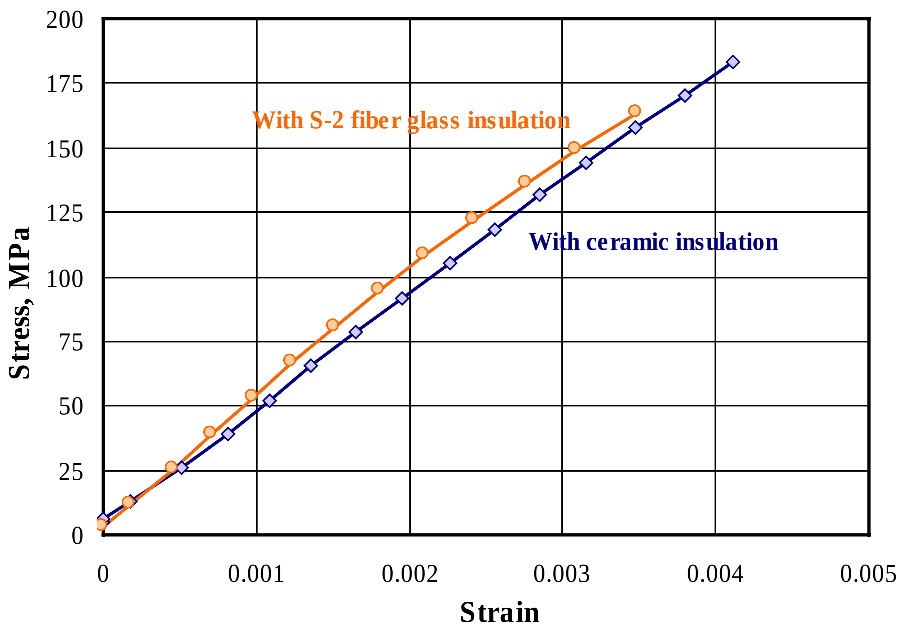

Figure 18: *Mechanical response of the Nb_3Sn composite in the axial direction.*

The effect of temperature on the mechanical response of the composite with fiber glass and ceramic insulation in the axial direction is shown in Figs. 19 and 20 respectively.

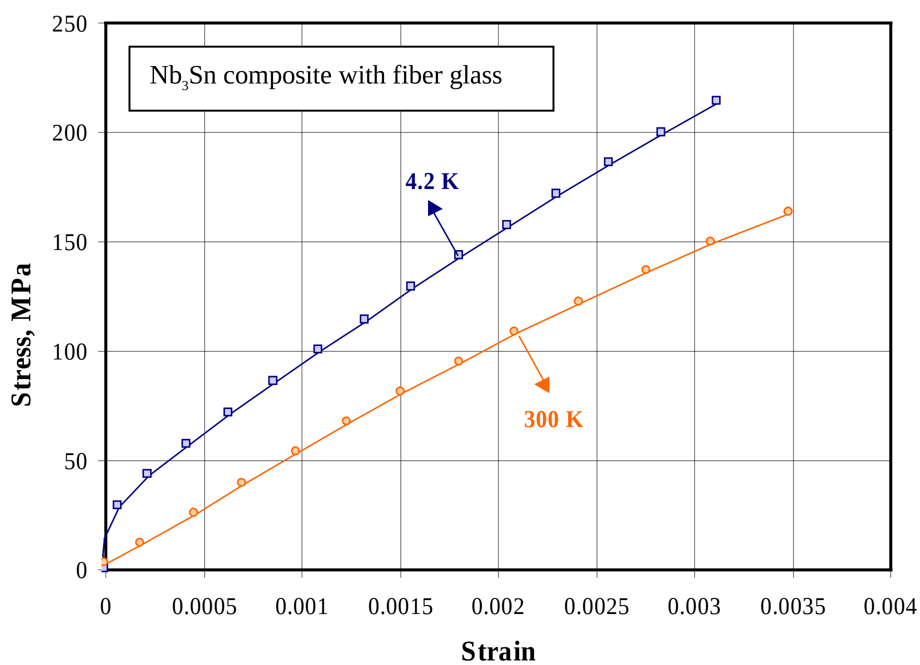

Figure 19: *Effect of temperature for Nb_3Sn composite with S-2 fiber glass insulation.*

Fig. 19 shows that the modulus of elasticity of an impregnated composite with S-2 fiber glass insulation increases with decreasing the temperature. However for the composite with ceramic insulation (Fig. 20) the modulus did not change at very low strains, but if the slope of the curve at higher strains is considered there is certainly an increase in modulus with decreasing temperature.

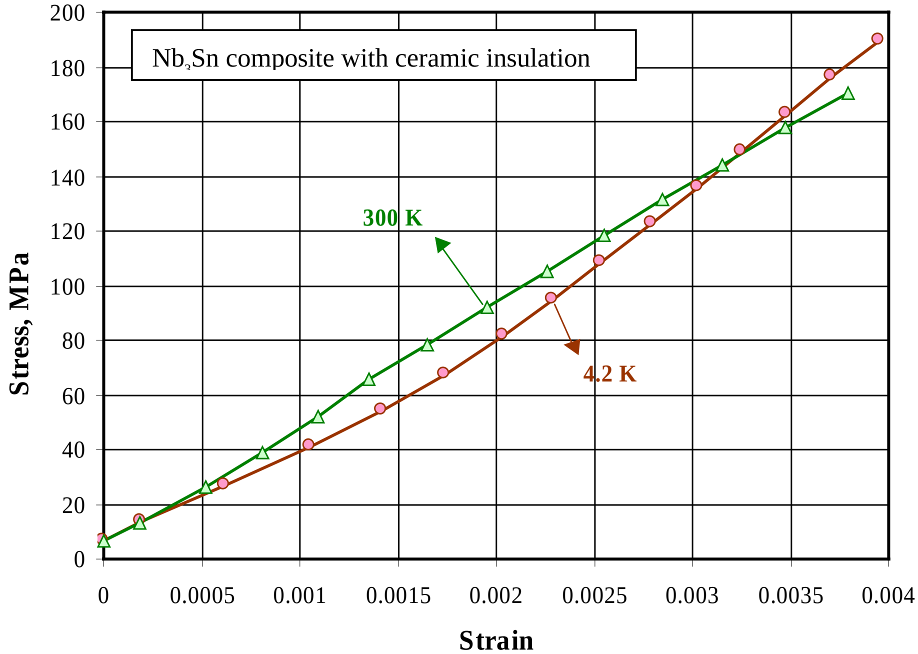

Figure 20: *Effect of temperature on the mechanical response of the composite with ceramic insulation.*

3.4 Radial Direction

Fig. 21 shows the mechanical response of Nb_3Sn composite with ceramic and S-2 fiber glass insulation along radial direction at room temperature. Note that the modulus of the composite with ceramic insulation is much higher than that with fiber glass insulation. Also shown in the figure is the response of the ten-stack with ceramic insulation which has been cured and reacted but not impregnated. The cured coils will be stiff enough to handle easily during fabrication and assembly, but it is not sufficient to handle the excitation forces and hence the need for impregnation.

It is usually expected that the elasticity modulus along axial and radial directions to be similar since the conductor controls the overall mechanical behavior assuming no delimitation under pressure. This is unlike in azimuthal direction where the epoxy and insulation material also effects the overall stiffness of the composite. However the present measurements show that the composite is much stiffer in axial direction than in radial direction. It is possible that under compression, the composite starts to delaminate in the radial direction much earlier than in axial direction. The exact reasons for this behavior still needs to be investigated.

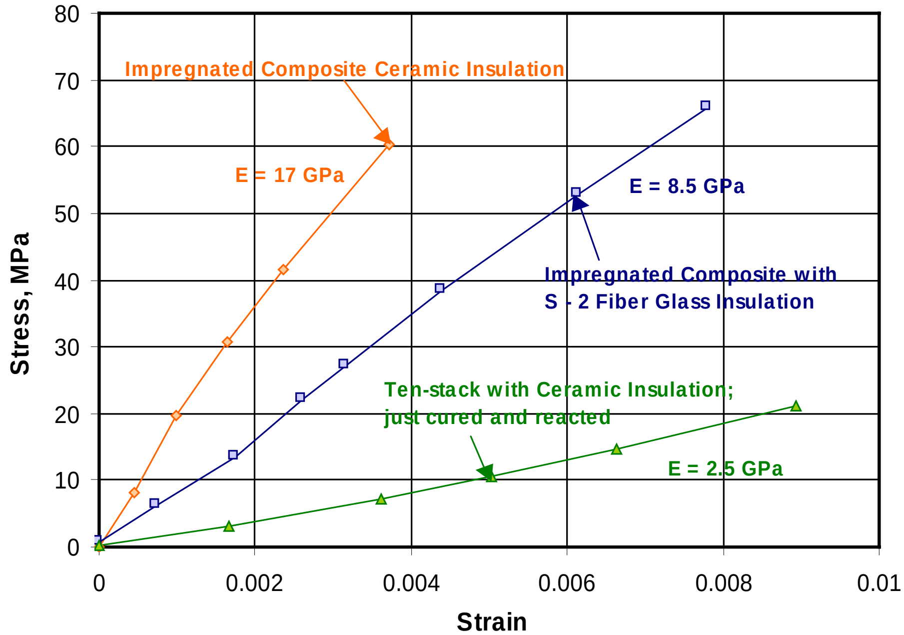

Figure 21: *Mechanical response of the composite along radial direction.*

4.0 SUMMARY

In the past year, we have been able to setup the infrastructure to study the various issues of Nb_3Sn magnet technology at Fermilab. Mechanical characteristics of the cable, insulation materials, epoxy impregnation, mechanical properties of the impregnated composite have been investigated. In cable insulation development, ceramic insulation by CTD seems to be promising new development which simplifies the tooling requirements as it makes the coils easier to handle by curing them before reaction.

The mechanical properties of the impregnated composite were investigated extensively. These properties are very essential to design and analyze the mechanical support structure for the magnet. Table 3 summarizes the mechanical properties in azimuthal direction under monotonic loading for different composites tested. At room temperature, the behavior is nonlinear and hence two moduli are specified, one at low pressures and the other at higher pressures. Included in the table also are the data reported by LBNL[4,8] and University of Twente [3]. The moduli of the composite tested here are much lower than that reported by LBNL and higher than that measured at [3]. These differences in the data quoted here and else where in the literature are not understood yet.

Table 4 provides the data in azimuthal direction for Nb_3Sn composite after massaging to 100 MPa. The idea is to massage the impregnated coils upto a peak stress before assembly which would then increase the modulus to 38 GPa both at 300K and at 4.2K with linear mechanical behavior.

Table 3: *Mechanical properties in azimuthal direction under monotonic loading* (* at low strains, + at high strains).

Composite	E, GPa		Poisson's Ratio
	300K	4.2K	
Nb_3Sn + S-2	17.5* 6.5+	26.0* 14.0+	$\nu_{21} = 0.16$ $\nu_{23} = 0.46$
Nb_3Sn + ceramic	27.0* 10.0+	22.0* 14.0+	$\nu_{21} = 0.14$ $\nu_{23} = 0.45$
NbTi + S-2	20.0	32.0	$\nu_{23} = 0.29$
Nb_3Sn + S-2 [4]	35.0		
Nb_3Sn + S-2 [8]	44.0		
Nb_3Sn + S-2 [3]	2 to 5		

Table 4: *Mechanical properties in azimuthal direction after massaging to 100 MPa*.

Composite	E, GPa		Poisson's Ratio
	300 K	4.2K	
Nb_3Sn with S-2 Glass	39	40	ν_{21}= 0.15; ν_{23}= 0.34
Nb_3Sn with ceramic	38	38	ν_{21}= 0.14; ν_{23}= 0.33

Table 5 shows the data along axial and radial direction.

Table 5: *Mechanical properties in axial and radial directions*

Composite	E (axial), GPa		E (radial), GPa
	300 K	4.2 K	300 K
Nb_3Sn with S-2	47	56	8.5
Nb_3Sn with ceramic	44	55	17
Nb_3Sn with S-2 [8]	56		53

The next step is to measure the thermal contraction coefficient of these composites. Two different fixtures are presently being designed and the experiments are expected to be completed by the end of April/May 1999.

ACKNOWLEDGMENTS

The authors would like to acknowledge helpful discussions with J. Hoffman regarding the epoxy impregnation, with J.A. Rice of Composite Technology Development Inc. regarding ceramic insulation and the members of Technical Division, Fermilab for their continued assistance.

REFERENCES

[1] T. Arkan et al., "Conceptual Design of the Fermilab Nb_3Sn High Field Dipole Model", PAC, NY (1999).

[2] I. Bogdanov et al., "Study of the Nb_3Sn Cable Characteristics for SC - Quadrupole with High Gradient", MT-15, Beijing, (1997).

[3] A. den Ouden et al., "An Experimental 11.5 T Nb_3Sn LHC Type of Dipole Magnet", IEEE Transactions of Magnetics, Vol. 30 (1994).

[4] D.Del'Orco et al., "Fabrication and Component Testing Results for a Nb_3Sn Dipole Magnet", IEEE Trans. of Applied Superconductivity, Vol. 5 (1995).

[5] T.Arkan et al., "Studies on S-2 Fiber Glass Insulation", Fermilab Technical Division Report, TD-98-063 (1998).

[6] D.Chichili et al., "Epoxy Impregnation of Ten-Stack NbTi cables with S-2 Fiber Glass Insulation", Fermilab Technical Divison Report, TD-98-059, 1998.

[7] D.Chichili, "Mechanical Properties of Epoxy Impregnated NbTi composite", Fermilab Technical Divison Report, TD-98-064, 1998

[8] K.Chow et. al., "Measurements of Modulus of Elasticity and Thermal Contraction of Epoxy Impregnated Niobium-Tin and Nb-Ti Composites", presented at ASC, Palm Desert CA (1998).