COMPOSITE TECHNOLOGY DEVELOPMENT, INC.

ENGINEERED MATERIAL SOLUTIONS

Final Report:

Princeton Plasma Physics Laboratory Test Program to Determine the Mechanical and Thermal Properties of the Epoxy/Insulation System for the NCSX Modular Coils

Subcontract S-04353-G

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Introduction

This report provides the final results of the mechanical and thermal testing performed for Princeton Plasma Physics Laboratory (PPPL) by Composite Technology Development, Inc. (CTD) during June – October 2003. The test program was undertaken to determine the mechanical and thermal properties of the epoxy/insulation system for the National Compact Stellarator Experiment (NCSX) modular coils. This test program was carried out in conjunction with, and under the direction of, PPPL. PPPL fabricated all test specimens, and CTD performed all test specimen preparation, including minor specimen machining, application of strain gages where necessary, strain gage wiring, specimen inspection, and assignment of specimen identification numbers, and testing. Testing consisted of cure shrinkage tests on the chosen epoxy vacuum impregnation resin system, CTD-101K, mechanical tests on insulated single modular coil and 2x2 modular coil bundle specimens, and thermal expansion tests on single modular coil specimens and individual turn and ground insulation specimens.

Test Procedures and Results

Cure Shrinkage Tests

Cure shrinkage tests were conducted to determine the amount of shrinkage that the CTD-101K epoxy resin system undergoes as it gels and cures from a liquid resin state to a solid state, using the same cure cycle to be used in the modular coil. The chemical reactions that occur when a thermosetting resin system cures usually result in a reduction of resin volume. While some shrinkage may occur prior to gelation (initial hardening) of the resin, this test only measured the shrinkage occurring after gelation and full cure of the epoxy resin.

This test was performed according to ASTM test standard D2566, "Linear Shrinkage of Cured Thermosetting Casting Resins During Cure." The test used a half-cylinder shaped steel mold, shown in Figure 1, that is approximately 10.0-in.hes in length, with a nominal inside radius of 2.25-inches. Prior to testing, the steel mold surface was coated with a thin film of oil and lined with a Teflon™-coated release film, approximately 0.001-inch thick, to prevent resin adhesion to the mold and to enable easier movement of the resin within the mold during cure.

A 100-gram batch of CTD-101K resin was used for each test. The resin was mixed according to manufacturer's directions by using 100 parts by weight (pbw) of Part A, 90 pbw of Part B, and 1.5 pbw of Part C. The resin was mixed and completely degassed at its processing temperature of 60°C and poured into the mold. The resin was then cured using the recommended cure cycle for CTD-101K of 2.5-hr ramp from its processing temperature to 110°C, a 5-hr hold at 110°C, a 1-hr ramp to 125°C, followed by a 16-hr hold at 125°C, and finally, a 10-hr cooldown to 25°C. The linear shrinkage of the resin was calculated from the known length of the mold and the final length of the cured resin, measured using calipers accurate to 0.001-inch. The release film thickness was accounted for in calculating the linear shrinkage. The cured resin castings were measured after holding at least 48 hours at ambient conditions.

Six tests were performed. The results showed an average contraction during cure of 1.48 percent, which is in the normal range for an epoxy resin system. Detailed test results are provided in Appendix A.

Figure 1. Steel mold used for cure shrinkage tests.

Mechanical Testing

Specimen Description

The mechanical test specimens were fabricated to be representative of the windings found within the NCSX modular coils. In application, the modular coils are wound into very complex shapes, and are fabricated by winding the stranded copper cable conductor onto machined stainless steel winding forms, which provide the structural support necessary to react the high electromagnetic loads. A single modular conductor turn is comprised of four, rectangular compacted copper ropes in a two-by-two configuration, measuring approximately 0.25 by 0.3125-inch. Prior to winding the modular coils, each single modular conductor turn would be wound, using multiple turns, with a combination of dry S-2 glass fabric and Kapton™ (polyimide film) tape. Nominally, the glass fabric tape was 0.007-inch thick, while the Kapton tape was 0.002-inch thick. The glass fabric and Kapton tape were wound around the conductor such that a low viscosity epoxy resin could easily reach and impregnate all of the conductor strands and glass fabric within the modular coil to form the turn insulation.

Two types of test specimens were used, the insulated single modular coil (ISMC) conductor specimen, representing a single conductor turn, and the insulated 2 x 2 modular coil bundle (MCB) specimen, which includes the turn insulation for each of the four conductors and the ground insulation surrounding all four conductors. Representative cross-sectional drawings of the insulated single modular coil specimen and of the insulated 2 x 2 modular coil bundle specimen are shown in Figures 2 and 3, respectively.

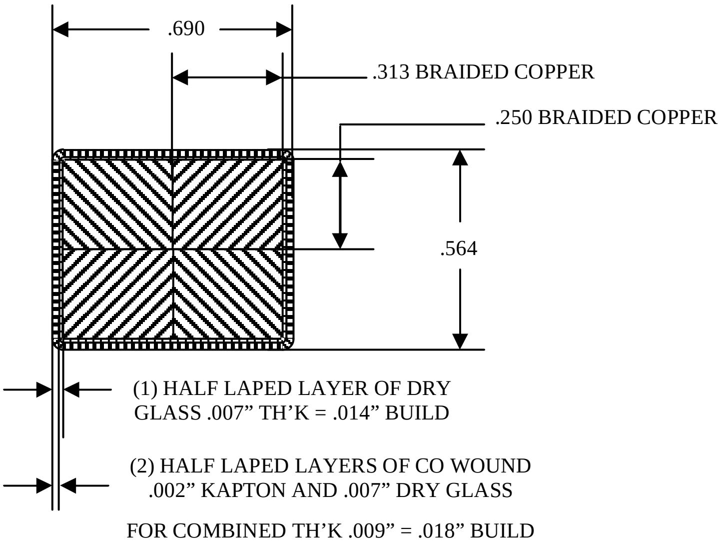

Figure 2. Cross-section of insulated single modular coil conductor (ISMC) specimen.

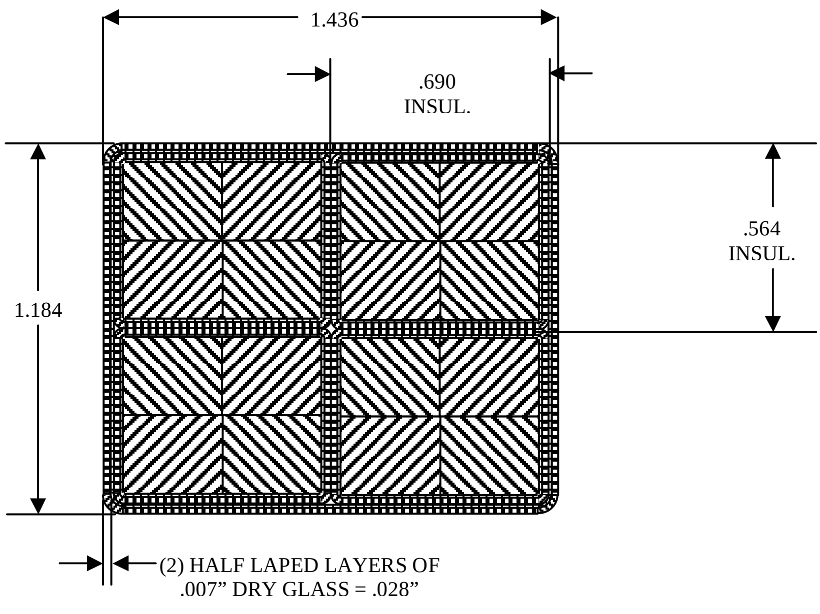

Figure 3. Cross-section of the insulated 2 x 2 modular coil bundle (MCB) specimen.

PPPL fabricated all specimens. The specimens were wrapped with the number of layers of S-2 glass fabric tape and Kapton as indicated in Figures 2 and 3, and then impregnated with the DGEBA epoxy resin system, CTD-101K, and cured. The specimens were then shipped to CTD for testing.

Test Equipment and General Procedures

All tests were performed on a MTS Systems Servo-Hydraulic test machine with a 100 kip load capacity. All tests were performed using a load card with a maximum range that encompassed the expected load capacity of the specimen. A Vishay Measurements Group 2120A strain conditioner was used to monitor the strain gage and strain gage extensometer response when necessary. Table 1 identifies each piece of equipment used for this test program as well as the date of calibration. All calibration certificates and related information on all equipment used in this program are available upon request.

Table 1. Test Equipment

Description	Model Number	Serial Number	Calibration Date	Comments
MTS Systems Corp.				
100 kip Load Cell	661.23E-01	105169	9/24/02	±100 kip range card ±50 kip range card
20 kip Load Cell	661.23E-03	57911	9/23/02	±20 kip range card ±4 kip range card
LVDT	LVDT	106826	2/24/03	±0.5 in. range card ±1.0 in. range card
Lakeshore Cryotronics, Inc.				
Silicon Diode	DT-470-CU-13-4L	D47357	3/25/03	
Vishay Measurements Group, Inc.				
Strain Conditioner	2120	63543	3/07/03	
Strain Conditioner	2120 A	100030	4/18/02	
Strain Conditioner	2120 A	100017	3/07/03	

All tests at 76 K, 100 K, and 150 K used liquid nitrogen as the cooling cryogen. For tests performed at 76 K, the entire test specimen and fixturing were submerged in liquid nitrogen contained in a cryogenic Dewar. For the intermediate test temperatures (100 K and 150 K), the temperature was controlled by manual modulation of the liquid nitrogen fill pressure within a cryogenic Dewar. The cryogenic test temperature was monitored by a Lakeshore Silicon Diode temperature sensor. Each test specimen was held at the test temperature for a minimum of 5 minutes prior to the start of the test, with the temperature being maintained to ±5 K throughout the duration of the test. The 29 5K tests were performed under ambient conditions.

All load, displacement, and strain gage data were recorded through a data acquisition system designed by CTD, using a data sampling frequency of 10 Hz. All data files were provided to PPPL.

Table 2 summarizes the tests performed for each type of specimen. Because the material configuration and specimen geometry were so unique, no ASTM test standard exists for these specific types of composite or metal specimens. However, the most relevant ASTM test standards were followed as closely as possible in terms of loading rates, data recorded, span ratios, and other testing parameters.

Table 2. Mechanical Test Types and Specifications

Specimen Type	**Test Type**	**ASTM Test Standard***	**Instrumentation**
ISMC	Compression	D695	2 - axial strain gages
	Tension	D3039	2 - 0/90 rosette strain gages
	Flexure	D790	NA
MCB	Shear	D2344	NA
	Flexure	D790	NA

* Tests were performed to comply with ASTM test standards as much as possible.

Insulated Single Modular Coil (ISMC) Specimen Testing

The ISMC specimens were subjected to compression, tension, and flexure testing. Each test was performed at 76 K, 100 K, 150 K, and 295 K, and used from four to six specimens at each temperature. Test procedures are described below.

<u>ISMC Compression Testing</u>

The specimen used for the ISMC compression tests was nominally 0.655-inch deep by 0.790-inch wide by 1.0-inch long, as received from PPPL. All specimens were tested in the longitudinal direction, or parallel to the axis of the copper conductor. Two 0.125-inch gage length strain gages were affixed to the outer surface of the insulation, one on either side of the specimen. Strain gages designed for use at cryogenic temperatures were used for all cryogenic tests. Two strain gages were used on either side of the specimen to account for any uneven loading due to misaligned loading platens or un-even cutting of the specimen edges. A photo of an ISMC compression specimen with an attached strain gage is shown in Figure 4.

For each test, the test specimen was placed between two hardened steel platens within the load frame cryostat and a 50-100-lb. preload was applied. For the cryogenic tests, the specimen was cooled to its test temperature using liquid nitrogen and held for approximately 5 minutes before testing. The specimen was then loaded to failure at a displacement rate of 0.00033 in/s. The load, displacement, and strain values were recorded at 10 Hz. Failure, usually seen within the insulation, was readily apparent and was verified by a significant drop in load during the test.

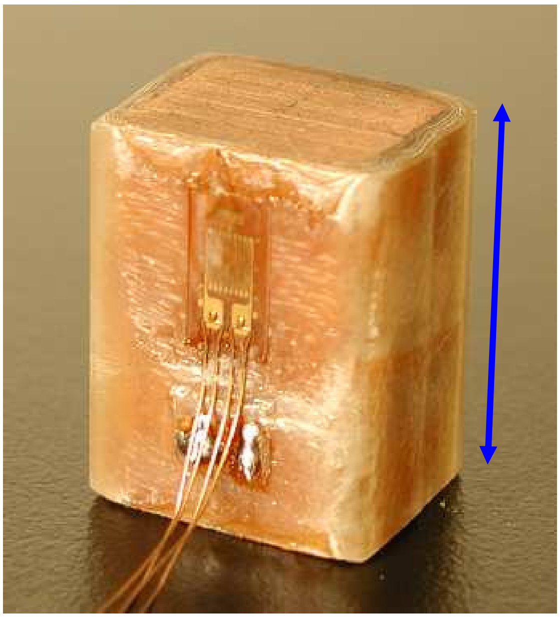

Figure 4. Typical ISMC compression specimen. The blue arrow indicates the loading direction.

The results of the ISMC compression tests are represented in Figure 5 and Figure 6, showing the measured compressive strength and calculated compressive modulus, respectively, at each test temperature. The results of all compression tests can be found in Appendix A.

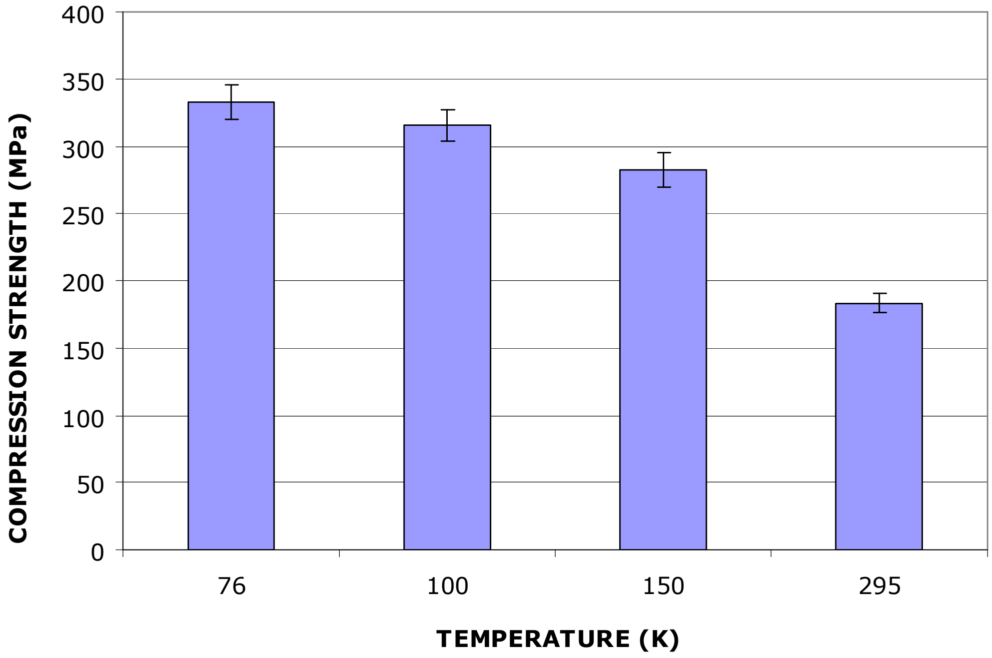

Figure 5. Measured compressive strength of ISMC specimens.

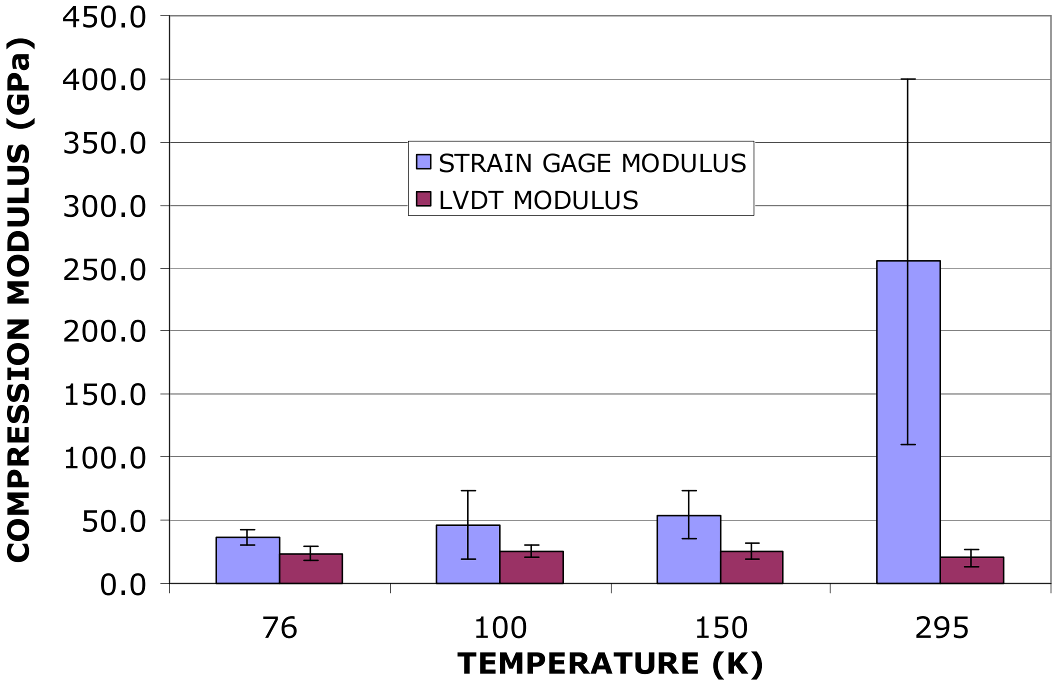

Figure 6. Compressive modulus of ISMC specimens, calculated using strain gages and test machine LVDT.

As can be seen in Figure 5, the ultimate compressive strength of the ISMC specimens behaves as expected, with the highest strength seen at the lowest temperature and decreasing strength as the temperature is raised to room temperature. Of particular note is that the compressive strength varies very little from 76 K to 150 K, losing only approximately 50 MPa between these two temperatures. However, the compressive strength almost doubles when the test temperature is lowered from room temperature to 76 K.

The compressive modulus, shown in Figure 6, was calculated using two different strain measurement techniques. As described above, two strain gages were mounted on each test specimen to measure strain during loading. The strain values from the two strain gages were averaged and a stress-strain curve produced, from which the modulus was then taken using the most linear section of the initial curve. As seen in Figure 6, the modulus calculated in this way did not make logical sense, since the results indicated an increasing modulus with increasing temperature, which is the opposite of what one would expect. In addition, the compressive modulus at 295 K was extremely high and was judged to be in error. The best explanation for this anomalous behavior is that the bond between the glass fabric insulation and the Kapton barrier was more susceptible to damage at the higher temperatures, causing premature de-bonding in these areas during loading, which resulted in the measurement of much smaller strains on the outer surface of the test specimen (where the strain gages were mounted). These very small strains would account for the very high modulus values reported from the strain gage measurements.

In an attempt to arrive at a more correct compressive modulus, the Linear Variable Differential Transformer (LVDT) mounted on the MTS test machine actuator was used to calculate the strain of these same specimens and thus, the modulus of the ISMC compression specimens. The calculated modulus values taken from the LVDT measurements are also shown in Figure 6. These values are significantly lower than those reported for the strain gage modulus. However, there is very little variation seen in these modulus values over the temperature range tested. CTD is continuing to study these results in the hope of arriving at some conclusive and representative compressive modulus values for these specimens.

Two types of insulation failure, termed “splitting” and “unwrapping,” were seen in these tests. These failure types are illustrated in Figure 7.

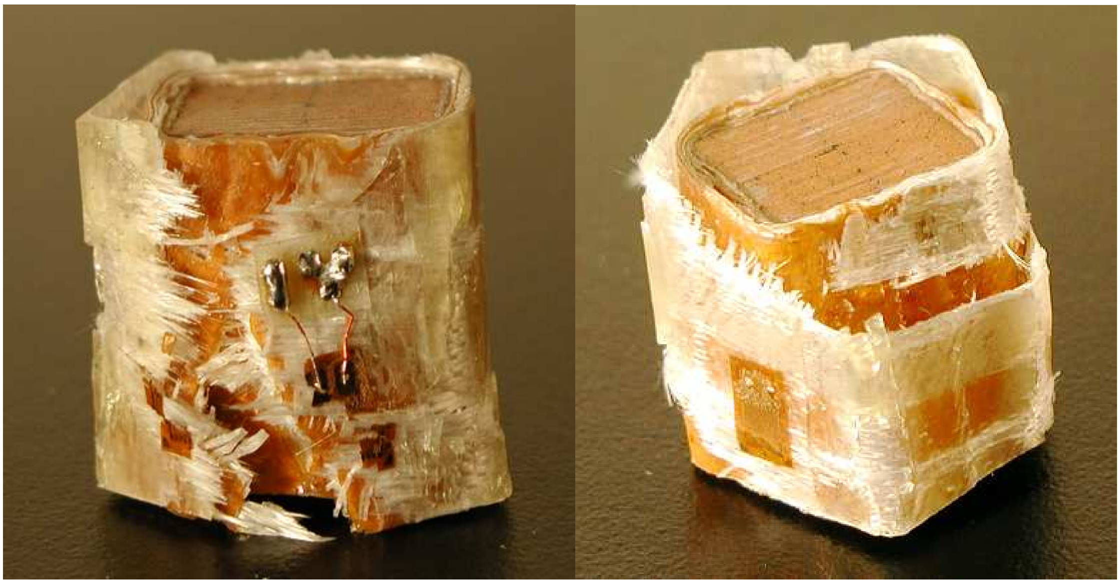

Figure 7. Failure modes called splitting (left) and unwrapping (right) seen in the ISMC compression tests.

ISMC Tension Testing

Specimens used in the ISMC tension testing were similar in cross-section to the compression specimens, at approximately 0.655-inch deep by 0.790-inch wide. However, the overall specimen length was nominally 15.0 inches. Approximately 4.0 inches of insulation was removed from either end of the test specimen, so that only the copper conductor would be gripped and loaded by the tensile grips, not the insulation. Therefore, only the insulation located in the center 7 inches of the tensile test specimens was left intact during the these tests. As in the compression tests, two strain gages were affixed to the outer surfaces of the insulation on each specimen, one on opposite sides. Each strain gage consisted of a 0°/90° rosette, so that both longitudinal and transverse strain measurements could be taken, allowing calculation of both modulus and Poisson’s Ratio. A typical tension specimen is shown in Figure 8.

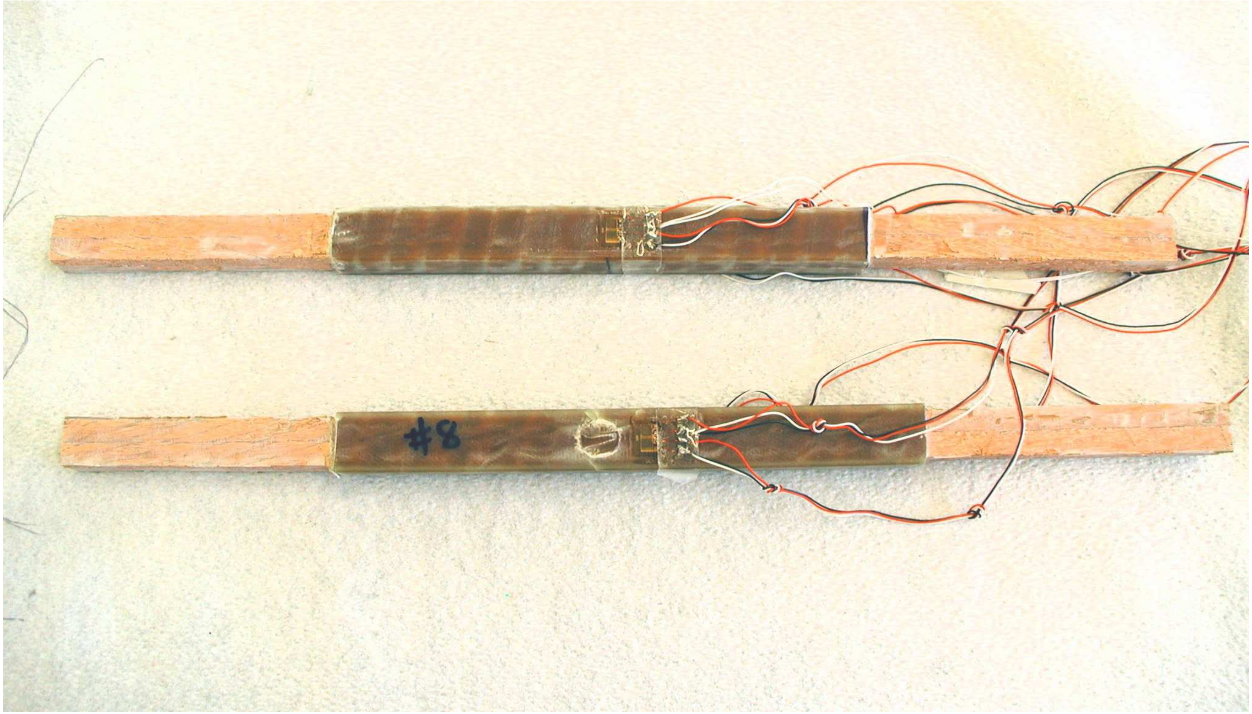

Figure 8. ISMC tension specimens with insulation removed from ends.

A special tensile grip was developed for the ISMC tension testing. A set of split, angular tension grips were fabricated to match the conductor cross-section. The grips were composed of three primary parts: split aluminum angular grips that fit directly onto the test specimen; a matching female stainless steel angular grip holder that the aluminum angular grips fit into; and clevis grip ends that the specimen/grip assembly fit into and attached directly to the test machine cryostat. Photos of the grips are shown in Figures 9 through 13.

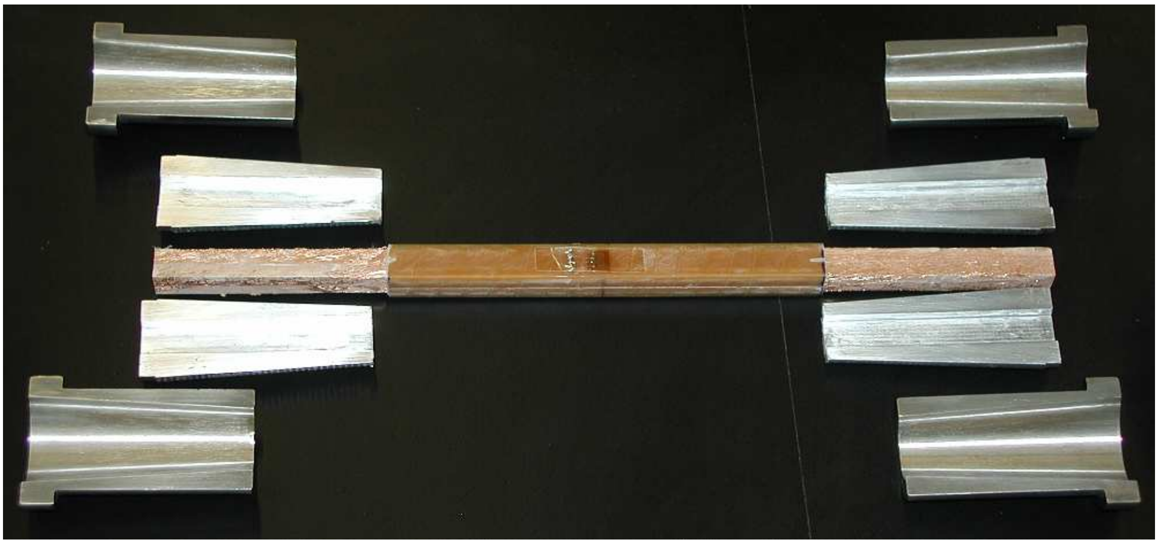

Figure 9. ISMC tension specimen, aluminum tension test angular grips, and stainless steel grip holders.

Figure 10. ISMC tension test specimen with split angular tension grips in place.

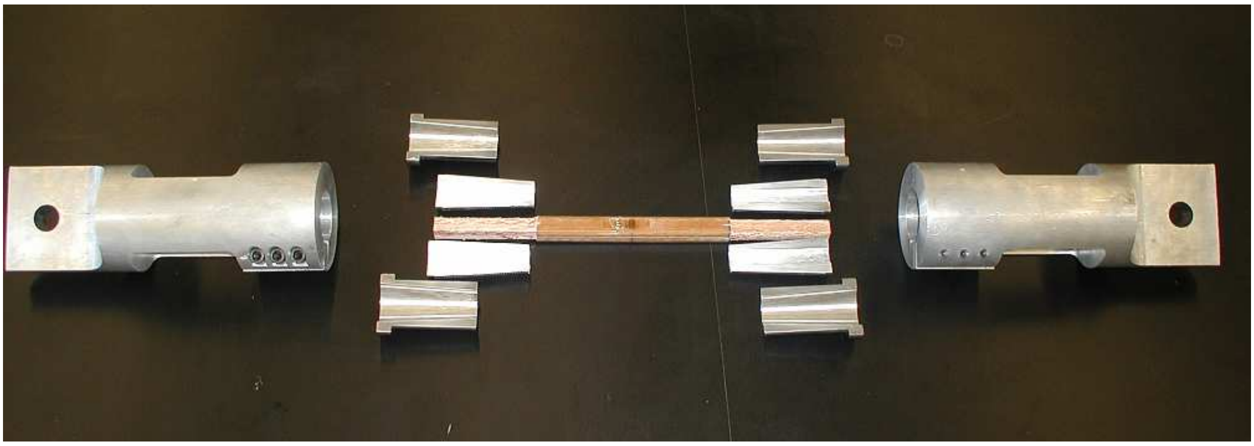

Figure 11. Test fixturing for ISMC tension tests.

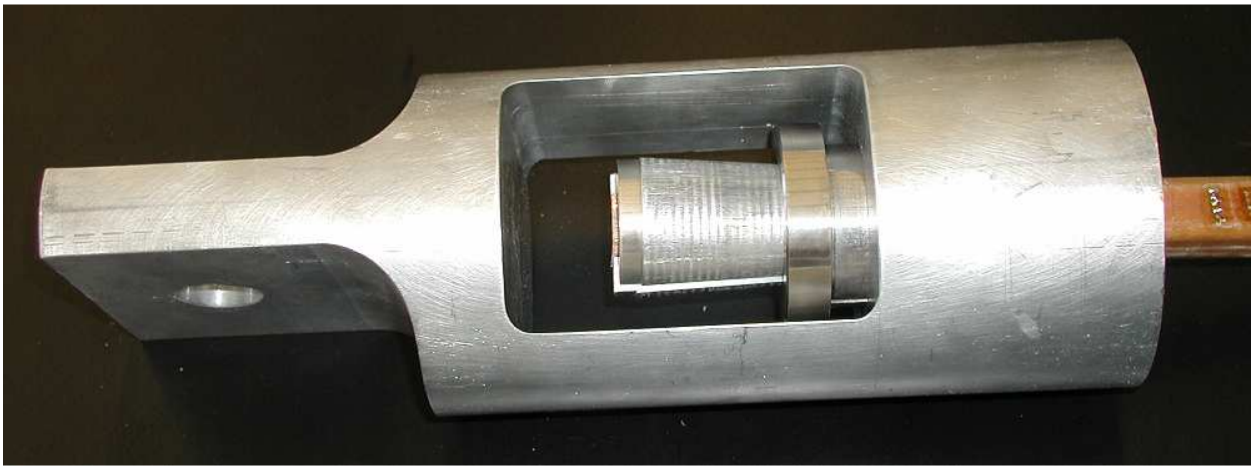

Figure 12. Assembly of angular tension grips, grip holders, and clevis reaction fixturing.

Figure 13. Assembled ISMC tension test grips and test fixturing.

The loading rates and data acquisition system used for the ISMC tension testing were the same as in the ISMC compression tests. Due to the unusual gripping mechanism, a preload of approximately 2000 lb. was used to fully seat the tension grips prior to the start of each test.

The ISMC tension test results are given in Figures 14, 15, and 16, showing the tensile strength, tensile modulus, and Poisson's Ratio, respectively. These results are the average of 4 to 6 individual tests at each test temperature. The individual test results and datasheets for all tension tests are provided in Appendix A.

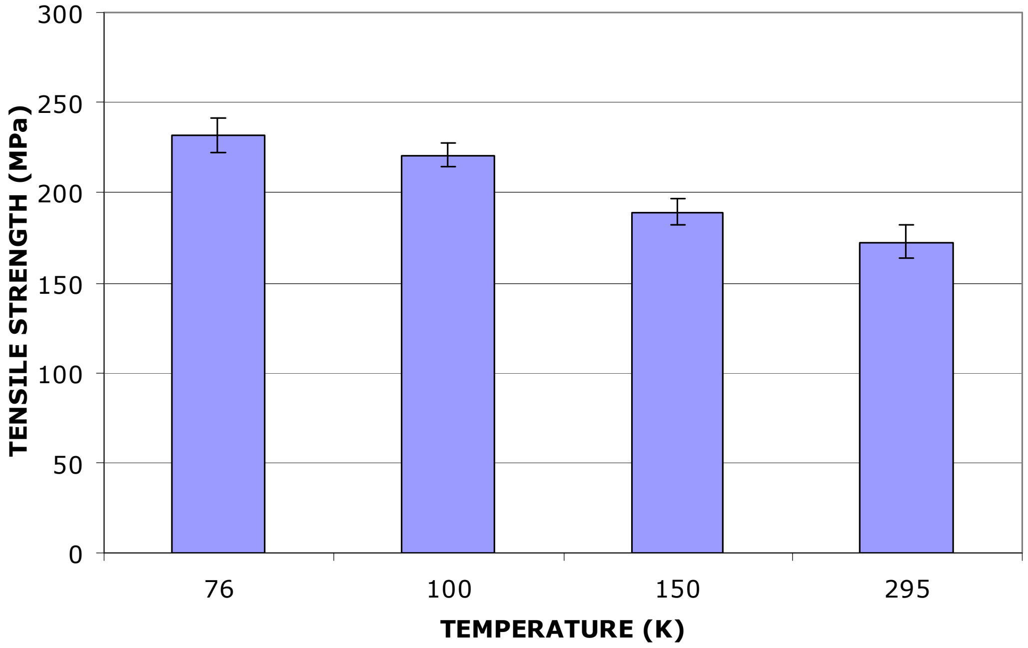

Figure 14. Measured ISMC Tensile strength.

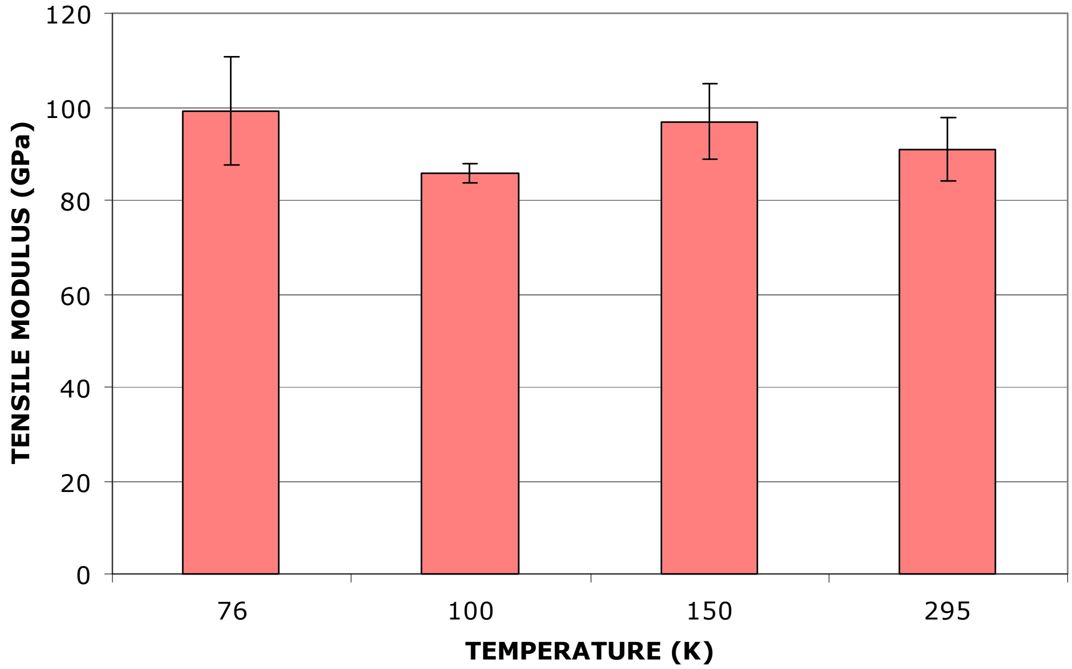

Figure 15. Calculated ISMC tensile modulus.

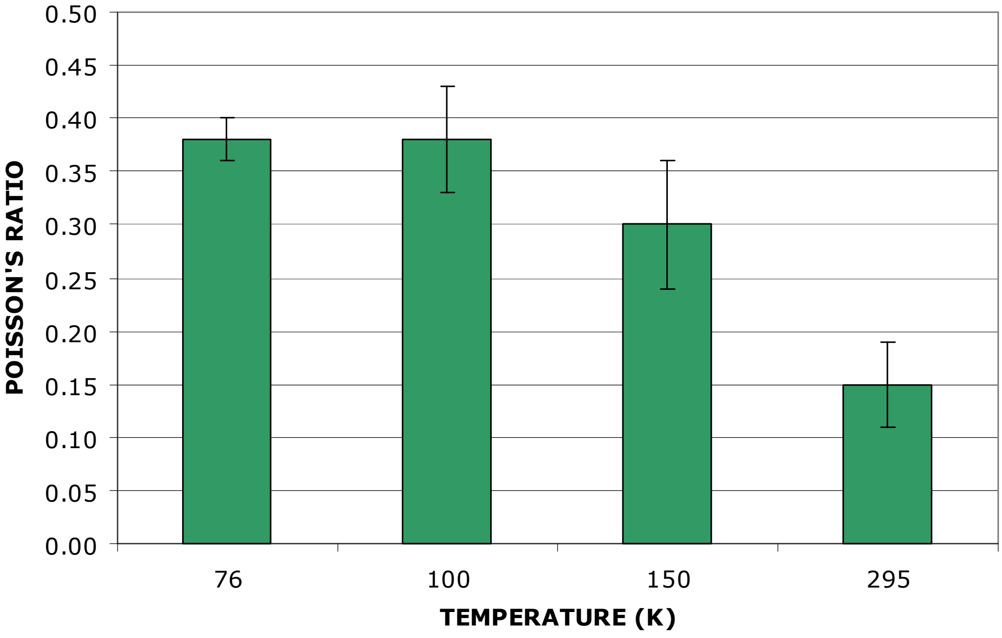

Figure 16. Calculated ISMC Poisson's Ratio.

As seen in Figure 14, the tensile strength of ISMC specimens decreases with temperature, as expected. It should be noted that since the copper conductor was being loaded through the tensile grip set-up described previously, these strength values reflect conductor failure, usually at the grip edge, rather than insulation failure.

The tensile modulus values, shown in Figure 15, show little variation with temperature, remaining almost constant from 76 K to 295 K. The overall modulus values reported, approaching 100 MPa (14.5 Mpsi) are very near that of copper itself, indicating that the bond between the insulation and the copper was maintained under initial tensile loading, even at temperatures down to 76 K.

The Poisson's Ratio, shown in Figure 16, remains relatively unchanged from 76 K to 100 K, there is a reduction seen in this property as the temperature increases to 295 K. Further testing is warranted at 295 K to accurately assess this property at that temperature since the results for both tensile modulus and Poisson's Ratio shown here represent only two tests due to malfunctioning strain gages.

ISMC Flexure Testing

The ISMC flexure test specimens were of the same insulated cross-section as the ISMC compression and tension test specimens. Specimens were nominally 0.655-inch deep by 0.790-inch wide by 10.0-inch long. The specimens were tested following ASTM D790, Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials, as closely as possible. Specimens were loaded at a rate of 0.00033 in/s in a three-point bend configuration, common to flexure and short-beam shear testing. Specimens were loaded until a discernable failure occurred, or until the load reached a maximum and started dropping off (for the 295 K tests). The specimens were tested in two different directions, each perpendicular to the longitudinal direction of the conductor strands. The two directions were designated as "edgewise" and "flatwise" and are shown, along with the test set-up and fixturing, in Figures 17 and 18.

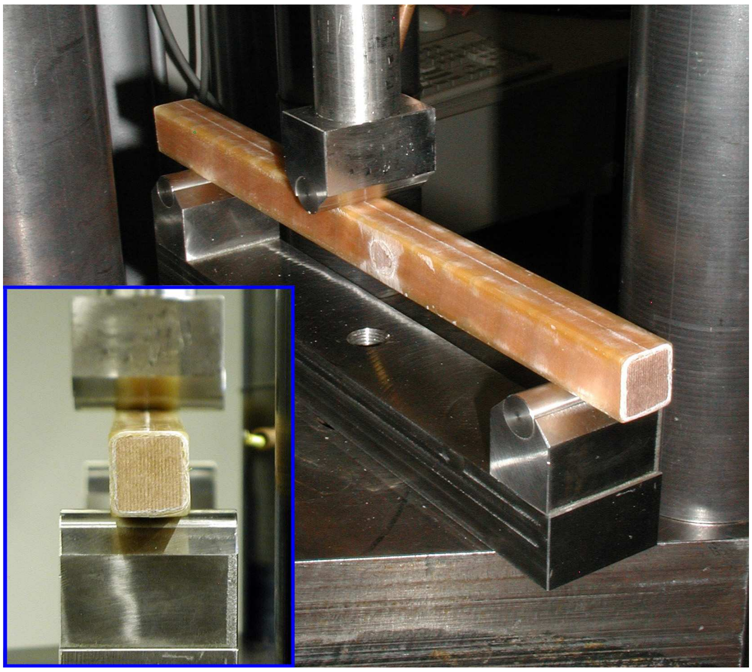

Figure 17. ISMC specimen orientation for edgewise flexure testing.

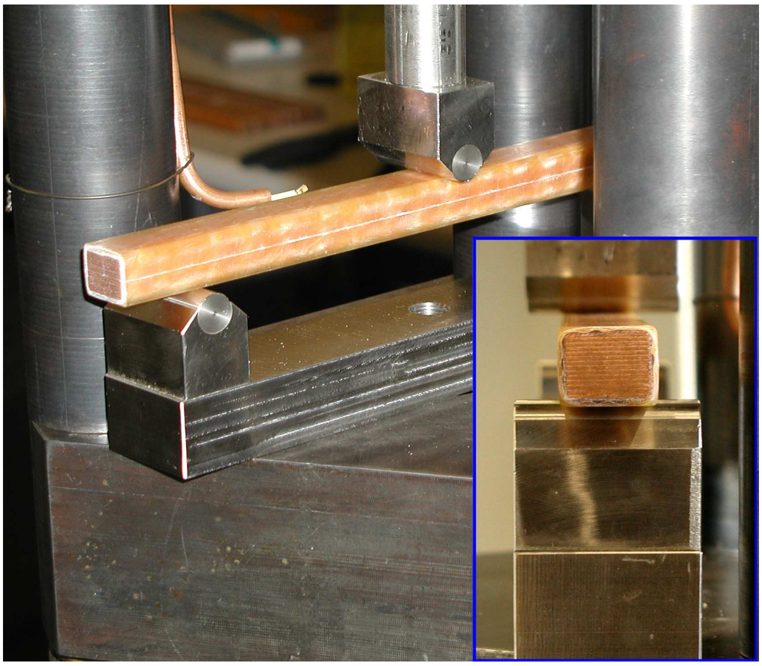

Figure 18. ISMC specimen orientation for flatwise flexure testing.

Because of test fixture size limitations, the maximum span between the lower loading noses was 8.0 inches, resulting in a span ratio (span to thickness ratio) of 10.4 and 12.2 for the edgewise and flatwise specimens, respectively. These span ratios were slightly smaller than the value of 16 called for in the ASTM standard.

ISMC flexural strength and flexural modulus values are shown in Figures 19 and 20, respectively. The results shown are the average of three tests in each orientation. There is very little discernable effect on flexural strength or modulus due to specimen orientation. Individual test results and datasheets for the ISMC flexural tests are provided in Appendix A.

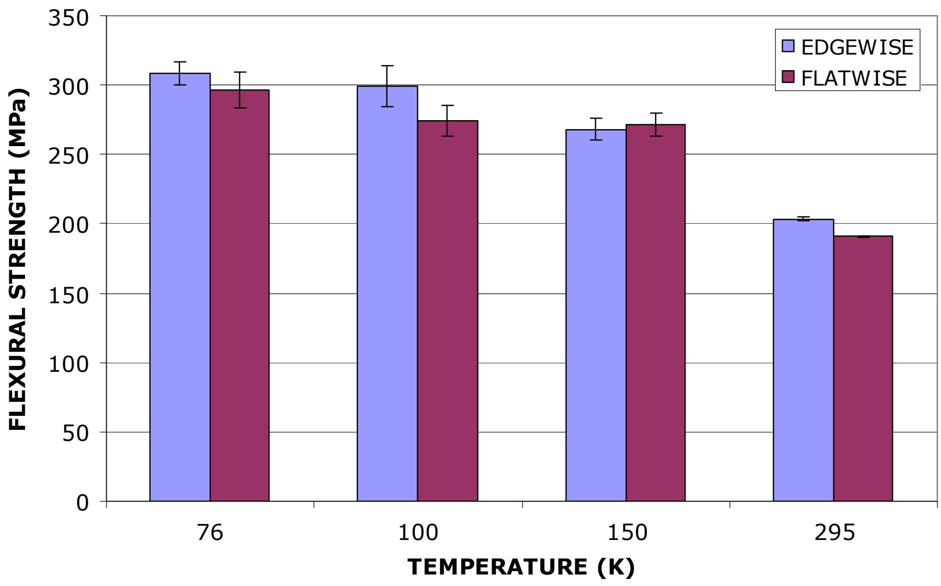

Figure 19. Measured ISMC flexural strength.

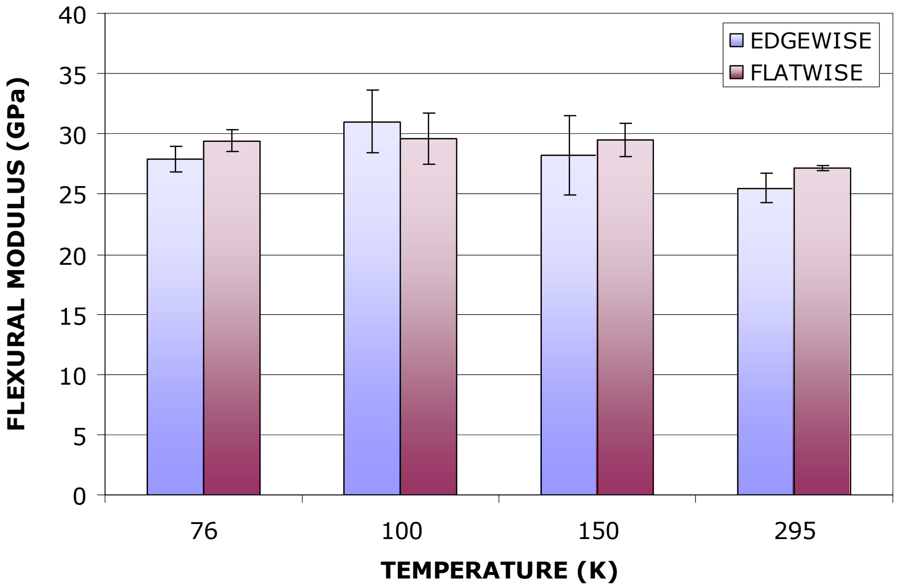

Figure 20. Calculated ISMC flexural modulus.

As expected, the flexural strength is reduced as the test temperature is increased from 76 K to 295 K. There is very little strength decrease from 76 K to 100K or from 100 K to 150 K, but a significant reduction in flexural strength from 150 K to 295 K. The flexural modulus exhibits very little change between 76 K to 150 K, and a very slight reduction at 295 K.

2 x 2 Modular Coil Bundle (MCB) Specimen Testing

The MCB specimens were subjected to flexure and shear tests performed at 76 K, 100 K, 150 K, and 295 K, with six specimens tested at each temperature. The procedures and results for these tests are described below.

<u>MCB Flexure and Shear Tests</u>

The 2 x 2 MCB flexure and shear test specimens, fabricated at PPPL, are composed of four individual ISMC specimens, bundled together to form a 2 x 2 matrix and insulated with a ground wrap insulation layer. A drawing of the cross-section for a 2 x 2 MCB specimen was shown in Figure 3. The actual, as fabricated, specimen cross-sectional dimensions were nominally 1.35-inch high x 1.55-inch wide. Figure 21 shows an MCB specimen. The MCB flexure and shear specimens were identical in cross-section, and differed only in their length. The flexure specimens were nominally 18 inches long, and the shear specimens were 7 inches long.

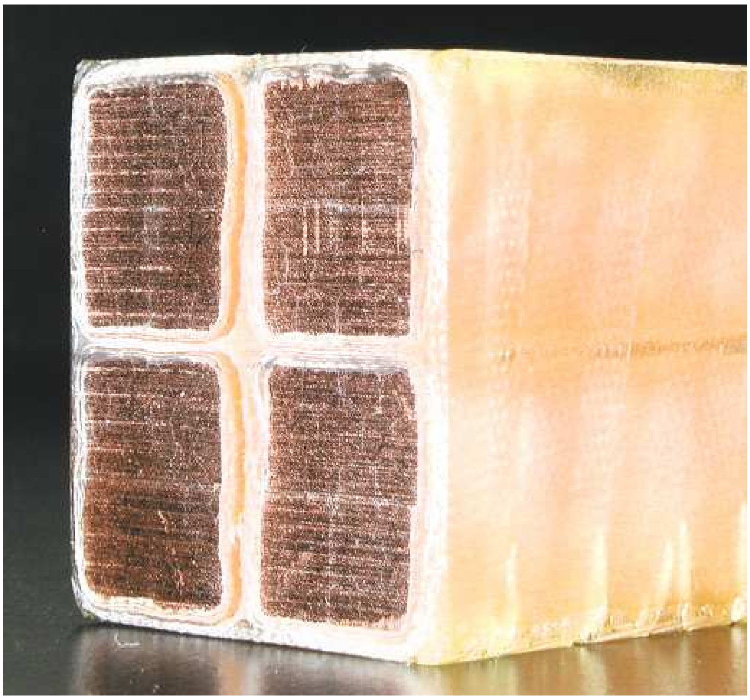

Figure 21. Typical cross-section of 2 x 2 MCB specimen.

Both the flexure and the shear tests were performed using a 3-point bend configuration, common to both the flexure test standard (ASTM D790) and to the shear test standard (ASTM D2344, Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates). Specimen orientation for both flexure and shear testing was flatwise, with the loading applied normal to the widest dimension of the specimen.

For the MCB flexure tests, a span of 16 inches was used, resulting in a span ratio of 12.0, as in the ISMC flexure tests. As expected from the standard flexure testing, failure typically occurred as a compressive failure at the top of the specimen or as a tensile failure at the bottom of the specimen. For the MCB shear tests, a span of 6.7 inches was used, resulting in a span ratio of 5.0. The span ratio for the shear tests follows convention outlined in the D2344 test standard that recommends the use of a span ratio of 5.0 for glass fiber-reinforced laminates. The 3-point bend shear test was used to simulate a shearing effect in the insulation between the top and bottom modular coil pieces. This type of shear loading was successful based on the shearing type of failure mode noted on the MCB shear specimens when visually analyzed after each test was completed.

In both the flexure and shear tests, each specimen was loaded at a rate of 0.00033 in/s until failure. At cryogenic temperatures, the failure point was usually readily discernable. However, at room temperature, failure was very gradual, with a progressively lower load carrying capacity noted after reaching a maximum load. A photo of a loaded MCB flexure test specimen is shown in Figure 22.

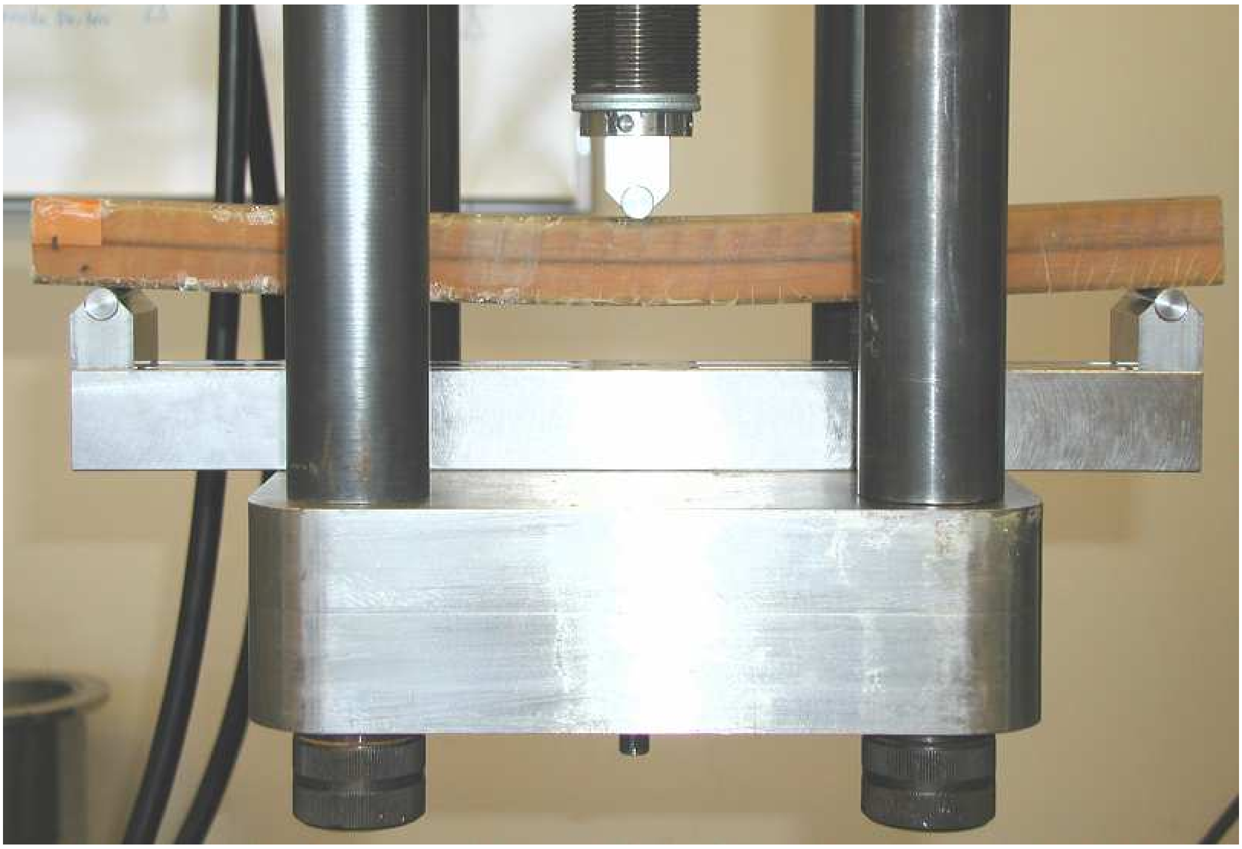

Figure 22. A 2 x 2 MCB flexure specimen under load at 295 K.

It should be noted that the strength values reported for the flexure test are calculated from the equation:

$$S = 3PL/2bd^2$$

Where:

S = stress at the outer surface of the midspan

P = maximum load

L = support span

b = width of the specimen

d = thickness of the specimen

Whereas, the strength values reported for the shear test are calculated from the equation:

$$S = 0.75\ P/bd$$

Where:

S = shear strength

P = maximum load

b = width of the specimen

d = thickness of the specimen

Therefore, the strength values reported for the flexure and shear tests are not directly comparable.

The flexural modulus was reported for all tests, both flexure and shear, and is calculated from equations taken from the flexure test standard (D790). Although the modulus calculation is not included in the shear test standard (D2344), it was calculated for the shear tests for comparison purposes. The flexural modulus was calculated from the equation:

$$E_B = L^3m/4\ bd^3$$

Where:

E_B = modulus of elasticity in bending (flexural modulus)

L = support span

b = width of the specimen

d = thickness of the specimen

m = slope of the tangent to the initial straight-line portion of the load-deflection curve

The 2 x 2 MCB flexural strength and flexural modulus results are given in Figures 23 and 24, respectively. The individual test results and the datasheets from the 2 x 2 MCB flexural tests are provided in Appendix A.

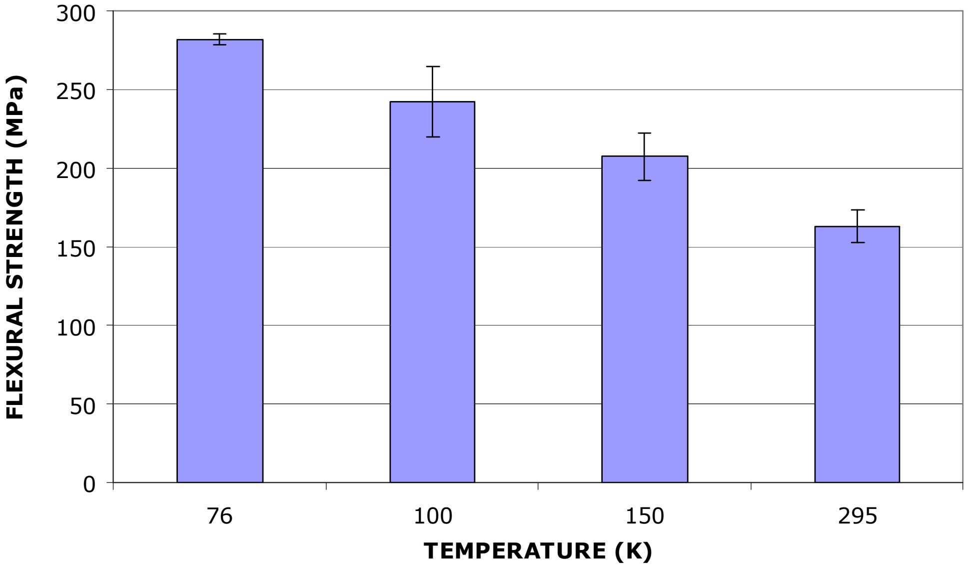

Figure 23. Measured flexural strength for 2 x 2 MCB.

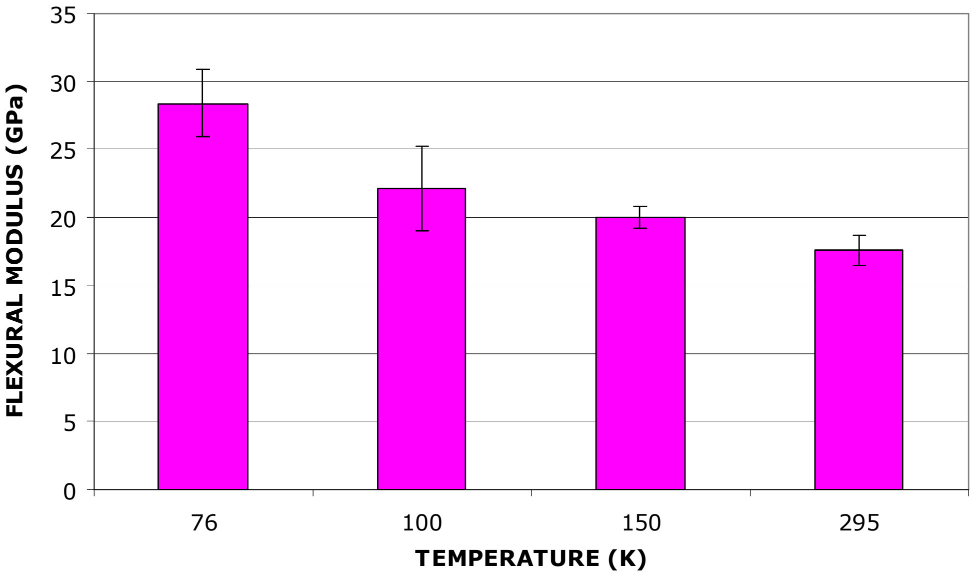

Figure 24. Calculated flexural modulus for 2 x 2 MCB.

Both the strength and modulus showed the expected higher values at lower temperatures. A nearly linear decrease in properties is seen between 76 K and 295 K, with the nominal values at 295 about 40 percent lower than at 76 K.

As previously mentioned, even though both tests used a similar 3-point bend configuration for testing, the equations used to calculate flexural strength are significantly different than those used for shear strength, resulting in completely different test results and data that are not directly comparable. While the flexural test is designed to evaluate materials in bending, the shear test is designed to maximize the shear stress within a laminated structure, such that interlaminar shear failures are obtained and the "apparent" interlaminar shear strength can be calculated. Therefore, the shear test uses a much shorter span between the two lower loading noses. Interlaminar-type shear failures were readily apparent upon visual examination of the shear test specimens.

Figures 25 and 26 show the apparent shear strength and flexural modulus, respectively. Individual test results and the corresponding datasheets for these tests are provided in Appendix A. Much like the flexural tests, the shear strength values for the 2 x 2 MCB shear tests decrease with increasing temperature, as seen in Figure 25. The shear strength at 100 K is only slightly less than that at 76 K, although the data scatter in the 100 K results is rather large. This same relationship was seen in the calculated flexural modulus, as shown in Figure 26. Once again, the data scatter for the flexural modulus at 100 K is quite high.

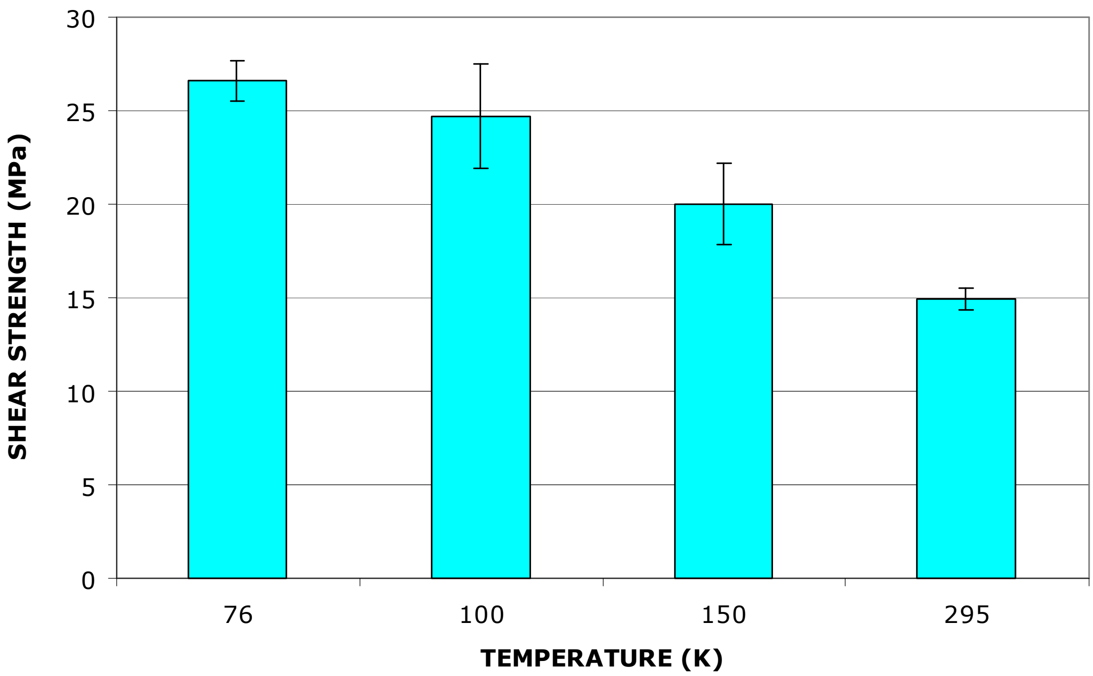

Figure 25. Apparent shear strength of 2 x 2 MCB.

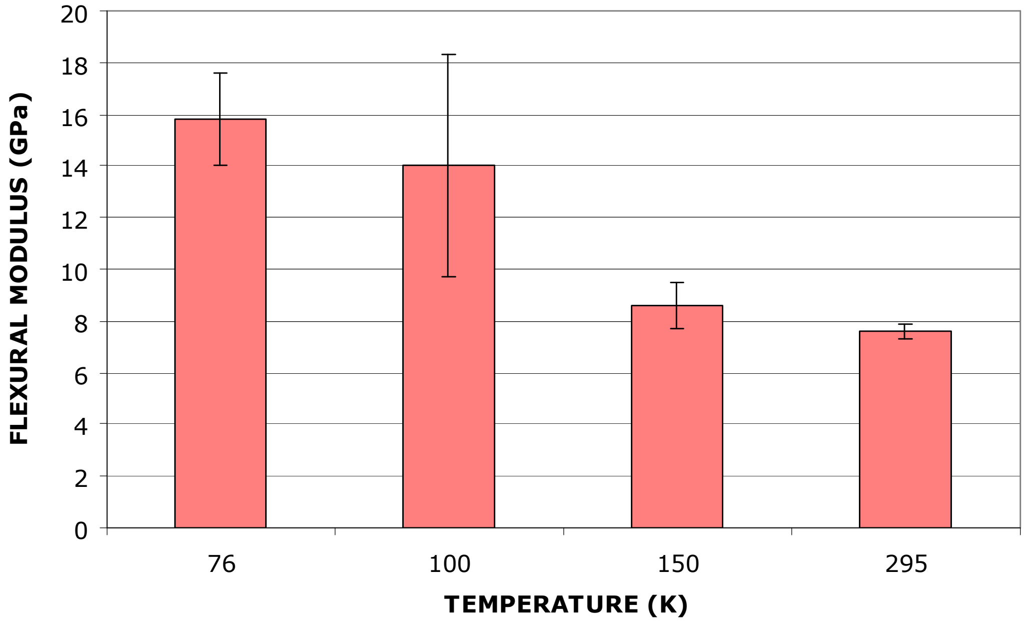

Figure 26. Calculated flexural modulus for 2 x 2 MCB.

Thermal Testing

Thermal expansion measurements were performed from 76 K to 295 K. The specimens used and the test procedures are described below.

Specimen Description

Three different types of specimens were tested for thermal expansion, including an ISMC specimen much like that shown in Figure 4, the ISMC turn insulation without the conductor, and the MCB ground insulation without the conductor. Two different specimens of each type were tested. The ISMC specimen that included the copper conductor was tested to determine if any effect could be discerned in the thermal expansion due to the conductor. This specimen was nominally 0.655-inch wide by 0.790-inch high by 1.0-inch long.

In order to evaluate the thermal effect of the copper on the insulation, the turn insulation, including the Kapton™ layers, had to be evaluated by itself, without the conductor. Therefore, a section of the turn insulation was removed from the surface of an ISMC tension test specimen for evaluation. Special care was taken in the removal of the insulation from the conductor to ensure that the bond between the glass insulation and the Kapton™ film was not damaged. The turn insulation specimen measured approximately 0.5-inch wide by 2.0-inch long by 0.07-inch thick.

A section of the ground insulation was cut and removed from one of the 2 x 2 MCB flexure specimens. The ground insulation included no Kapton™ layers, but was composed entirely of fiberglass reinforcement and CTD-101K epoxy resin. The specimens used for these thermal tests measured approximately 1.5-inch wide by 2.0-inch long by 0.04-inch thick.

Thermal Expansion Test Procedures

All of the thermal expansion tests were performed using the strain gage method. This test method is a modified version of other strain gage thermal expansion measurement methods used previously by Composite Technology Development, Inc. (CTD) and others,[1, 2, 3] and is intended primarily for use at cryogenic temperatures. This test method was first developed and used by the National Institute for Standards and Technology (NIST) in Boulder, Colorado, and has been used by CTD for many years on numerous government and industry cryogenic test programs. The accuracy of the thermal expansion measurements is approximately 1 percent, and the reproducibility is usually $\pm$ 20 $\mu\varepsilon$ in the temperature range from 4K to 300K.

In preparation of the specimen for use in thermal expansion testing using the strain gage method, each specimen was cut or machined to size suitable for used in the test fixturing. A suitable strain gage, rated for use at cryogenic temperatures, was adhered to the specimen in the correct orientation in order to measure the thermal expansion in that direction. Strain gages with gage lengths of 0.125-inch were used for all tests. For all specimens, separate strain gages were aligned in the longitudinal or axial direction of the conductor as well as in the transverse direction or 90° from the longitudinal direction. All strain gages were adhered to the outer surface of the specimen using a strain gage adhesive suitable for use at cryogenic temperatures. A NIST traceable copper standard of known thermal expansion characteristics was also strain gaged with the same type and lot of strain gages used on the other test specimens to help eliminate any variation in strain measurement. The gages on both the specimen and the standard were wired in order to transmit strain data to a strain conditioner, which in turn, transmitted strain data into a PC-based data acquisition system. Thermocouples were attached to the specimen and to the Cu test standard.

The specimen and standard, both with wired strain gages and thermocouples, were placed inside an insulated specimen holder that is equipped with a heater on the outer surface. The specimen holder was lowered into a cryogenic Dewar and the strain gage wires and thermocouples were attached to the strain conditioner. The strain gages were balanced so that the strain was zero at room temperature. The gages were also calibrated for gage factor change with temperature, using the internal shunt calibration resistor in the strain conditioner. The temperature of the specimen and standard was then lowered using liquid nitrogen (76 K), until equilibrium of the test specimens at the desired temperature was reached. Once the temperature was stable, the data acquisition program was started and the temperature and strain were recorded at set intervals, usually every 20 seconds. The temperature and strain data were recorded at these intervals while the temperature of the specimen and standard slowly warmed up to ambient temperature. After all desired data had been collected, the data acquisition program was stopped.

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[1] "Low Temperature Thermal Properties of Composite Insulation Systems," P. Fabian, T. Bauer-McDaniel, and R. Reed, *Cryogenics*, V35, No. 11, 719, (1995).

[2] "Thermal Expansion Measurements of Resins (4 K - 300 K)," R. Walsh, R. Reed, Adv. Cryo. Eng. - Mater. 40: 1145, (1994).

[3] "Measurement of Thermal Expansion Coefficient Using Strain Gages," Tech Note TN-513, Measurement Group, Inc., P.O. Box 27777, Raleigh, NC (1986).

To analyze the data set, the known thermal expansion of copper was subtracted from the reference copper data to give the strain gage thermal output, as illustrated in Figure 27. The strain data were normalized to zero at 293K. The gage thermal response was then subtracted from each specimen's data set to calculate the thermal expansion (TE) of the specimen. To obtain the coefficient of thermal expansion (CTE) of each material, the derivative of the polynomial equation fitting the thermal expansion curve was calculated. The actual CTE curves and values calculated for any given temperature are more susceptible to small errors in the measurements since they are calculated from the derivative of a polynomial curve fit. Each data set was plotted as micro-strain versus temperature and CTE versus temperature.

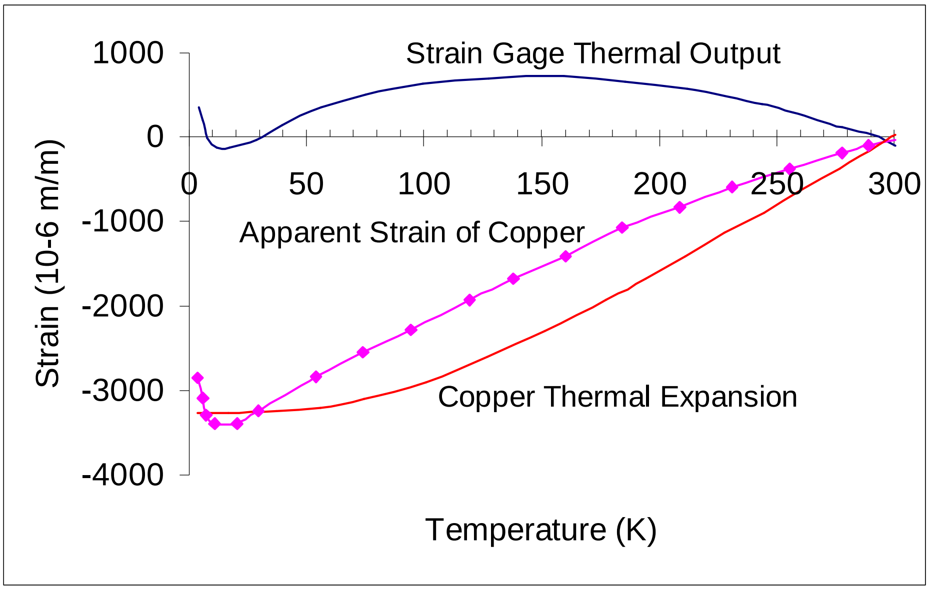

Figure 27. Calculation of strain gage thermal output from the measured apparent strain of the copper reference and the known thermal expansion of copper.

Thermal Expansion Test Results

The thermal expansion characteristics of three different types of specimens were evaluated to 76 K. The first specimen was an ISMC specimen which included the copper conductor. Two separate tests were conducted on this type of specimen and the results, showing the thermal expansion and coefficient of thermal expansion, are shown graphically for the ISMC specimen in Figures 28 and 29. The tabular data and the datasheets for each of the CTE tests are provided in Appendix A. As seen in these two figures, agreement between the two different tests is quite good throughout the 76 – 295 K temperature range, with the exception of some variation from approximately 76 – 120 K.

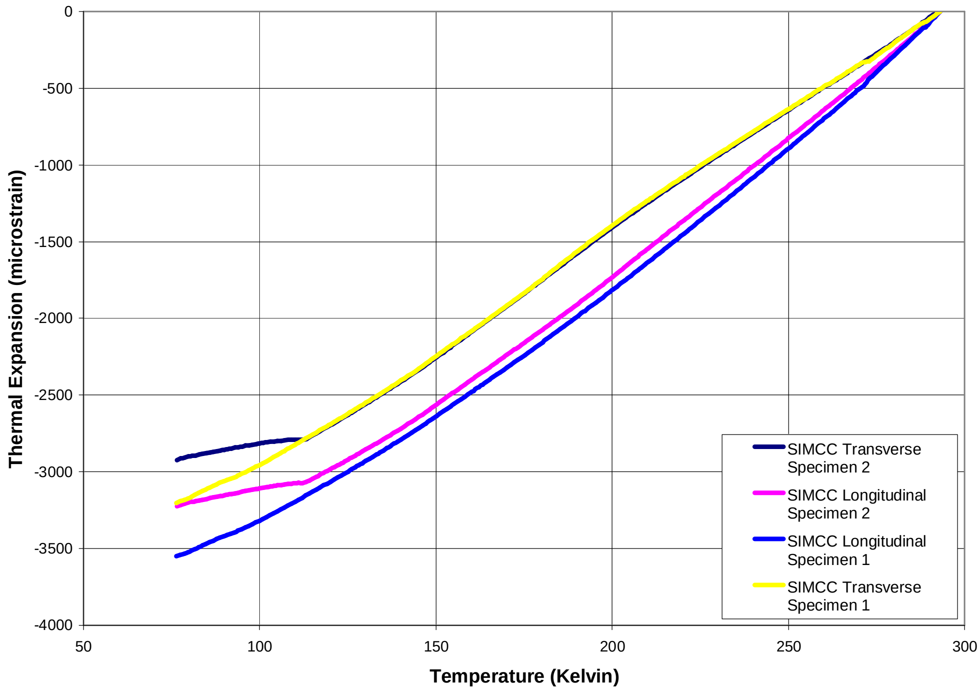

Figure 28. Thermal expansion of ISMC specimens. SIMCC – Single Insulated Modular Coil with Conductor.

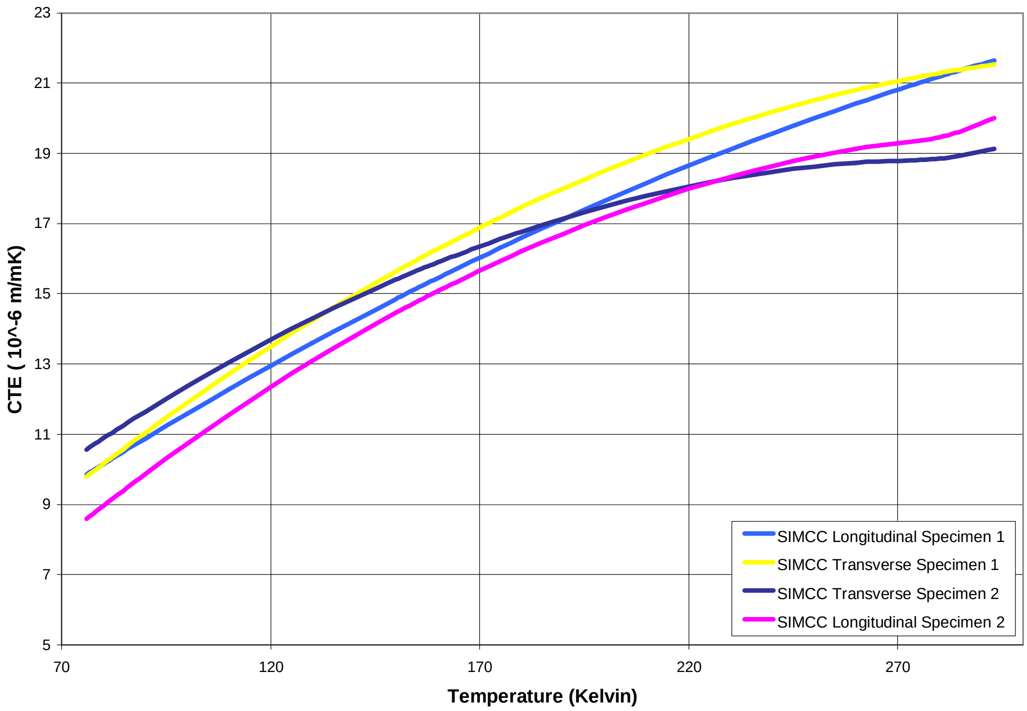

Figure 29. CTE of ISMC specimens. SIMCC – Single Insulated Modular Coil with Conductor.

The second type of specimen tested was the ISMC turn insulation without the copper conductor. The thermal expansion and coefficient of thermal expansion test results from these tests are shown in Figures 30 and 31, respectively. The tabular data and datasheets for these tests are provided in Appendix A. As seen in Figure 30, there is very good agreement between the two different tests conducted on the turn insulation. There appears to be very little difference between the transverse and longitudinal directions. When comparing the thermal expansion results of the ISMC specimen (Figure 28) and the ISMC turn insulation without the conductor (Figure 30), there is very little difference in overall contraction at 76 K. This would indicate that the thermal contraction measured on the outer surface of the ISMC specimen is affected very little by the copper conductor.

The coefficient of thermal expansion for the turn insulation, shown in Figure 31, does exhibit a difference between the two different directions, with a greater variation over the temperature range seen in the longitudinal direction when compared to the transverse direction.

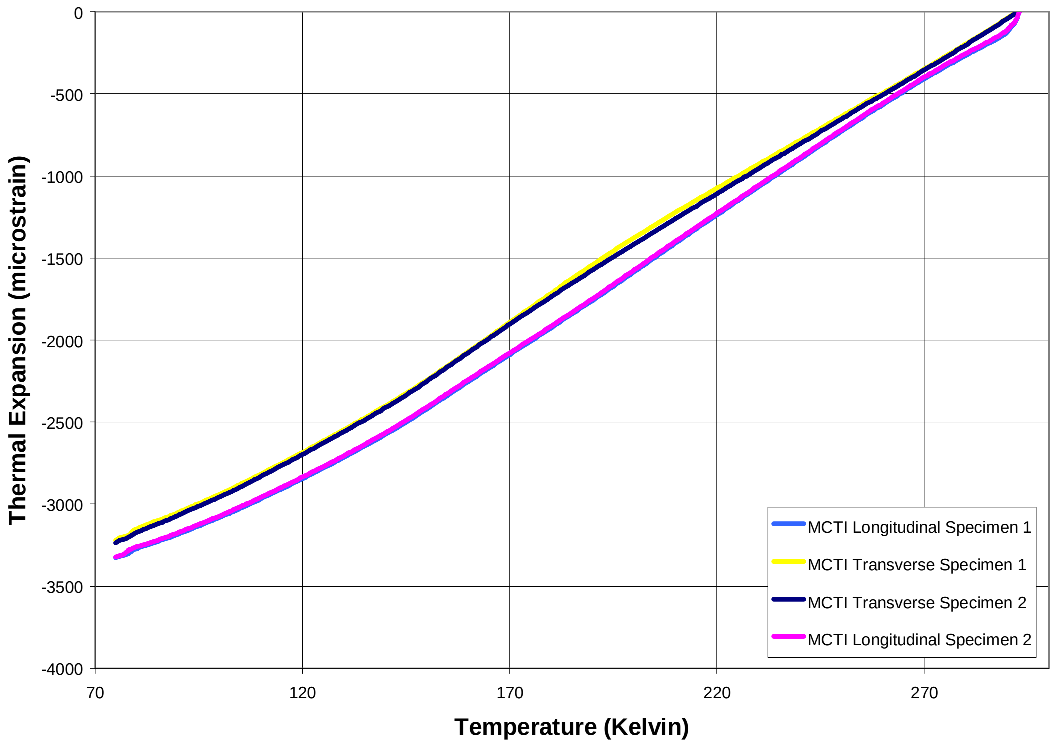

Figure 30. Thermal expansion of single modular coil turn insulation without conductor. MCTI – Modular Coil Turn Insulation.

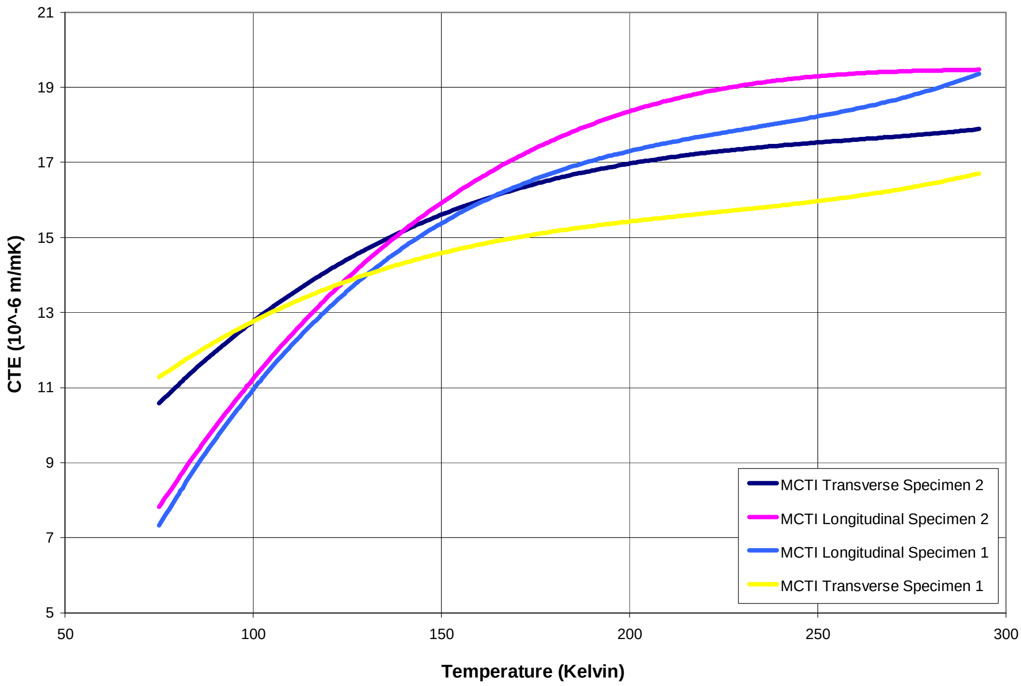

Figure 31. CTE for single modular coil turn insulation without conductor. MCTI – Modular Coil Turn Insulation.

The third type of specimen measured for thermal expansion was the Modular Coil Bundle (MCB) ground insulation that was removed from the 2 x 2 MCB test specimens used in the mechanical tests. The ground insulation was composed of only glass fabric and the CTD-101K epoxy resin and contained no Kapton™ or copper conductor. The thermal expansion and coefficient of thermal expansion test results are shown in Figures 32 and 33, respectively. Tabular data and datasheets for these tests are provided in Appendix A.

As seen in these Figures 32 and 33, there is little variation seen between the two test specimens in overall thermal contraction and CTE down to 76 K. There is, however, a slight difference between the transverse and longitudinal directions, with a larger contraction seen in the longitudinal direction than the transverse direction at the lowest temperature. The overall value of thermal contraction at 76 K is not significantly different for the ground insulation than that shown previously for the other two types of test specimens, which is to be expected since all of the materials tested are composed primarily of glass fabric and epoxy resin.

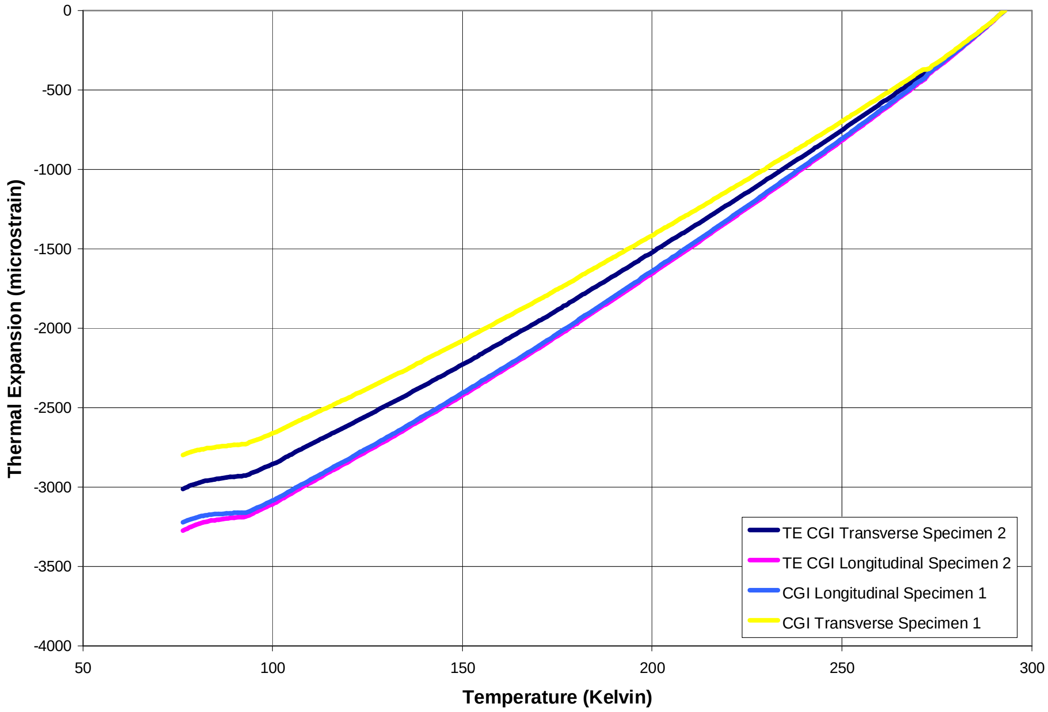

Figure 32. Thermal expansion of modular coil bundle ground insulation without conductor.
CGI – Coil Ground Insulation.

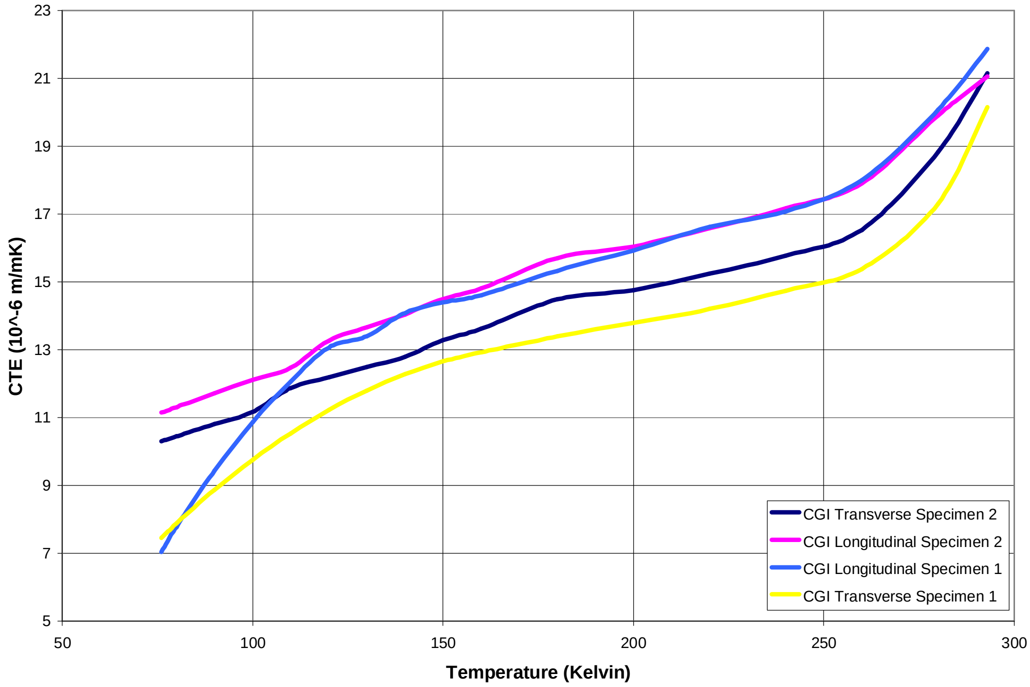

Figure 33. CTD of modular coil bundle ground insulation without conductor.
CGI – Coil Ground Insulation.

Appendix A

Individual Test Results and Datasheets

Linear Cure Shrinkage Test Results - ASTM D2566

TEST CONDITIONS

Material:	**CTD-101K Neat Resin**	**Resin weight of casting:**	**100 grams**
Matrix:	**CTD-101K**	**Ambient temperature:**	**72 - 76°F**
Reinforcement:	**NA**		
Fiber Lay-up:	**NA**	**Cure Cycle:**	**2.5h ramp to 110°C**
Nominal Specimen Dimensions:	**10 In.**		**5h @ 110°C**
Material Reference:	**7021-300**		**1h ramp to 125°C**
Customer:	**PPPL**		**16h @ 125°C**
Specimen Conditioning:	**NA**		**10h cool to 25°C**
Test Fixture:	**10" linear shrinkage mold**		
Test Date:	**5/14/03 - 5/26/03**		

TEST RESULTS

Specimen #	Inside Mold Length (in)	Specimen Length (in)	Difference in Length (in)	Film Thickness (in)	Linear Shrinkage	Percent Linear Shrinkage
1	10.00	9.830	0.170	0.0010	0.017	1.68%
2	10.00	9.877	0.123	0.0010	0.012	1.21%
3	10.00	9.851	0.149	0.0010	0.015	1.47%
4	10.00	9.838	0.162	0.0010	0.016	1.60%
5	10.00	9.850	0.150	0.0010	0.015	1.48%
6	10.00	9.855	0.145	0.0010	0.014	1.43%

Average:	0.015	1.48%
Standard Deviation:	0.002	0.16%
Coefficient of Variation:	0.108	0.108

Compression Test Results

TEST CONDITIONS

Matrix System:	**101K**	**Load Range Card:**	**+/- 50 Kip**
Reinforcement:	**Glass Tape**	**Stroke Range Card:**	**+/- 0.5 in.**
Barrier:	**Kapton Film**	**Temperature Contr**	**Lakeshore 330**
Specimen Type:	**Single Modular Coil Compres**	**Temperature Senso**	**Thermocouple**
Material Reference:	**Princeton NCSX**		
	7021-300	**Specimen**	
		Conditioning:	**NA**
Load Rate:	**0.00033 in/s**		
Strain Measurement:	**2 Strain Gages- SK-06-S080W-350**		
		Test	
Test Fixture:	**3 inch platens**	**Temperature:**	**76 K**
Test Date:	**6/3/2003**		

TEST RESULTS

Specimen #	Thickness (in)	Width (in)	Length (in)	X-Section Area (in^2)	Young's Modulus (Msi)	LVDT Young's Modulus (Msi)	Ultimate Load (lbs)	Comp. Strength (ksi)	Failure Mode
3	0.995	0.654	0.786	0.514	6.7	3.1	25048.8	48.8	Split
4	0.991	0.656	0.785	0.515	5.5	2.6	25243.7	49.1	Unwrap
9	0.987	0.655	0.790	0.517	5.0	4.7	25096.2	48.5	Split
11	0.985	0.655	0.790	0.517	4.0	4.1	23379.9	45.2	Unwrap
23*	0.984	0.635	0.792	0.503	5.4	3.3	25484.9	50.7	Split
24*	0.989	0.651	0.786	0.512	5.1	3.0	24097.2	47.1	Split

	Compression Strength		Compression Modulus		Compression Modulus LVDT	
	ksi	MPa	Msi	GPa	Msi	GPa
Average	48.2	332.5	5.3	36.4	3.4	23.7
Std. Dev.:	1.9	12.9	0.9	6.1	0.8	5.3
CV:	0.04	0.04	0.17	0.17	0.22	0.22

* these two additional tests performed on 6/17/03

Compression Test Results

TEST CONDITIONS

Matrix System:	**101K**	**Load Range Card:**	**+/- 50 Kip**
Reinforcement:	**Glass Tape**	**Stroke Range Card:**	**+/- 0.5 in**
Barrier:	**Kapton Film**	**Temperature Control**	**Lakeshore 330**
Specimen Type:	**Single Modular Coil Compres**	**Temperature Sensor:**	**Thermocouple**
Material Reference:	**Princeton NCSX**		
	7021-300	**Specimen Conditioning:**	**NA**
Load Rate:	**0.00033 in/s**		
Strain Measurement:	**2 Strain Gages- SK-06-S080W-350**		
Test Fixture:	**1 inch platens**	**Test Temperature:**	**100 K**
Test Date:	**6/4/2003**		

TEST RESULTS

Specimen #	Thickness (in)	Width (in)	Length (in)	X-Section Area (in^2)	Young's Modulus (Msi)	LVDT Young's Modulus (Msi)	Ultimate Load (lbs)	Comp. Strength (ksi)	Failure Mode
5	0.983	0.655	0.788	0.516	5.0	3.5	23510.7	45.6	Unwrap
6	0.990	0.655	0.785	0.514	5.4	4.3	22354.5	43.5	Unwrap
7	0.992	0.654	0.790	0.516	5.4	4.6	24734.4	47.9	Split
8	0.992	0.655	0.786	0.515	4.7	3.5	23682.1	46.0	Split
12*	0.992	0.659	0.787	0.518	5.5	2.7	22870.6	44.2	Unwrap
17*	0.980	0.655	0.783	0.512	14.7	3.5	24292.5	47.4	Unwrap

	Compression Strength		Compression Modulus		Compression Modulus LVDT	
	ksi	MPa	Msi	GPa	Msi	GPa
Average	45.8	315.5	6.8	46.7	3.7	25.4
Std. Dev.:	1.8	12.1	3.9	26.8	0.7	4.6
CV:	0.04	0.04	0.57	0.57	0.18	0.18

* these two additional tests performed on 6/17/03

Compression Test Results

TEST CONDITIONS

Matrix System:	**101K**	**Load Range Card:**	**+/- 50 Kip**
Reinforcement:	**Glass Tape**	**Stroke Range Card:**	**+/- 0.5 in.**
Barrier:	**Kapton Film**	**Temperature Controll**	**Lakeshore 330**
Specimen Type:	**Single Modular Coil Compres**	**Temperature Sensor:**	**Thermocouple**
Material Reference:	**Princeton NCSX**		
	7021-300	**Specimen Conditioning:**	**NA**
Load Rate:	**0.00033 in/s**		
Strain Measurement:	**2 Strain Gages- SK-06-S080W-350**		
Test Fixture:	**3 inch platens**	**Test Temperature:**	**150 K**
Test Date:	**6/4/2003**		

TEST RESULTS

Specimen #	Thickness (in)	Width (in)	Length (in)	X-Section Area (in^2)	Young's Modulus (Msi)	LVDT Young's Modulus (Msi)	Ultimate Load (lbs)	Comp. Strength (ksi)	Failure Mode
2	0.984	0.654	0.788	0.515	12.2	4.0	21026.4	40.8	Split
10	0.989	0.655	0.789	0.517	7.2	3.6	20733.4	40.1	Split
13	0.991	0.655	0.789	0.516	4.5	4.3	20836.9	40.3	Unwrap
19	0.993	0.658	0.789	0.519	6.6	2.7	20336.4	39.2	Split
18*	0.992	0.651	0.787	0.512	10.3	5.2	20629.9	40.3	Split
22*	0.990	0.652	0.782	0.509	6.7	3.1	22702.1	44.6	Unwrap

	Compression Strength		Compression Modulus		Compression Modulus LVDT	
	ksi	MPa	Msi	GPa	Msi	GPa
Average	40.9	281.9	7.9	54.4	3.8	26.1
Std. Dev.:	1.9	12.9	2.8	19.3	0.9	6.3
CV:	0.05	0.05	0.35	0.35	0.24	0.24

* these two additional tests performed on 6/17/03

Compression Test Results

TEST CONDITIONS

Matrix System:	**101K**	**Load Range Card:**	**+/- 50 Kip**
Reinforcement:	**Glass Tape**	**Stroke Range Card**	**+/- 0.5 in.**
Barrier:	**Kapton Film**	**Temperature Cont**	**Lakeshore 330**
Specimen Type:	**Single Modular Coil Compr**	**Temperature Senso**	**Thermocouple**
Material Reference:	**Princeton NCSX**		
	7021-300	**Specimen Conditioning:**	**NA**
Load Rate:	**0.00033 in/s**		
Strain Measurement:	**2 Strain Gages- J2A-06-S033P-350**		
Test Fixture:	**3 inch platens**	**Test Temperature:**	**295 K (RT)**
Test Date:	**6/3/2003**		

TEST RESULTS

Specimen #	Thickness (in)	Width (in)	Length (in)	X-Section Area (in^2)	Young's Modulus (Msi)	LVDT Young's Modulus (Msi)	Ultimate Load (lbs)	Comp. Strength (ksi)	Failure Mode
14	0.991	0.655	0.789	0.516	62.6	3.0	13638.2	26.4	Unwrap
15	0.987	0.652	0.789	0.514	28.2	2.6	12978.0	25.2	Unwrap
16	0.991	0.653	0.787	0.514	48.9	2.3	13110.4	25.5	Unwrap
1	0.990	0.656	0.789	0.517	20.4	2.6	14209.0	27.5	Unwrap
20*	0.990	0.650	0.784	0.509	8.9	4.8	13999.5	27.5	Split
21*	0.989	0.655	0.786	0.515	53.1	2.5	14039.6	27.3	Split

	Compression Strength		Compression Modulus		Compression Modulus LVDT	
	ksi	MPa	Msi	GPa	Msi	GPa
Average	26.6	183.2	37.0	255.1	2.9	20.2
Std. Dev.:	1.0	6.9	21.0	144.7	0.9	6.3
CV:	0.04	0.04	0.57	0.57	0.31	0.31

* these two additional tests performed on 6/16/03

Tension Test Results

TEST CONDITIONS

Matrix System:	**CTD-101K**	***Load Range Card:***	**±50 Kip**
Reinforcement:	**Glass Tape**	***Stroke Range Card:***	**±1.0 in.**
Barrier:	**Kapton**	***Temperature Controller:***	**Lakeshore 330**
Specimen Type:	**Single Modular Coil Tension**	***Temperature Sensor:***	**Si Diode #D47355**
Material Reference:	**Princeton NCSX**		
Material Reference:	**7021-300**		
Load Rate:	**0.00033 in/s**	***Specimen Conditioning:***	**NA**
Strain Measurement:	**Dual 0°/90° strain gages**		
Strain Gage Type:	**SK-06-125TM-350**		
Test Fixture:	**Tension fixture**	***Test Temperature:***	**76 K**
Test Date:	**9/11-12/2003**		

TEST RESULTS

Specimen #	Length (in)	Width (in)	Depth (in)	Area (in^2)	Ultimate Load (lbs)	Tensile Strength (ksi)	Tensile Modulus (Msi)	Poisson's Ratio
1	7.20	0.495	0.638	0.316	10961.9	34.7	17.4	0.39
5	7.20	0.503	0.646	0.325	11450.2	35.2	13.7	0.39
10	7.20	0.528	0.653	0.345	11355.0	32.9	13.6	0.39
19	7.20	0.526	0.641	0.337	11168.5	33.1	13.6	0.35
20	7.20	0.510	0.645	0.329	10495.6	31.9	13.6	0.40

	Tensile Strength	
	ksi	MPa
Average	33.6	231.6
Std. Dev.	1.4	9.4
CV:	0.04	0.04

	Tensile Modulus	
	ksi	GPa
Average	14.4	99.2
Std. Dev.	1.69	11.6
CV:	0.12	0.12

	Poisson's Ratio
Average	0.38
Std. Dev.	0.02
CV:	0.05

Tension Test Results

TEST CONDITIONS

Matrix System:	**CTD-101K**	***Load Range Card:***	**±50 Kip**
Reinforcement:	**Glass Tape**	***Stroke Range Card:***	**±1.0 in.**
Barrier:	**Kapton**	***Temperature Controller:***	**Lakeshore 330**
Specimen Type:	**Single Modular Coil Tension**	***Temperature Sensor:***	**Si Diode #D47355**
Material Reference:	**Princeton NCSX**		
Material Reference:	**7021-300**		
Load Rate:	**0.00033 in/s**	***Specimen Conditioning:***	**NA**
Strain Measurement:	**Dual 0°/90° strain gages**		
Strain Gage Type:	**SK-06-125TM-350**		
Test Fixture:	**Tension fixture**	***Test Temperature:***	**100 K**
Test Date:	**9/9-10/2003**		

TEST RESULTS

Specimen #	Length (in)	Width (in)	Depth (in)	Area (in^2)	Ultimate Load (lbs)	Tensile Strength (ksi)	Tensile Modulus (Msi)	Poisson's Ratio
2	7.33	0.519	0.643	0.334	11010.7	33.0	12.7	0.37
16	7.30	0.526	0.644	0.339	10465.3	30.9	12.5	0.35
21	7.12	0.514	0.652	0.335	10913.6	32.6	12.0	0.34
22	7.30	0.518	0.638	0.330	10412.1	31.5	12.5	0.45

	Tensile Strength ksi	Tensile Strength MPa
Average	32.0	220.6
Std. Dev.	1.0	6.6
CV:	0.03	0.03

	Tensile Modulus ksi	Tensile Modulus GPa
Average	12.4	85.7
Std. Dev.	0.30	2.1
CV:	0.02	0.02

	Poisson's Ratio
Average	0.38
Std. Dev.	0.05
CV:	0.13

Tension Test Results

TEST CONDITIONS

Matrix System:	**CTD-101K**	***Load Range Card:***	**±50 Kip**
Reinforcement:	**Glass Tape**	***Stroke Range Card:***	**±1.0 in.**
Barrier:	**Kapton**	***Temperature Controller:***	**Lakeshore 330**
Specimen Type:	**Single Modular Coil Tension**	***Temperature Sensor:***	**Si Diode #D47355**
Material Reference:	**Princeton NCSX**		
Material Reference:	**7021-300**		
Load Rate:	**0.00033 in/s**	***Specimen Conditioning:***	**NA**
Strain Measurement:	**Dual 0°/90° strain gages**		
Strain Gage Type:	**SK-06-125TM-350**		
Test Fixture:	**Tension fixture**	***Test Temperature:***	**150 K**
Test Date:	**8/14/2003**		

TEST RESULTS

Specimen #	Length (in)	Width (in)	Depth (in)	Area (in^2)	Ultimate Load (lbs)	Tensile Strength (ksi)	Tensile Modulus (Msi)	Poisson's Ratio
4	6.87	0.527	0.631	0.333	9130.9	27.5	15.3	0.32
8	7.36	0.519	0.625	0.324	9033.2	27.8	13.7	0.29
17	6.95	0.514	0.628	0.323	8453.6	26.2	12.6	0.28
18	6.97	0.500	0.647	0.324	8618.7	26.6	13.5	0.22
24	7.02	0.520	0.622	0.323	9399.4	29.1	15.2	0.38

	Tensile Strength	
	ksi	MPa
Average	27.4	189.2
Std. Dev.	1.1	7.7
CV:	0.04	0.04

	Tensile Modulus	
	ksi	GPa
Average	14.1	96.9
Std. Dev.	1.16	8.0
CV:	0.08	0.08

	Poisson's Ratio
Average	0.30
Std. Dev.	0.06
CV:	0.20

Tension Test Results

TEST CONDITIONS

Matrix System:	**CTD-101K**	***Load Range Card:***	**±50 Kip**
Reinforcement:	**Glass Tape**	***Stroke Range Card:***	**±1.0 in.**
Barrier:	**Kapton**	***Temperature Controller:***	**Lakeshore 330**
Specimen Type:	**Single Modular Coil Tension**	***Temperature Sensor:***	**Si Diode #D47355**
Material Reference:	**Princeton NCSX**		
Material Reference:	**7021-300**		
Load Rate:	**0.00033 in/s**	***Specimen Conditioning:***	**NA**
Strain Measurement:	**Dual 0°/90° strain gages**		
Strain Gage Type:	**SK-06-125TM-350**		
Test Fixture:	**Tension fixture**	***Test Temperature:***	**295 K**
Test Date:	**8/12/2003**		

TEST RESULTS

Specimen #	Length (in)	Width (in)	Depth (in)	Area (in^2)	Ultimate Load (lbs)	Tensile Strength (ksi)	Tensile Modulus (Msi)	Poisson's Ratio
3	7.69	0.497	0.622	0.309	8287.1	26.8	*	*
6	7.32	0.491	0.608	0.299	7763.7	26.0	*	*
7	7.27	0.522	0.618	0.323	7763.7	24.1	*	*
9	7.25	0.529	0.626	0.331	8225.6	24.8	13.9	0.12
12	7.28	0.544	0.649	0.353	8303.7	23.5	12.5	0.17

* Invalid strain gage data

	Tensile Strength ksi	Tensile Strength MPa
Average	25.0	172.7
Std. Dev.	1.4	9.4
CV:	0.05	0.05

	Tensile Modulus ksi	Tensile Modulus GPa
Average	13.2	91.0
Std. Dev.	0.99	6.8
CV:	0.07	0.07

	Poisson's Ratio
Average	0.15
Std. Dev.	0.04
CV:	0.24

ISMC Flexure Test Results - ASTM D 790

TEST CONDITIONS

Matrix System:	**101K**	**Load Range Card:**	**+/- 4 Kip**
Reinforcement:	**Glass Tape**	**Stroke Range Card:**	**+/- 1 in.**
Barrier:	**Kapton Film**	**Temperature Controller:**	**Lakeshore 330**
Specimen Type:	**Single Modular Coil Flexure B**	**Temperature Sensor:**	**Silicon Diode**
Material Reference:	**Princeton NCSX 7021-300**	**Specimen Orientation:**	**Specimens loaded Flatwise**
Load Rate:	**0.00033 in/s**		
Strain Measurement:	**MTS LVDT**		
Test Fixture:	**3 point bend**	**Test Temperature:**	**76 K**
Test Date:	**6/20/2003**		

TEST RESULTS

Specimen #	Thickness (in)	Width (in)	Length (in)	Span (in)	Span Ratio	Flex. Modulus (Msi)	Ultimate Load (lbs)	Flexural Strength (ksi)
2	0.658	0.773	10.06	8.000	12.2	4.1	1137.3	40.9
7	0.650	0.773	10.02	8.000	12.3	4.3	1149.2	42.3
8	0.655	0.771	10.00	8.000	12.2	4.3	1241.7	45.1
23	0.645	0.772	9.99	8.000	12.4	4.4	1168.4	43.7

	Flexural Strength	
	ksi	MPa
Average	43.0	296.5
Std. Dev.	1.8	12.7
CV:	0.04	0.04

	Flexural Modulus	
	ksi	GPa
Average	4.3	29.4
Std. Dev.	0.13	0.9
CV:	0.03	0.03

ISMC Flexure Test Results - ASTM D 790

TEST CONDITIONS

Matrix System:	**101K**	**Load Range Card:**	**+/- 4 Kip**
Reinforcement:	**Glass Tape**	**Stroke Range Card:**	**+/- 1 in.**
Barrier:	**Kapton Film**	**Temperature Controller:**	**Lakeshore 330**
Specimen Type:	**Single Modular Coil Flexure B**	**Temperature Sensor:**	**Silicon Diode**
Material Reference:	**Princeton NCSX 7021-300**	**Specimen Orientation:**	**Specimens loaded Edgewise**
Load Rate:	**0.00033 in/s**		
Strain Measurement:	**MTS LVDT**		
Test Fixture:	**3 point bend**	**Test Temperature:**	**76 K**
Test Date:	**6/20/2003**		

TEST RESULTS

Specimen #	Thickness (in)	Width (in)	Length (in)	Span (in)	Span Ratio	Flex. Modulus (Msi)	Ultimate Load (lbs)	Flexural Strength (ksi)
10	0.772	0.652	10.02	8.000	10.4	3.9	1475.2	45.6
19	0.775	0.650	9.98	8.000	10.3	4.2	1426.3	43.9

	Flexural Strength	
	ksi	MPa
Average	44.8	308.6
Std. Dev.	1.2	8.1
CV:	0.03	0.03

	Flexural Modulus	
	ksi	GPa
Average	4.0	27.9
Std. Dev.	0.16	1.1
CV:	0.04	0.04

ISMC Flexure Test Results - ASTM D 790

TEST CONDITIONS

Matrix System:	**101K**	**Load Range Card:**	**+/- 4 Kip**
Reinforcement:	**Glass Tape**	**Stroke Range Card:**	**+/- 1 in.**
Barrier:	**Kapton Film**	**Temperature Controller:**	**Lakeshore 330**
Specimen Type:	**Single Modular Coil Flexure B**	**Temperature Sensor:**	**Silicon Diode**
Material Reference:	**Princeton NCSX 7021-300**	**Specimen Orientation:**	**Specimens loaded Flatwise**
Load Rate:	**0.00033 in/s**		
Strain Measurement:	**MTS LVDT**		
Test Fixture:	**3 point bend**	**Test Temperature:**	**100 K**
Test Date:	**6/23/2003**		

TEST RESULTS

Specimen #	Thickness (in)	Width (in)	Length (in)	Span (in)	Span Ratio	Flex. Modulus (Msi)	Ultimate Load (lbs)	Flexural Strength (ksi)
5	0.650	0.771	10.06	8.000	12.3	4.6	1123.8	41.4
13	0.653	0.772	9.94	8.000	12.3	4.1	1088.8	39.7
14	0.652	0.771	10.00	8.000	12.3	4.1	1042.7	38.2

	Flexural Strength	
	ksi	MPa
Average	39.8	274.1
Std. Dev.	1.6	11.1
CV:	0.04	0.04

	Flexural Modulus	
	ksi	GPa
Average	4.3	29.6
Std. Dev.	0.30	2.1
CV:	0.07	0.07

ISMC Flexure Test Results - ASTM D 790

TEST CONDITIONS

Matrix System:	**101K**	**Load Range Card:**	**+/- 4 Kip**
Reinforcement:	**Glass Tape**	**Stroke Range Card:**	**+/- 1 in.**
Barrier:	**Kapton Film**	**Temperature Controller:**	**Lakeshore 330**
Specimen Type:	**Single Modular Coil Flexure B**	**Temperature Sensor:**	**Silicon Diode**
Material Reference:	**Princeton NCSX 7021-300**	**Specimen Orientation:**	**Specimens loaded Edgewise**
Load Rate:	**0.00033 in/s**		
Strain Measurement:	**MTS LVDT**		
Test Fixture:	**3 point bend**	**Test Temperature:**	**100 K**
Test Date:	**6/24/2003**		

TEST RESULTS

Specimen #	Thickness (in)	Width (in)	Length (in)	Span (in)	Span Ratio	Flex. Modulus (Msi)	Ultimate Load (lbs)	Flexural Strength (ksi)
17	0.773	0.651	10.00	8.000	10.3	4.9	1346.0	41.5
22	0.770	0.657	10.00	8.000	10.4	4.5	1389.9	42.9
24	0.771	0.652	10.05	8.000	10.4	4.1	1473.4	45.7

	Flexural Strength	
	ksi	MPa
Average	43.4	299.0
Std. Dev.	2.1	14.6
CV:	0.05	0.05

	Flexural Modulus	
	ksi	GPa
Average	4.5	31.0
Std. Dev.	0.37	2.6
CV:	0.08	0.08

ISMC Flexure Test Results - ASTM D 790

TEST CONDITIONS

Matrix System:	**101K**	**Load Range Card:**	**+/- 4 Kip**
Reinforcement:	**Glass Tape**	**Stroke Range Card:**	**+/- 1 in.**
Barrier:	**Kapton Film**	**Temperature Controller:**	**Lakeshore 330**
Specimen Type:	**Single Modular Coil Flexure B**	**Temperature Sensor:**	**Silicon Diode**
Material Reference:	**Princeton NCSX 7021-300**	**Specimen Orientation:**	**Specimens loaded Flatwise**
Load Rate:	**0.00033 in/s**		
Strain Measurement:	**MTS LVDT**		
Test Fixture:	**3 point bend**	**Test Temperature:**	**150 K**
Test Date:	**6/23/2003**		

TEST RESULTS

Specimen #	Thickness (in)	Width (in)	Length (in)	Span (in)	Span Ratio	Flex. Modulus (Msi)	Ultimate Load (lbs)	Flexural Strength (ksi)
3	0.648	0.771	9.98	8.000	12.3	4.5	1098.2	40.7
9	0.654	0.770	10.02	8.000	12.2	4.3	1060.4	38.7
12	0.646	0.770	9.98	8.000	12.4	4.1	1036.9	38.8

	Flexural Strength	
	ksi	MPa
Average	39.4	271.5
Std. Dev.	1.1	7.9
CV:	0.03	0.03

	Flexural Modulus	
	ksi	GPa
Average	4.3	29.5
Std. Dev.	0.21	1.4
CV:	0.05	0.05

ISMC Flexure Test Results - ASTM D 790

TEST CONDITIONS

Matrix System:	**101K**	**Load Range Card:**	**+/- 4 Kip**
Reinforcement:	**Glass Tape**	**Stroke Range Card:**	**+/- 1 in.**
Barrier:	**Kapton Film**	**Temperature Controller:**	**Lakeshore 330**
Specimen Type:	**Single Modular Coil Flexure B**	**Temperature Sensor:**	**Silicon Diode**
Material Reference:	**Princeton NCSX 7021-300**	**Specimen Orientation:**	**Specimens loaded Edgewise**
Load Rate:	**0.00033 in/s**		
Strain Measurement:	**MTS LVDT**		
Test Fixture:	**3 point bend**	**Test Temperature:**	**150 K**
Test Date:	**6/23/2003**		

TEST RESULTS

Specimen #	Thickness (in)	Width (in)	Length (in)	Span (in)	Span Ratio	Flex. Modulus (Msi)	Ultimate Load (lbs)	Flexural Strength (ksi)
16	0.773	0.648	9.99	8.000	10.4	3.9	1294.1	40.2
18	0.775	0.650	9.98	8.000	10.3	3.7	1258.0	38.7
21	0.772	0.659	9.97	8.000	10.4	4.6	1239.4	37.9

	Flexural Strength	
	ksi	MPa
Average	38.9	268.2
Std. Dev.	1.2	8.0
CV:	0.03	0.03

	Flexural Modulus	
	ksi	GPa
Average	4.1	28.2
Std. Dev.	0.48	3.3
CV:	0.12	0.12

ISMC Flexure Test Results - ASTM D 790

TEST CONDITIONS

Matrix System:	**101K**	**Load Range Card:**	**+/- 4 Kip**
Reinforcement:	**Glass Tape**	**Stroke Range Card:**	**+/- 1 in.**
Barrier:	**Kapton Film**	**Temperature Controller:**	**Lakeshore 330**
Specimen Type:	**Single Modular Coil Flexure B**	**Temperature Sensor:**	**Silicon Diode**
Material Reference:	**Princeton NCSX 7021-300**	**Specimen Orientation:**	**Specimens loaded Flatwise**
Load Rate:	**0.00033 in/s**		
Strain Measurement:	**MTS LVDT**		
Test Fixture:	**3 point bend**	**Test Temperature:**	**295 K**
Test Date:	**6/19/2003**		

TEST RESULTS

Specimen #	Thickness (in)	Width (in)	Length (in)	Span (in)	Span Ratio	Flex. Modulus (Msi)	Ultimate Load (lbs)	Flexural Strength (ksi)
1*	0.654	0.777	10.05	8.000	12.2	3.9	765.1	27.7
6	0.651	0.771	9.96	8.000	12.3	4.0	756.4	27.8
15	0.651	0.770	9.98	8.000	12.3	3.9	752.3	27.7

	Flexural Strength	
	ksi	MPa
Average	27.7	191.1
Std. Dev.	0.1	0.5
CV:	0.00	0.00

	Flexural Modulus	
	ksi	GPa
Average	3.9	27.2
Std. Dev.	0.02	0.2
CV:	0.01	0.01

ISMC Flexure Test Results - ASTM D 790

TEST CONDITIONS

Matrix System:	**101K**	**Load Range Card:**	**+/- 4 Kip**
Reinforcement:	**Glass Tape**	**Stroke Range Card:**	**+/- 1 in.**
Barrier:	**Kapton Film**	**Temperature Controller:**	**Lakeshore 330**
Specimen Type:	**Single Modular Coil Flexure Be**	**Temperature Sensor:**	**Silicon Diode**
Material Reference:	**Princeton NCSX 7021-300**	**Specimen Orientation:**	**Specimens loaded Edgewise**
Load Rate:	**0.00033 in/s**		
Strain Measurement:	**MTS LVDT**		
Test Fixture:	**3 point bend**	**Test Temperature:**	**295 K**
Test Date:	**6/19/2003**		

TEST RESULTS

Specimen #	Thickness (in)	Width (in)	Length (in)	Span (in)	Span Ratio	Flex. Modulus (Msi)	Ultimate Load (lbs)	Flexural Strength (ksi)
4	0.771	0.655	10.06	8.000	10.4	3.8	960.3	29.7
11	0.770	0.654	9.98	8.000	10.4	3.8	949.2	29.4
20	0.770	0.650	9.99	8.000	10.4	3.5	948.3	29.6

	Flexural Strength	
	ksi	MPa
Average	29.5	203.6
Std. Dev.	0.1	1.0
CV:	0.00	0.00

	Flexural Modulus	
	ksi	GPa
Average	3.7	25.5
Std. Dev.	0.18	1.2
CV:	0.05	0.05

2 x 2 MCB Flexure Test Results - ASTM D 790

TEST CONDITIONS

Matrix System:	**101K**	**Load Range Card:**	**+/- 50 Kip**
Reinforcement:	**Glass Tape**	**Stroke Range Card:**	**+/- 1 in.**
Barrier:	**Kapton Film**	**Temperature Controll**	**Lakeshore 330**
Specimen Type:	**2x2 Coil Flexure Beam**	**Temperature Sensor:**	**Silicon Diode**
Material Reference:	**Princeton NCSX 7021-300**	**Specimen Orientation:**	
Load Rate:	**0.00033 in/s**		
Strain Measurement:	**MTS LVDT**		
Test Fixture:	**3 point bend**	**Test Temperature:**	**76 K**
Test Date:	**9/26/2003**		

TEST RESULTS

Specimen #	Thickness (in)	Width (in)	Length (in)	Span (in)	Span Ratio	Flex. Modulus (Msi)	Ultimate Load (lbs)	Flexural Strength (ksi)
3A	1.337	1.634	18.13	16.0	12.0	3.4	5002.4	41.1
8B	1.341	1.605	18.05	16.0	11.9	4.1	4883.8	40.6
9B	1.344	1.603	18.00	16.0	11.9	4.4	4863.8	40.4
10A	1.339	1.599	18.05	16.0	11.9	4.4	4999.0	41.9
11B	1.332	1.592	18.00	16.0	12.0	4.2	4801.8	40.8
12B	1.345	1.578	18.05	16.0	11.9	4.2	4824.2	40.6

	Flexural Strength	
	ksi	MPa
Average	40.9	282.0
Std. Dev.	0.5	3.7
CV:	0.01	0.01

	Flexural Modulus	
	Msi	GPa
Average	4.1	28.4
Std. Dev.	0.37	2.5
CV:	0.09	0.09

2 x 2 MCB Flexure Test Results - ASTM D 790

TEST CONDITIONS

Matrix System:	**101K**	**Load Range Card:**	**+/- 50 Kip**
Reinforcement:	**Glass Tape**	**Stroke Range Card:**	**+/- 1 in.**
Barrier:	**Kapton Film**	**Temperature Controll**	**Lakeshore 330**
Specimen Type:	**2x2 Coil Flexure Beam**	**Temperature Sensor:**	**Silicon Diode**
Material Reference:	**Princeton NCSX 7021-300**	**Specimen Orientation:**	
Load Rate:	**0.00033 in/s**		
Strain Measurement:	**MTS LVDT**		
Test Fixture:	**3 point bend**	**Test Temperature:**	**100 K**
Test Date:	**9/26/2003**		

TEST RESULTS

Specimen #	Thickness (in)	Width (in)	Length (in)	Span (in)	Span Ratio	Flex. Modulus (Msi)	Ultimate Load (lbs)	Flexural Strength (ksi)
2A	1.335	1.621	18.00	16.0	12.0	3.1	4082.5	33.9
4B	1.336	1.608	18.05	16.0	12.0	3.6	4293.0	35.9
6A	1.337	1.608	18.00	16.0	12.0	2.9	3736.8	31.2
7A	1.360	1.573	18.00	16.0	11.8	3.9	4882.8	40.3
8A	1.344	1.607	18.05	16.0	11.9	2.8	4443.8	36.8
9A	1.333	1.609	18.05	16.0	12.0	2.9	3871.1	32.5

	Flexural Strength ksi	Flexural Strength MPa
Average	35.1	242.0
Std. Dev.	3.3	22.5
CV:	0.09	0.09

	Flexural Modulus Msi	Flexural Modulus GPa
Average	3.2	22.1
Std. Dev.	0.45	3.1
CV:	0.14	0.14

2 x 2 MCB Flexure Test Results - ASTM D 790

TEST CONDITIONS

Matrix System:	**101K**	**Load Range Card:**	**+/- 50 Kip**
Reinforcement:	**Glass Tape**	**Stroke Range Card:**	**+/- 1 in.**
Barrier:	**Kapton Film**	**Temperature Controll**	**Lakeshore 330**
Specimen Type:	**2x2 Coil Flexure Beam**	**Temperature Sensor:**	**Silicon Diode**
Material Reference:	**Princeton NCSX**		
	7021-300	**Specimen Orientation:**	
Load Rate:	**0.00033 in/s**		
Strain Measurement:	**MTS LVDT**		
Test Fixture:	**3 point bend**	**Test Temperature:**	**150 K**
Test Date:	**9/26/2003**		

TEST RESULTS

Specimen #	Thickness (in)	Width (in)	Length (in)	Span (in)	Span Ratio	Flex. Modulus (Msi)	Ultimate Load (lbs)	Flexural Strength (ksi)
1B	1.377	1.606	18.13	16.0	11.6	2.7	3734.9	29.4
2B	1.332	1.615	18.13	16.0	12.0	2.9	3554.7	29.8
3B	1.353	1.609	18.00	16.0	11.8	2.9	3515.6	28.6
4A	1.344	1.620	18.00	16.0	11.9	2.9	3856.5	31.6
6B	1.336	1.592	18.13	16.0	12.0	2.9	3248.1	27.4
11A	1.357	1.602	18.05	16.0	11.8	3.1	4125.8	33.6

	Flexural Strength	
	ksi	MPa
Average	30.1	207.5
Std. Dev.	2.2	15.2
CV:	0.07	0.07

	Flexural Modulus	
	Msi	GPa
Average	2.9	20.0
Std. Dev.	0.12	0.8
CV:	0.04	0.04

2 x 2 MCB Flexure Test Results - ASTM D 790

TEST CONDITIONS

Matrix System:	**101K**	**Load Range Card:**	**+/- 50 Kip**
Reinforcement:	**Glass Tape**	**Stroke Range Card:**	**+/- 1 in.**
Barrier:	**Kapton Film**	**Temperature Controll**	**Lakeshore 330**
Specimen Type:	**2x2 Coil Flexure Beam**	**Temperature Sensor:**	**Silicon Diode**
Material Reference:	**Princeton NCSX 7021-300**	**Specimen Orientation:**	
Load Rate:	**0.00033 in/s**		
Strain Measurement:	**MTS LVDT**		
Test Fixture:	**3 point bend**	**Test Temperature:**	**295 K**
Test Date:	**9/19/2003**		

TEST RESULTS

Specimen #	Thickness (in)	Width (in)	Length (in)	Span (in)	Span Ratio	Flex. Modulus (Msi)	Ultimate Load (lbs)	Flexural Strength (ksi)
1A	1.378	1.605	18.00	16.0	11.6	2.4	3315.4	26.1
5A	1.340	1.621	18.00	16.0	11.9	2.6	3272.5	27.0
7B	1.361	1.580	18.00	16.0	11.8	2.6	3011.2	24.7
10B	1.338	1.599	18.00	16.0	12.0	2.7	3002.9	25.2
12A	1.332	1.595	18.00	16.0	12.0	2.4	2953.1	25.0
*	-	-	-	-	-	-	-	-

	Flexural Strength	
	ksi	MPa
Average	25.6	176.6
Std. Dev.	0.9	6.4
CV:	0.04	0.04

	Flexural Modulus	
	Msi	GPa
Average	2.6	17.6
Std. Dev.	0.16	1.1
CV:	0.06	0.06

2 x 2 MCB Shear Test Results - ASTM D 2344

TEST CONDITIONS

Matrix System:	**101K**	**Load Range Card:**	**+/- 50 Kip**
Reinforcement:	**Glass Tape**	**Stroke Range Card:**	**+/- 1 in.**
Barrier:	**Kapton Film**	**Temperature Controll**	**Lakeshore 330**
Specimen Type:	**2x2 Coil Short Beam Shear**	**Temperature Sensor:**	**Silicon Diode**
Material Reference:	**Princeton NCSX 7021-300**	**Specimen Orientation:**	
Load Rate:	**0.00033 in/s**		
Strain Measurement:	**MTS LVDT**		
Test Fixture:	**3 point bend**	**Test Temperature:**	**76 K**
Test Date:	**9/24/2003**		

TEST RESULTS

Specimen #	Thickness (in)	Width (in)	Length (in)	Span (in)	Span Ratio	Flex. Modulus (Msi)	Ultimate Load (lbs)	Apparent Shear Strength (ksi)
13C	1.362	1.509	6.99	6.7	4.9	2.5	10253.9	3.7
13D	1.351	1.526	7.09	6.7	5.0	1.8	10790.5	3.9
14C	1.365	1.520	7.04	6.7	4.9	2.4	11035.6	4.0
16B	1.338	1.497	7.07	6.7	5.0	2.1	10889.2	4.1
16D	1.341	1.521	7.01	6.7	5.0	2.5	9938.5	3.7
16E	1.350	1.522	7.03	6.7	5.0	2.4	10277.3	3.8

	Shear Strength ksi	Shear Strength MPa
Average	3.9	26.6
Std. Dev.	0.2	1.1
CV:	0.04	0.04

	Flexural Modulus Msi	Flexural Modulus GPa
Average	2.3	15.8
Std. Dev.	0.27	1.8
CV:	0.12	0.12

2 x 2 MCB Shear Test Results - ASTM D 2344

TEST CONDITIONS

Matrix System:	**101K**	**Load Range Card:**	**+/- 50 Kip**
Reinforcement:	**Glass Tape**	**Stroke Range Card:**	**+/- 1 in.**
Barrier:	**Kapton Film**	**Temperature Controll**	**Lakeshore 330**
Specimen Type:	**2x2 Coil Short Beam Shear**	**Temperature Sensor:**	**Silicon Diode**
Material Reference:	**Princeton NCSX**		
	7021-300	**Specimen Orientation:**	
Load Rate:	**0.00033 in/s**		
Strain Measurement:	**MTS LVDT**		
Test Fixture:	**3 point bend**	**Test Temperature:**	**100 K**
Test Date:	**9/23/2003**		

TEST RESULTS

Specimen #	Thickness (in)	Width (in)	Length (in)	Span (in)	Span Ratio	Flex. Modulus (Msi)	Ultimate Load (lbs)	Apparent Shear Strength (ksi)
13B	1.359	1.525	7.00	6.7	4.9	1.3	8632.8	3.1
14A	1.339	1.493	7.09	6.7	5.0	1.3	8054.7	3.0
15C	1.352	1.524	7.01	6.7	5.0	2.1	10501.0	3.8
15E	1.337	1.509	7.03	6.7	5.0	2.6	10511.2	3.9
17A	1.343	1.483	7.05	6.7	5.0	2.3	10422.9	3.9
17D	1.347	1.501	7.07	6.7	5.0	2.6	9985.4	3.7

	Shear Strength	
	ksi	MPa
Average	3.6	24.7
Std. Dev.	0.4	2.8
CV:	0.11	0.11

	Flexural Modulus	
	Msi	GPa
Average	2.0	14.0
Std. Dev.	0.62	4.3
CV:	0.31	0.31

2 x 2 MCB Shear Test Results - ASTM D 2344

TEST CONDITIONS

Matrix System:	**101K**	**Load Range Card:**	**+/- 50 Kip**
Reinforcement:	**Glass Tape**	**Stroke Range Card:**	**+/- 1 in.**
Barrier:	**Kapton Film**	**Temperature Controll**	**Lakeshore 330**
Specimen Type:	**2x2 Coil Short Beam Shear**	**Temperature Sensor:**	**Silicon Diode**
Material Reference:	**Princeton NCSX 7021-300**	**Specimen Orientation:**	
Load Rate:	**0.00033 in/s**		
Strain Measurement:	**MTS LVDT**		
Test Fixture:	**3 point bend**	**Test Temperature:**	**150 K**
Test Date:	**9/22/2003**		

TEST RESULTS

Specimen #	Thickness (in)	Width (in)	Length (in)	Span (in)	Span Ratio	Flex. Modulus (Msi)	Ultimate Load (lbs)	Apparent Shear Strength (ksi)
13E	1.352	1.530	7.03	6.7	5.0	1.5	9668.0	3.5
14D	1.367	1.507	7.07	6.7	4.9	1.2	7861.8	2.9
14E	1.360	1.532	7.02	6.7	4.9	1.1	7473.1	2.7
15A	1.325	1.509	7.04	6.7	5.1	1.3	7031.7	2.6
16C	1.342	1.507	7.04	6.7	5.0	1.2	7446.3	2.8
17B	1.341	1.532	7.00	6.7	5.0	1.2	7934.6	2.9

	Shear Strength ksi	Shear Strength MPa
Average	2.9	20.0
Std. Dev.	0.3	2.2
CV:	0.11	0.11

	Flexural Modulus Msi	Flexural Modulus GPa
Average	1.2	8.6
Std. Dev.	0.13	0.9
CV:	0.10	0.10

2 x 2 MCB Shear Test Results - ASTM D 2344

TEST CONDITIONS

Matrix System:	**101K**	**Load Range Card:**	**+/- 50 Kip**
Reinforcement:	**Glass Tape**	**Stroke Range Card:**	**+/- 1 in.**
Barrier:	**Kapton Film**	**Temperature Controll**	**Lakeshore 330**
Specimen Type:	**2x2 Coil Short Beam Shear**	**Temperature Sensor:**	**Silicon Diode**
Material Reference:	**Princeton NCSX 7021-300**	**Specimen Orientation:**	
Load Rate:	**0.00033 in/s**		
Strain Measurement:	**MTS LVDT**		
Test Fixture:	**3 point bend**	**Test Temperature:**	**295 K**
Test Date:	**9/19/2003**		

TEST RESULTS

Specimen #	Thickness (in)	Width (in)	Length (in)	Span (in)	Span Ratio	Flex. Modulus (Msi)	Ultimate Load (lbs)	Apparent Shear Strength (ksi)
13A	1.344	1.536	7.04	6.7	5.0	1.0	6082.0	2.2
14B	1.353	1.510	7.05	6.7	5.0	1.1	5855.5	2.2
15D	1.341	1.527	7.03	6.7	5.0	1.1	5545.9	2.0
16A	1.340	1.506	7.08	6.7	5.0	1.1	5688.5	2.1
17C	1.343	1.483	7.05	6.7	5.0	1.1	6074.7	2.3
15B	1.338	1.520	7.06	6.7	5.0	1.1	5788.1	2.1

	Shear Strength	
	ksi	MPa
Average	2.2	14.9
Std. Dev.	0.1	0.6
CV:	0.04	0.04

	Flexural Modulus	
	Msi	GPa
Average	1.1	7.6
Std. Dev.	0.04	0.3
CV:	0.03	0.03

CTE Test Results

TEST CONDITIONS

Material:	Single Insulated Modular Coil Conductor, #1	**Load Range Card:**	NA
Matrix:	CTD-101K	**Stroke Range Card:**	NA
Reinforcement:	Kapton film interwoven w/ glass fabric attached to Cu Conductor		
Fiber Lay-up:	NA		
Nominal Specimen Dimensions:	26 mm L x 20 mm W x 17 mm T		
Material Reference:	7021-300		
Customer:	PPPL		
Load Rate:	NA		
Strain Measurement:	.125 inch Strain Gage Zero/90 Configuration	**Specimen Conditioning:**	NA
Strain Gage Type:	SK-06-125TM-350		
Test Fixture:	CTE Test Fixture	**Test Temperature:**	76-293 K
Test Date:	7/30/2003	**Temperature Hold Time:**	Natural Warm-up

TEST RESULTS

Specimen	Single Insulated Modular Coil Conductor Longitudinal Direction		
Temperature (Kelvin)	TE (microstrain)	Percent TE	CTE 10x-6 m/mK
76	-3563	-0.36	9.53
80	-3515	-0.35	9.84
90	-3413	-0.34	10.57
100	-3309	-0.33	11.74
110	-3194	-0.32	12.70
120	-3064	-0.31	13.10
130	-2931	-0.29	13.51
140	-2790	-0.28	14.62
150	-2636	-0.26	15.42
160	-2479	-0.25	15.76
180	-2156	-0.22	16.44
200	-1810	-0.18	17.64
220	-1447	-0.14	18.34
240	-1074	-0.11	18.86
260	-686	-0.07	19.40
280	-264	-0.03	21.66
293	0	0.00	22.35

Specimen	Single Insulated Modular Coil Conductor Transverse Direction		
Temperature (Kelvin)	TE (microstrain)	Percent TE	CTE 10x-6 m/mK
76	-3203	-0.32	9.41
80	-3163	-0.32	9.89
90	-3054	-0.31	10.97
100	-2944	-0.29	12.00
110	-2824	-0.28	12.85
120	-2689	-0.27	13.73
130	-2551	-0.26	14.53
140	-2405	-0.24	15.27
150	-2245	-0.22	15.94
160	-2081	-0.21	16.54
180	-1743	-0.17	17.53
200	-1388	-0.14	18.08
220	-1073	-0.11	18.92
240	-776	-0.08	19.77
260	-479	-0.05	20.63
280	-187	-0.02	21.49
293	0	0.00	22.00

CTE Test Results

TEST CONDITIONS

Material:	Single Insulated Modular Coil Conductor, #2	**Load Range Card:**	NA
Matrix:	CTD-101K	**Stroke Range Card:**	NA
Reinforcement:	Kapton film interwoven w/ glass fabric attached to Cu Conductor		
Fiber Lay-up:	NA		
Nominal Specimen Dimensions:	26 mm L x 20 mm W x 17 mm T		
Material Reference:	7021-300		
Customer:	PPPL		
Load Rate:	NA		
Strain Measurement:	.125 inch Strain Gage Zero/90 Configuration	**Specimen Conditioning:**	NA
Strain Gage Type:	SK-06-125TM-350		
Test Fixture:	CTE Test Fixture	**Test Temperature:**	76-293 K
Test Date:	8/6/2003	**Temperature Hold Time:**	Natural Warm-up

TEST RESULTS

Specimen 2	Single Insulated Modular Coil Conductor Longitudinal Direction		
Temperature (Kelvin)	TE (microstrain)	Percent TE	CTE 10x-6 m/mK
76	-3224	-0.32	8.87
80	-3195	-0.32	9.14
90	-3150	-0.31	9.79
100	-3108	-0.31	10.37
110	-3074	-0.31	11.01
120	-2983	-0.30	11.65
130	-2855	-0.29	13.39
140	-2718	-0.27	15.77
150	-2561	-0.26	15.97
160	-2400	-0.24	16.17
180	-2074	-0.21	16.57
200	-1724	-0.17	17.38
220	-1360	-0.14	17.72
240	-1001	-0.10	18.06
260	-631	-0.06	18.61
280	-245	-0.02	19.69
293	0	0.00	20.50

Specimen 2	Single Insulated Modular Coil Conductor Transverse Direction		
Temperature (Kelvin)	TE (microstrain)	Percent TE	CTE 10x-6 m/mK
76	-2923	-0.29	11.14
80	-2895	-0.29	11.28
90	-2853	-0.29	11.62
100	-2814	-0.28	11.92
110	-2790	-0.28	12.26
120	-2696	-0.27	12.59
130	-2558	-0.26	14.06
140	-2412	-0.24	15.15
150	-2254	-0.23	16.24
160	-2087	-0.21	16.71
180	-1749	-0.17	17.24
200	-1401	-0.14	17.43
220	-1085	-0.11	17.80
240	-784	-0.08	18.16
260	-485	-0.05	18.53
280	-183	-0.02	18.91
293	0	0.00	19.13

CTE Test Results

TEST CONDITIONS

Material:	Modular Coil Turn Insulation, #1	**Load Range Card:**	NA
Matrix:	CTD-101K	**Stroke Range Card:**	NA
Reinforcement:	Kapton film interwoven w/ glass fabric		
Fiber Lay-up:	NA		
Nominal Specimen Dimensions:	44mm L x 14mm W x 2.3 mm T		
Material Reference:	7021-300		
Customer:	PPPL		
Load Rate:	NA		
Strain Measurement:	.125 inch Strain Gage Zero/90 Configuration	**Specimen Conditioning:**	NA
Strain Gage Type:	SK-06-125TM-350		
Test Fixture:	CTE Test Fixture	**Test Temperature:**	76-293 K
Test Date:	8/14/2003	**Temperature Hold Time:**	Natural Warm-up

TEST RESULTS

Specimen 1	Modular Coil Turn Insulation Longitudinal Direction		
Temperature (Kelvin)	TE (microstrain)	Percent TE	CTE 10x-6 m/mK
76	-3325	-0.33	7.33
80	-3271	-0.33	8.17
90	-3181	-0.32	9.67
100	-3077	-0.31	11.00
110	-2962	-0.30	12.16
120	-2837	-0.28	13.17
130	-2705	-0.27	14.05
140	-2563	-0.26	14.80
150	-2404	-0.24	15.43
160	-2254	-0.23	15.91
180	-1925	-0.19	16.74
200	-1584	-0.16	17.30
220	-1235	-0.12	17.71
240	-896	-0.09	18.05
260	-559	-0.06	18.43
280	-253	-0.03	18.95
293	0	0.00	19.36

Specimen 1	Modular Coil Turn Insulation Transverse Direction		
Temperature (Kelvin)	TE (microstrain)	Percent TE	CTE 10x-6 m/mK
76	-3221	-0.32	11.28
80	-3150	-0.32	11.62
90	-3049	-0.30	12.24
100	-2935	-0.29	12.78
110	-2809	-0.28	13.26
120	-2677	-0.27	13.67
130	-2537	-0.25	14.03
140	-2389	-0.24	14.34
150	-2228	-0.22	14.60
160	-2071	-0.21	14.81
180	-1714	-0.17	15.16
200	-1376	-0.14	15.43
220	-1073	-0.11	15.64
240	-782	-0.08	15.85
260	-488	-0.05	16.11
280	-183	-0.02	16.45
293	0	0.00	16.71

CTE Test Results

TEST CONDITIONS

Material:	**Modular Coil Turn Insulation, #2**	**Load Range Card:**	**NA**
Matrix:	**CTD-101K**	**Stroke Range Card:**	**NA**
Reinforcement:	**Kapton film interwoven w/ glass fabric**		
Fiber Lay-up:	**NA**		
Nominal Specimen Dimensions:	**44mm L x 14mm W x 2.3 mm T**		
Material Reference:	**7021-300**		
Customer:	**PPPL**		
Load Rate:	**NA**		
Strain Measurement:	**.125 inch Strain Gage Zero/90 Configuration**	**Specimen Conditioning:**	**NA**
Strain Gage Type:	**SK-06-125TM-350**		
Test Fixture:	**CTE Test Fixture**	**Test Temperature:**	**76-293 K**
Test Date:	**8/14/2003**	**Temperature Hold Time:**	**Natural Warm-up**

TEST RESULTS

Specimen 2	Modular Coil Turn Insulation Longitudinal Direction		
Temperature (Kelvin)	TE (microstrain)	Percent TE	CTE 10x-6 m/mK
76	-3321	-0.33	7.81
80	-3258	-0.33	8.59
90	-3172	-0.32	10.00
100	-3068	-0.31	11.29
110	-2952	-0.30	12.45
120	-2828	-0.28	13.49
130	-2695	-0.27	14.43
140	-2552	-0.26	15.26
150	-2243	-0.22	15.99
160	-1915	-0.19	16.57
180	-1591	-0.16	17.61
200	-1573	-0.16	18.36
220	-1226	-0.12	18.87
240	-887	-0.09	19.19
260	-549	-0.05	19.37
280	-242	-0.02	19.45
293	0	0.00	19.47

Specimen 2	Modular Coil Turn Insulation Transverse Direction		
Temperature (Kelvin)	TE (microstrain)	Percent TE	CTE 10x-6 m/mK
76	-3235	-0.32	10.58
80	-3172	-0.32	11.08
90	-3067	-0.31	11.98
100	-2952	-0.30	12.80
110	-2825	-0.28	13.52
120	-2690	-0.27	14.16
130	-2549	-0.25	14.72
140	-2400	-0.24	15.22
150	-2235	-0.22	15.64
160	-2077	-0.21	15.97
180	-1736	-0.17	16.56
200	-1414	-0.14	16.97
220	-1106	-0.11	17.25
240	-803	-0.08	17.45
260	-499	-0.05	17.61
280	-188	-0.02	17.77
293	0	0.00	17.89

CTE Test Results

TEST CONDITIONS

Material:	Coil Ground Insulation, #1	**Load Range Card:**	NA
Matrix:	CTD-101K	**Stroke Range Card:**	NA
Reinforcement:			
Fiber Lay-up:	NA		
Nominal Specimen Dimensions:	44mm L x 14mm W x 2.3 mm T		
Material Reference:	7021-300		
Customer:	PPPL		
Load Rate:	NA		
Strain Measurement:	.125 inch Strain Gage Zero/90 Configuration	**Specimen Conditioning:**	NA
Strain Gage Type:	SK-06-125TM-350		
Test Fixture:	CTE Test Fixture	**Test Temperature:**	76-293 K
Test Date:	7/30/2003	**Temperature Hold Time:**	Natural Warm-up

TEST RESULTS

Specimen 1	Coil Ground Insulation Longitudinal Direction		
Temperature (Kelvin)	TE (microstrain)	Percent TE	CTE 10x-6 m/mK
76	-3220	-0.3200	7.12
80	-3183	-0.3200	7.12
90	-3160	-0.3200	8.58
100	-3072	-0.3100	12.02
110	-2951	-0.3000	12.92
120	-2819	-0.2800	13.16
130	-2686	-0.2700	13.39
140	-2547	-0.2500	13.95
150	-2404	-0.2400	14.36
160	-2258	-0.2300	14.76
180	-1954	-0.2000	15.57
200	-1634	-0.1600	16.03
220	-1308	-0.1300	16.51
240	-972	-0.1000	17.10
260	-619	-0.0600	17.72
280	-240	-0.0200	19.54
293	0	0.0000	20.32

Specimen 1	Coil Ground Insulation Transverse Direction		
Temperature (Kelvin)	TE (microstrain)	Percent TE	CTE 10x-6 m/mK
76	-2796.208	-0.28	7.75
80	-2763.31	-0.28	7.75
90	-2731.675	-0.27	7.71
100	-2651.199	-0.27	10.66
110	-2547.239	-0.25	10.98
120	-2434.336	-0.24	11.34
130	-2318.887	-0.23	11.70
140	-2198.346	-0.22	12.06
150	-2073.405	-0.21	12.42
160	-1947.676	-0.19	12.75
180	-1685.112	-0.17	13.39
200	-1409.682	-0.14	13.80
220	-1129.757	-0.11	14.20
240	-840.3753	-0.08	14.75
260	-534.6406	-0.05	15.39
280	-224.2617	-0.02	17.30
293	0	0.00	20.16

CTE Test Results

TEST CONDITIONS

Material:	Coil Ground Insulation, #2	**Load Range Card:**	NA
Matrix:	CTD-101K	**Stroke Range Card:**	NA
Reinforcement:			
Fiber Lay-up:	NA		
Nominal Specimen Dimensions:	44mm L x 14mm W x 2.3 mm T		
Material Reference:	7021-300		
Customer:	PPPL		
Load Rate:	NA		
Strain Measurement:	.125 inch Strain Gage Zero/90 Configuration	**Specimen Conditioning:**	NA
Strain Gage Type:	SK-06-125TM-350		
Test Fixture:	CTE Test Fixture	**Test Temperature:**	76-293 K
Test Date:	8/6/2003	**Temperature Hold Time:**	Natural Warm-up

TEST RESULTS

Specimen 2	Coil Ground Insulation Longitudinal Direction		
Temperature (Kelvin)	TE (microstrain)	Percent TE	CTE 10x-6 m/mK
76	-3272	-0.3272	11.15
80	-3228	-0.3228	11.32
90	-3188	-0.3188	11.71
100	-3094	-0.3094	12.11
110	-2970	-0.2970	12.47
120	-2837	-0.2837	13.28
130	-2703	-0.2703	13.66
140	-2563	-0.2563	14.05
150	-2419	-0.2419	14.50
160	-2273	-0.2273	14.81
180	-1969	-0.1969	15.70
200	-1648	-0.1648	16.04
220	-1321	-0.1321	16.58
240	-984	-0.0984	17.16
260	-629	-0.0629	17.90
280	-247	-0.0247	19.91
293	0	0.0000	21.05

Specimen 2	Coil Ground Insulation Transverse Direction		
Temperature (Kelvin)	TE (microstrain)	Percent TE	CTE 10x-6 m/mK
76	-3009	-0.30	10.30
80	-2969	-0.30	10.45
90	-2931	-0.29	10.81
100	-2843	-0.28	11.17
110	-2729	-0.27	11.88
120	-2606	-0.26	12.18
130	-2484	-0.25	12.49
140	-2357	-0.24	12.79
150	-2225	-0.22	13.28
160	-2091	-0.21	13.62
180	-1811	-0.18	14.48
200	-1516	-0.15	14.76
220	-1215	-0.12	15.24
240	-905	-0.09	15.78
260	-578	-0.06	16.54
280	-238	-0.02	18.83
293	0	0.00	21.16