NSTX

NATIONAL SPHERICAL TORUS EXPERIMENT

CENTER STACK RESEARCH AND DEVELOPMENT

FINAL REPORT
No. 13-970430-JHC

Prepared By: James H. Chrzanowski
April 30, 1997

PRINCETON UNIVERSITY
PLASMA PHYSICS LABORATORY
(PPPL)
P.O. BOX 451
PRINCETON, N.J. 08543

ACKNOWLEDGMENT

This author acknowledges the hard work and efforts put forth by the following people to complete the R&D activities outlined in this report.

Thomas G. Meighan
Carl Lindemuth
Stephen Jurczynski
Joseph Bartzak
Thomas Sines
Joseph Vannozzi
William Zimmer

TABLE OF CONTENTS

SECTION NO.	DESCRIPTION	PAGE NO.
1.0	INTRODUCTION	1
2.0	INSULATION SHEAR TESTS	1
	2.1 Insulation Schemes	1
	2.2 Specimen Preparation	3
	2.3 Double Lap Shear Tests	3
	2.4 Shear/Compression Tests	6
3.0	INSULATION ELECTRICAL TESTS	9
	3.1 DC Hi-Pot Tests	9
	3.2 AC Hi-Pot Test Results	10
	3.3 DC Megger Tests	10
4.0	OH COIL JOINT DEVELOPMENT TESTS	10
	4.1 Specimen Preparations	10
	4.2 Soft-soldering/ TIG Brazing Operation	11
	4.3 Description of OH Coil Joint Types	11
	4.4 Summary of Static Test Results	14
	4.5 Fatigue Tests of OH Joint	15
5.0	TF JOINT LOAD TESTS	16
	5.1 Joint Resistance Tests	16
	5.2 Bare vs. Silver Plated Joint Test Results	17
	5.3 Vertical Loading Test Results	18
	5.4 Horizontal Loading Test Results	20

TABLE OF CONTENTS

SECTION NO.	DESCRIPTION	PAGE NO.
6.0	TF JOINT INSERT PULL OUT TESTS	22
7.0	OH CONDUCTOR KEYSTONE/WINDING TENSION TESTS	22
	7.1 Test Setup	22
	7.2 Conductor Description	22
	7.3 Trial Winding Results	23
	7.4 Trial Winding Preliminary Conclusions	24
	7.5 Trial Winding No. 3- Machined Conductor	24
	7.6 Winding Tension vs. Insulation Compression	26
8.0	CONCLUSIONS	27
	APPENDIX	28

"CMI" FINAL REPORT ON INSULATION SHEAR TESTS

INDEX OF TABLES

TABLE NO.	DESCRIPTION	PAGE NO.
2-1	Double Lap Shear Test Results- CTD-112 (TF Coil Insulation)	4
2-2	Double Lap Shear Test Results- CTD-112 (TF Coil Insulation)	5
2-3	Double Lap Shear Test Results- Fusa-Fab (TF Coil Insulation)	5
2-4	Bi-Axial Shear Test Results- CTD-112 (TF Coil Insulation)	7
2-5	Bi-Axial Shear Test Results- CTD-112/ with Kapton (OH/PF Coil Insulation)	7
2-6	Shear/Compression Fatigue Test Results- CTD-112 (TF Coil Insulation)	8
2-7	Shear/Compression Fatigue Test Results- CTD-112/ with Kapton (OH/PF Coil Insulation)	8
3-8	DC Hi-Pot Test Results (CTD-112 Insulation)	9
3-9	DC Megger Test Results (CTD-112 Insulation)	10
4-10	Static Test Results- OH Joints	14
4-11	Fatigue Test Results- OH Type VII Joint	15
5-12	Joint Resistance Measurements	16
5-13	Bare vs. Silver Plated Joint Test Results	17
5-14	Vertical Loading Test Results	18
5-15	Vertical Loading Test Results	19
5-16	Vertical Loading Test Results	19
5-17	Horizontal Loading Test Results	20
5-18	Horizontal Loading Test Results	21
5-19	Horizontal Loading Test Results- Load vs. Gap	21
6-20	TF Joint Insert Pull Out Test Results	26

INDEX OF FIGURES

FIGURE NO.	DESCRIPTION	PAGE NO.
2-1	Double Lap Shear Specimen	4
2-2	Shear/Compression Test Specimen	6
4-3	Type I OH Joint	11
4-4	Type II OH Joint	11
4-5	Type III OH Joint	12
4-6	Type IV OH Joint	12
4-7	Type V OH Joint	12
4-8	Type VI OH Joint	13
4-9	Type VII OH Joint	13
4-10	Type VIII OH Joint	13
5-11	Joint Resistance Test Setup	16
5-12	Bare vs. Silver Plated Joint Test Setup	17
5-13	Vertical Load Test Specimen	18
5-14	Horizontal Load Test Specimen	20
7-15	Keystone Trial Winding Results No.1	23
7-16	Keystone Trial Winding Results No. 2	23
7-17	Trial Winding Station	24
7-18	Original OH Copper Cross-Section	25
7-19	OH Copper Conductor With Keystone Cross-Section	25
7-20	Winding Tension vs. Insulation Compression	26

NSTX FINAL REPORT No. 13-970430-JHC
CENTER STACK R&D

1.0 INTRODUCTION:

This NSTX Report summarizes the R&D efforts which have been performed in support of the CenterStack design. Various design issues were investigated including insulation schemes and reliable coil electrical joints. These tests were performed at both PPPL and "Cryogenic Materials Inc." (CMI), an outside consulting firm. A copy of CMI's final report is in Appendix. This report will review those activities which were performed at PPPL. A review of the findings from both reports will be discussed in the conclusion of this report. The R&D tests which are described in this report include:

a. Insulation Shear Tests

b. Insulation Electrical Tests

c. OH Joint Development Tests

d. TF Joint Load Tests

e. TF Joint Insert Pull Out Tests

f. OH Conductor Keystone Tests

g. Winding Tension vs. Insulation Compression Tests

2.0 INSULATION SHEAR TESTS

The purpose of these tests was to evaluate the shear characteristics of the insulation schemes being proposed for the NSTX Center Stack coil bundle. Insulation shear tests were performed at both PPPL and "Cryogenic Materials Inc." (CMI), an outside insulation consultant company. Only PPPL's test data will be presented in this report. CTD's results will be discussed in the conclusion of this report.

Maximum Calculated Insulation Shear Stress

TF Coil	2000 psi
OH Coil	1000 psi

2.1 Insulation Schemes

a. TF Coil Turn Insulation

Two (2) insulation schemes were investigated for use as the turn insulation in the Center Stack TF coil. These insulation products were "GE's Fusa-Fab and "Composite Technology Development Inc." CTD-112P insulation, both pre-impregnated (B-stage) tapes. Description of these insulation's follow.

CTD-112P Pre-impregnated Tape

Resin Type: TGDM epoxy, aromatic amine cure agent
Composite Technology Development (CTD), Boulder, Co
Glass tape: S-2 (satin weave) std. silane finish
Temperature Class: 180° C
Nominal Thk.: 0.0075 in. (0.19 mm.) tape
Nominal Width: 1.0 in. tape
Supplier: Insulating Materials (IMI), Schenectady, NY

IMI Fusa-Fab (76590P) Semi-Cured Polyester Treated Glass Tape

Resin Type: Polyester
Glass Tape: E-glass cloth
Temperature Class: 180° C
Nominal Thk.: 0.006 in. (0.152 mm.) tape
Nominal Width: 1.0 in. tape
Supplier: Insulating Materials (IMI), Schenectady, NY

b. OH and PF Coil Turn Insulation

Only one (1) insulation product was tested for use as the turn insulation in the Center Stack OH and PF coils This product was CTD-112P/ with Kapton.

CTD-112P Pre-impregnated Glass/Co-wound with Kapton

Resin Type: TGDM epoxy, aromatic amine cure agent
Composite Technology Development (CTD), Boulder, Co
Glass tape: S-2 (satin weave) std. silane finish
Temperature Class: 180° C
Nominal Thk.: 0.0075 in. (0.19 mm.) tape
Nominal Width: 1.0 in. tape
Barrier: Kapton
Nominal Thk.: 0.002 (0.05 mm)
Nominal Width: 1.0 in. tape
Supplier: Insulating Materials (IMI), Schenectady, NY

c. Equipment Listing:

- MTS 10 KIP Servo Hydraulic Testing Machine (property No. P07213
- Machine Load Cell (Mod. No. 661.21A-01/ SN 1273
- Revere Load Cell -for horizontal loading (Mod.No. CP1-25-A/ SN 965462-00)
- Love Temp. Controller (Mod.No.151-786-718/ SN 81286-4)
- Biddle Thermocouple Test Set -Mark II (SN 82369)
- Fluke 8060A Multimeter (SN 3020080)

- HP X-Y Recorder (Mod. 7046A/ SN 1914A06544)
- MTS Controller (Mod. No.436/ SN 865)

2.2 Specimen Preparation:

Two (2) types of test specimens were manufactured for use in the insulation tests. These are shown in Figures 2-1 and 2-2.

a. Specimen Substrate: Specimens were cut from 1/8 inch thick ETP 110 copper bar.

b. Substrate Preparation: Substrate surfaces were cleaned, degreased and the insulation contact faces sandblasted.

c. Primer: A thin layer of primer was applied by brush to the sandblasted surfaces which would be in direct contact with the insulation. A product of "Ciba-Geigy (UK) Limited Plastics Division, "DZ-80-1" was used as the conductor primer. The samples were then allowed to air dry prior to proceeding.

d. Insulation: The insulation being tested was applied in layers onto the prepared substrate surfaces. (Refer to specific test sections for description of insulation schemes)

2.3 Double Lap Shear Tests

a. Specimen Preparation:

Figure Number 2-1 shows the details of the double lap specimens. Three (3) layers of pre-impregnated insulation were applied between the prepared (section 2.2) copper plates to form the test specimens. These specimens were oven cured to manufacturers prescribed cure cycle (time vs. temperature). The specimens were compressed 10% of their nominal insulation thickness prior to the cure cycle to enhance their shear strength. The samples were monitored for temperature during the cure cycle.

****

Insulation Cure Cycles

CTD-112P and CTD-112P with Kapton	Fusa-Fab
Ramp up to 177°C in (1) hour	Ramp up to 150°C for (1) hour
Hold at 177°C for 2 hours	Hold at 150°C for (1) hour
Ramp up to 200°C in (1) hour	
Hold at 200°C for 6 hours	

* Air cool all specimens to room temperature while in mold

****

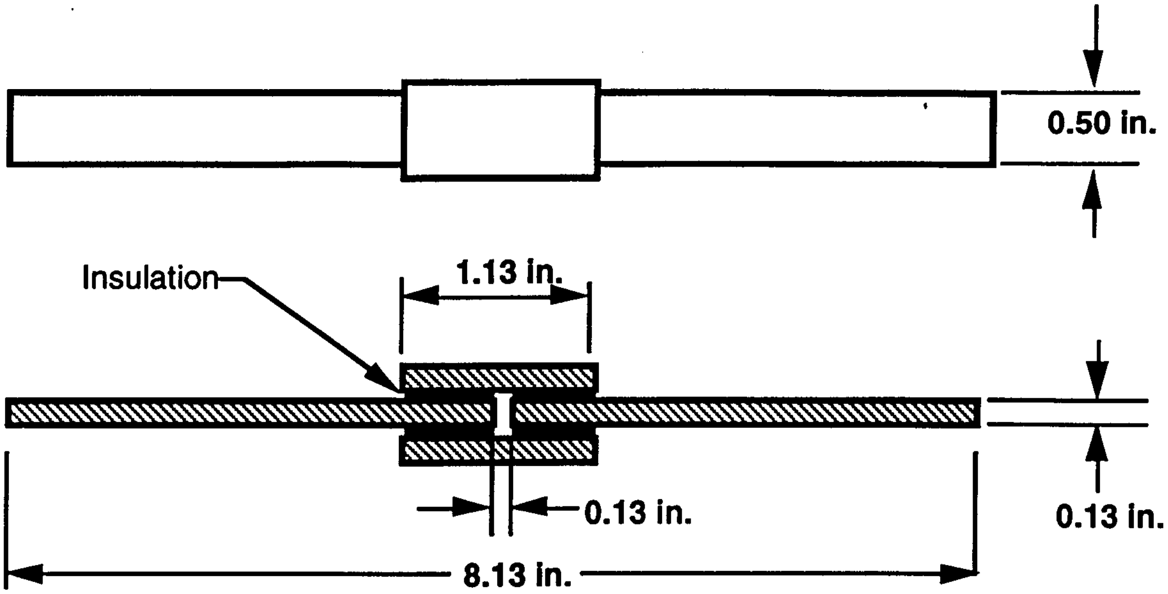


Figure No. 2-1
Double Lap Shear Specimen

b. The double lap shear specimens were tested on a MTS 10 KIP Servo Hydraulic Testing Machine. A machine load cell was utilized to monitored the tensile load applied to the specimen and the results were recorded on a HP X-Y recorder. The shear test results are shown in tables 2-1 thru 2-3.

Table No.2-1
DOUBLE LAP SHEAR TEST RESULTS (TF Coil Insulation)

Insulation Tested:	CTD-112P without Kapton (3) layers
Test Description:	Samples were compressed 10% of nominal insulation thickness during cure cycle. (177°C for 2 hours and 200°C for 6 hours)
Test Date:	2/12/97

Specimen ID No.	Cure Information	Specimen Test Temp. (°C)	Shear Load (Lbs)	Shear Load (psi)	Type of Failure
4	6 hrs. @ 200°C	21.7 *	1385	2770	Inter-laminar
5	2 hrs. @ 177°C	21.7 *	1800	3600	Inter-laminar
6	6 hrs. @ 200°C	21.7 *	1812	3624	Inter-laminar
7	6 hrs. @ 200°C	21.7 *	1385	3770	Inter-laminar
8	6 hrs. @ 200°C	21.7 *	1690	3380	Inter-laminar
9	6 hrs. @ 200°C	100	1630	3260	Inter-laminar
10	6 hrs. @ 200°C	100	640	1280	Inter-laminar
11	6 hrs. @ 200°C	100	2110	4220	Inter-laminar
12	6 hrs. @ 200°C	100	520	1040	Inter-laminar

* Room Temperature 21.7°C (71°F)

Table No.2-2
DOUBLE LAP SHEAR TEST RESULTS (TF Coil Insulation)

Insulation Tested: CTD-112P without Kapton (3) layers
Test Description: Samples were compressed 10% of nominal insulation thickness during cure cycle (177°C for 2 hours and 200°C for 6 hours).
Test Date: 2/22/97

Specimen ID No.	Cure Information	Specimen Temp. (°C)	Shear Load (Lbs)	Shear Load (psi)	Type of Failure
1	6 hrs.@ 200°C	23.9 *	1310	2620	Copper/DZ-80
2	6 hrs.@ 200°C	23.9 *	1340	2680	Inter-laminar
3	6 hrs.@ 200°C	23.9 *	1050	2100	Cu & Inter-laminar
4	6 hrs.@ 200°C	23.9 *	1810	3620	Copper/DZ-80
5	6 hrs.@ 200°C	23.9 *	1310	2620	Inter-laminar
6	6 hrs.@ 200°C	23.9 *	1330	2660	Cu & Inter-laminar
7	6 hrs.@ 200°C	23.9 *	1540	3080	Cu & Inter-laminar
8	6 hrs.@ 200°C	100	910	1820	Cu & Inter-laminar
9	6 hrs.@ 200°C	100	1335	2670	Inter-laminar
10	6 hrs.@ 200°C	60	1630	3260	Cu & Inter-laminar
11	6 hrs.@ 200°C	23.9 *	1680	3360	Inter-laminar
12	6 hrs.@ 200°C	60	1370	2740	Inter-laminar
13	6 hrs.@ 200°C	23.9 *	1240	2480	Cu & Inter-laminar
14	6 hrs.@ 200°C	23.9 *	1210	2420	Copper/DZ-80
15	6 hrs.@ 200°C	23.9 *	1340	2680	Inter-laminar
16	6 hrs.@ 200°C	23.9 *	1220	2440	Cu & Inter-laminar

* Room Temperature 23.9°C (75°F)

Table No.2-3
DOUBLE LAP SHEAR TEST RESULTS (TF Coil Insulation)

Insulation Tested: Fusa Fab without Kapton (3) layers
Test Description: Samples were compressed 10% of nominal insulation thickness during cure cycle.
Test Date: 1/30/97

Specimen ID No.	Cure Information	Specimen Temp. (°C)	Shear Load (Lbs)	Shear Load (psi)	Type of Failure
2	2 hrs.@ 150°C	22 *	1000	2000	Inter-laminar
3	2 hrs.@ 150°C	22 *	912	1824	Inter-laminar
4	2 hrs.@ 150°C	22 *	650	1300	Inter-laminar
5	2 hrs.@ 150°C	22 *	780	1560	Inter-laminar
6	2 hrs.@ 150°C	22 *	260	520	Inter-laminar
7	2 hrs.@ 150°C	22 *	520	1040	Inter-laminar
10	2 hrs.@ 150°C	100	100	200	Inter-laminar
12	2 hrs.@ 150°C	100	105	210	Inter-laminar
14	2 hrs.@ 150°C	100	105	210	Inter-laminar

* Room Temperature 22°C (72°F)

2.4 Shear/Compression Tests

a. Specimen Preparation:

Figure Number 2-2 shows the details of the shear/compression specimens. Three (3) layers of pre-impregnated insulation were applied between the copper plates to form the test specimens. These specimens were cured in an oven to their prescribed cure cycle (See section 2.3a for insulation cure cycles). The specimens were compressed 10% of their nominal insulation thickness prior to the cure cycle. This was done to enhance the shear strength of the samples. The samples were monitored during the cure cycle for temperature..

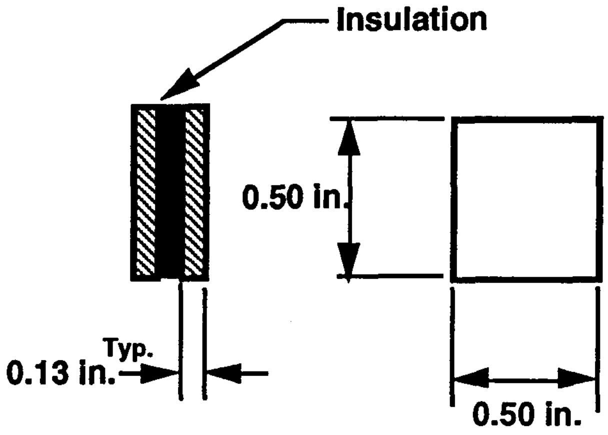


Figure No. 2-2
Shear/Compression Test Specimen

b. The Bi-axial shear specimens were tested on a MTS 10 KIP Servo Hydraulic Testing Machine. Two (2) specimens were held in a fixture which allowed both shear and side compressive loads to be applied. Load cells were utilized to monitor the loads applied to the specimens. The shear loads were recorded on a HP X-Y recorder. Heat was applied using a heat lamp and a Biddle thermocouple test set for monitoring temperature. The Bi-Axial Shear test results are shown in tables 2-4 and 2-5.

Table No. 2-4
BI-AXIAL SHEAR TEST RESULTS (TF Coil Insulation)

Insulation Tested: CTD-112P without Kapton (3) layers
Test Description: Samples were compressed 10% of nominal insulation thickness prior to cure cycle (177°C for 2 hours and 200°C for 6 hours)

Specimen ID No.	Shear Load (Lbs.)	Shear Load (psi) *	Compressive Load (psi)	Specimen Temp (°C)
11	3125	6250	600	60
12	3125	6250	600	60
13	3000	6000	600	60
14	3000	6000	600	60
19	3350	6750	600	60
20	3350	6750	600	60
21	2625	5250	600	60
22	2625	5250	600	60
3	3100	6200	2000	60
4	3100	6200	2000	60
9	3525	7050	1000	60
10	3525	7050	1000	60

* Destructive load

Table No. 2-5
BI-AXIAL SHEAR TEST RESULTS
(OH/PF Coil Insulation)

Insulation Tested: CTD-112P with Kapton
(1) layer CTD-112/ w Kapton
(1) layer CTD-112
(1) layer CTD-112/ w Kapton
Test Description: Samples were compressed 10% of nominal B-stage insulation thickness prior to cure cycle (177°C for 2 hours and 200°C for 6 hours)

Specimen ID No.	Shear Load (Lbs)	Shear Load (psi)*	Compressive Load (psi)	Specimen Temp (°C)
K3	2100	4200	600	100
K4	2100	4200	600	100
K5	2250	4500	600	100
K6	1250	4500	600	100
K7	1550	3100	600	100
K8	1550	3100	600	100
K11	1625	3250	600	100
K12	1625	3250	600	100
K13	1750	3500	600	100
K14	1750	3500	600	100

* Destructive load

c. The Bi-axial Shear Fatigue Tests were conducted on a MTS 10 KIP Servo Hydraulic Testing Machine. Two (2) specimens were held in a fixture which allowed both shear and side compressive loads to be applied. The side compressive load remained constant while the shear load was cycled to represent operational life. Load cells were utilized to monitor the loads applied to the specimens. Heat was applied using a heat lamp and a Biddle thermocouple test set for monitoring temperature. The Bi-Axial Shear test results are shown in tables 2-6 and 2-7.

Table No. 2-6
SHEAR/COMPRESSION FATIGUE TEST RESULTS
(TF Coil Insulation)

Insulation Tested: CTD-112P without Kapton (3) layers
Test Description: Samples were compressed 10% of nominal insulation thickness prior to cure cycle (177°C for 2 hours and 200°C for 6 hours)

Specimen ID No.	Shear Load (psi)	Compressive Load (psi)	Specimen Temp (°C)	Cycles Completed
11	2400	600	60	1,000,000
12	2400	600	60	1,000,000
13	2400	600	60	1,000,000
14	2400	600	60	1,000,000
19	2400	600	60	1,000,000
20	2400	600	60	1,000,000

Table No. 2-7
SHEAR/COMPRESSION FATIGUE TEST RESULTS
(OH/PF Coil Insulation)

Insulation Tested: CTD-112P with Kapton
(1) layer CTD-112/ w Kapton
(1) layer CTD-112
(1) layer CTD-112/ w Kapton

Test Description: Samples were compressed 10% of nominal insulation thickness prior to cure cycle (177°C for 2 hours and 200°C for 6 hours)

Specimen ID No.	Shear Load (psi)	Compressive Load (psi)	Specimen Temp (°C)	Cycles Completed
K3	1000	600	100	300,000
K4	1000	600	100	300,000
K5	1000	600	100	300,000
K6	1000	600	100	300,000
K7	1000	600	100	300,000
K8	1000	600	100	300,000

3.0 INSULATION ELECTRICAL TEST RESULTS

AC and DC electrical tests were performed on the CTD-112P insulation to verify its dielectric integrity. Copper bars were insulated with three (3) half-lapped layers of CTD-112P pre-impregnated insulation. These test specimens were cured with a 10-12% compression of the nominal thickness of the insulation using the manufacturers recommended cure cycle. (2 hours at 177°C and 6 hours at 200°C)

3.1 DC Hi-pot Tests

These tests were performed using a "Von" 100 KV DC Test Set (model No.E-1/ Serial No. 760501).

Table No. 3-8
DC HI-POT TEST RESULTS

Specimen ID	Breakdown Voltage (KV)	Leakage Current Prior to Breakdown (μamps)	Remarks
Bar A - TP A	14	0	3/3/97
Bar A - TP B	22	0	3/3/97
Bar A - TP C	13	0	3/3/97
Bar A - TP D	27	0	3/3/97
Bar A - TP E	17	0.1	3/3/97
Bar A - TP F	16	0.1	3/3/97
Bar A - TP G	19	0.1	3/3/97
Bar A - TP H	19	0.1	3/3/97
Bar A - TP I	23	0.1	3/3/97
Bar A - TP J	26	0.1	3/3/97
Bar B to Bar C #1	13	Breakdown	
Bar B to Bar C #2	13	Breakdown	
Bar B- TP#1	8	Breakdown	Single pt. location
Bar B- TP#2	13	Breakdown	Single pt. location
Bar B- TP#3	4	Breakdown	Single pt. location
Bar B- TP#4	10	Breakdown	Single pt. location

Results: Average breakdown voltage......... 16 KV
Dielectric Strength .... 420 volts/mil

3.2 AC Hi-pot Test Results

These tests were performed using a "Peschel" 60 kV AC Hipot test set (model no. CT-60-10Y/ serial no. 6030A/ P07504)

Test Bar B was tested at an AC voltage of 3 KV and held for a period of 90 minutes without breakdown. (equivalent to 216,000 cycles)

3.3 DC Meggar Tests

DC Megger tests were performed on an uncured insulation specimen to verify the test level to be performed on the TF coil quadrants after assembly and prior to heat cure. Three half-lapped layers of CTD-112P pre-impregnated insulation were applied to a copper test bar. This test specimen remained uncured during testing. These tests were performed using a "Biddle" 5 kV DC Megger test set (cat.no. 210400/ serial no. 75-2736)

Table No. 3-9
DC MEGGER TEST RESULTS

Voltage (volts)	Resistance (MΩ)
500	5,000
1000	10,000
2500	50,000
5000	100,000

4.0 OH COIL JOINT DEVELOPMENT TEST RESULTS

A variety of OH coil joint designs were fabricated and tensile tested determine the most reliable design. The general requirements for the OH coil joint were:

a. Joint must allow current to continue from one coil layer to the next.

b. Each conductor (2 per layer) needed to be cooled separately.

c. Low temperature joining methods needed to be utilized to minimize any annealing of the copper conductor in the joint area due to the calculated coil stresses of (20,000 ksi)

4.1 Specimen Preparations

Test specimens were manufactured using both ETP and CDA 104 copper bar. Each conductor was cleaned and degreased with no additional surface preparation. The following section describes the various joint designs and the results from the static and fatigue tests.

4.2 Soft-Soldering/TIG Brazing Operation

a. The majority of the test joints were made using 96% Tin/ 4% Silver soft-solder, which has a melt temperature of 430°F. The copper specimens were pre-tinned using the 96/4 solder with the assistance of "Stay Clean", a liquid flux. (product of "J.W. Harris")

b. TIG brazing was utilized to provide additional strength in conjunction with the 96/4 solder. Helium was used as the shield gas and Sil-Fos (BCuP-5) the braze material.

c. During the soldering and brazing operations, extreme care was taken to minimize the time that the heat was applied to the copper conductor. The brazing operations took approximately 7-10 seconds. Thermocouples were utilized to monitor the temperature gradient in the joint area.

4.3 Description of OH Coil Joint Types

a. TYPE I JOINT

This joint had a four (4) inch overlap of conductors with square cut ends. The conductors were joined using 96% Tin/ 4% Silver soft solder and liquid flux.

Specimen #1

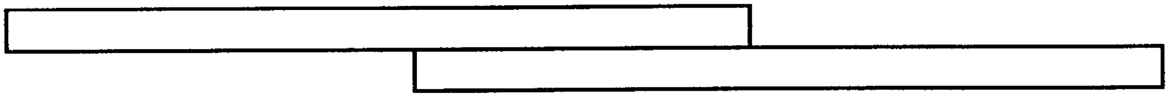


Figure 4-3
Type I OH Joint Specimen

b. TYPE II JOINT

This joint had a four (4) inch overlap of conductors with square cut ends. The conductors were joined using 96% Tin/ 4% Silver soft solder and liquid flux. Two (2) steel clamps were installed to help secure the conductor ends.

Specimen #2

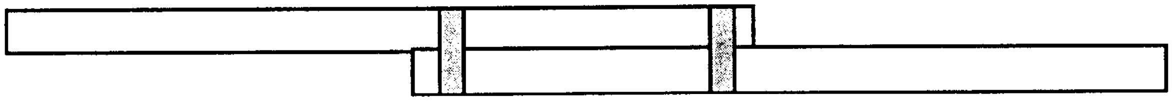


Figure 4-4
Type II OH Joint Specimen

c. TYPE III JOINT

This joint had a four (4) inch overlap of conductors with chamfer cut ends. The conductors were joined using 96% Tin/ 4% Silver soft solder and liquid flux.

Specimen #3

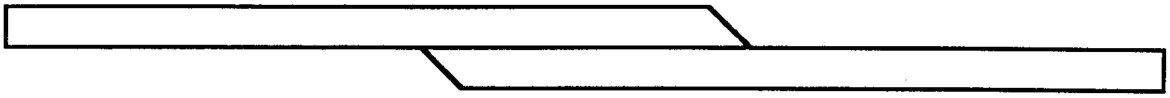


Figure 4-5
Type III OH Joint Specimen

d. TYPE IV JOINT

This joint had a four (4) inch overlap of conductors with chamfer cut ends. The conductors were joined using 96% Tin/ 4% Silver soft solder and liquid flux. Two (2) steel clamps were installed to help secure the conductor ends.

Specimen #4

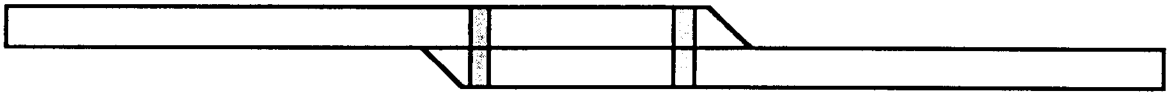


Figure 4-6
Type IV OH Joint Specimen

e. TYPE V JOINT

This type joint was tested with varying overlaps and chamfer end cuts. Varying length 0.032 in. thick copper plates were soldered on both sides of the joint area. The conductors including the side plates were joined using 96% Tin/ 4% Silver soft solder and liquid flux.

Specimen #5	Four (4) inch overlap
Specimen #6	Two (2) inch overlap
Specimen #9	Five (5) inch overlap

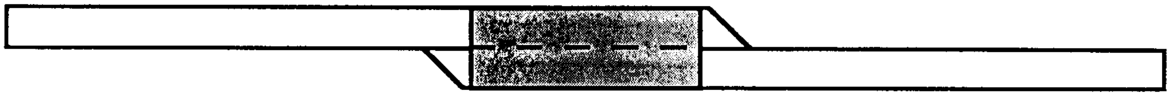


Figure 4-7
Type V OH Joint Specimen

f. TYPE VI JOINT

This joint had a four (4) inch overlap of conductors with chamfer cut ends. Three (3) inch long 0.032 inch thick copper plates were soldered on both sides of the joint area. The conductors including the side plates were joined using 96% Tin/ 4% Silver soft solder. Two (2) steel clamps were installed to help secure the conductor ends.

Specimen #7

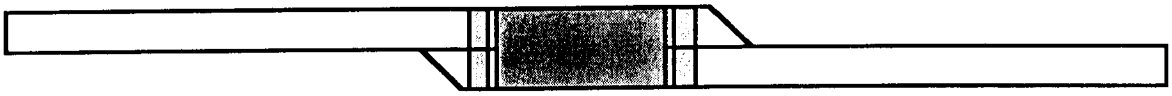


Figure 4-8
Type VI OH Joint Specimen

g. TYPE VII JOINT

This joint had a four (4) inch overlap of conductors with chamfer cut ends. The conductors were joined using 96% Tin/ 4% Silver soft solder. A Sil-Fos TIG braze tack was made at each end of the conductor.

Specimens #8, 10, 11 and 12	
Specimen # 13	Small TIG brazes at each end
Specimen # 14	Small TIG brazes and longer chamfer at each end
Specimen # 16	Conductor had coolant hole through braze area
Specimen # 17	No silver solder. TIG braze only.
Specimen # 18	Full TIG braze and longer chamfer at each end

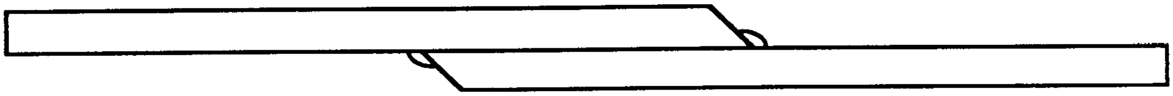


Figure 4-9
Type VII OH Joint Specimen

h. TYPE VIII JOINT

This joint had a four (4) inch overlap of conductors with chamfer cut ends. It was made using Sil-Fos TIG braze tacks at each end of the conductor with two (2) additional tacks on one (1) side and one (1) tack on the other mid-span. No soft-solder was used.

Note: This joint was made to test the mechanical integrity of the TIG braze tacks. No current carrying capabilities were considered in these tests.

Specimens # 19 and 20

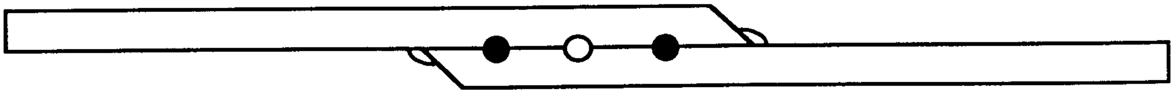


Figure 4-10
Type VIII OH Joint Specimen

Table No. 4-10
STATIC TEST RESULTS- OH JOINT

Specimen ID No.	Joint Type	Destructive Load (Lbs)	Conductor Area (in.^{2})	Ultimate Strength (psi)	Location of Failure
1	I	3940	------	------	Joint
2	II	5440	------	------	Joint
3	III	4100	------	------	Joint
4	IV	4780	------	------	Joint
5	V	3660	------	------	Joint
6	V	7000	------	------	Joint
7	VI	7300	0.1875	40,000	Conductor
8	VII	6680	0.1875	35,627	Conductor
9	V	6900	------	------	Joint
10	VII	6000	0.1875	32,000	Conductor
11	VII	6000	0.1875	32,000	Conductor
12	VII	6120	0.1875	32,640	Conductor
13	VII	7260	0.1875	38,720	Conductor
14	VII	5750	------	------	Joint
15 *	-----	7560	0.1875	39,250	Conductor
16	VII	7660	0.225	34,000	Conductor
17	VII	3340	------	------	TIG Braze
18	VII	6250	0.1875	33,467	Conductor
19	VIII	5880	------	31,956	Conductor
20	VIII	5500	------	------	TIG Braze

* Bar #15 was an uncut copper bar with no joint. It was heated in oven @ 200°C (392°F) for 8 hours with no joint.

Note: No side restraints were used during testing of specimens.

4.4 Summary of Static Test Results

Joint type number VII was the design selected for the OH coil in-line joint. The design provided the maximum strength and durability of any of the joints tested. Every static test performed on the type VII joint resulted in the conductor breaking and the joint remaining intact.

4.5 Fatigue Tests of OH Joint

Fatigue tests were performed on the Type VII OH Joint design using the "MTS 100 KIP Servo Hydraulic Testing Machine". The joints were cycled under load until failure to represent normal operating conditions. Other equipment utilized in these tests were:

a. Machine Load Cell (model 661.23A-02/ serial no. 261)

b. MTS Controller (model no. 442/ serial no.661)

c. MTS Digital Function Generator (model no. 410/ serial no. 27030903)

Table No. 4-11
FATIGUE TEST RESULTS-OH TYPE VII JOINT

Note: Joints were restrained with side clamps (loosely held) to minimize moment in joint.

Specimen ID No.	Conductor Area (in^2)*	Conductor Loading (psi.)	Cyclic Loading (Lbs.)	Completed Cycles ~	Location of Failure
E	0.184	20,000	350-3680	302,100	In conductor away from joint
F	0.1845	20,000	350-3680	417,980	In conductor away from joint
G	0.1844	20,000	350-3688	555,730	In conductor away from joint

* Measured prior to start of cyclic test

5.0 TF COIL JOINT LOAD TESTS

A series of tests were performed to investigate the integrity of the proposed TF coil joints under load conditions. A full size copper joint was fabricated for this purpose.

5.1 Joint Resistance Tests

This test was performed to determine the current distribution through a typical TF joint with a single point feed and return. A power supply was utilized to flow 100 amperes of current through the test bar while resistance measurements were taken along the electrical joint.

Figure No. 5-11
Joint Resistance Test Specimen

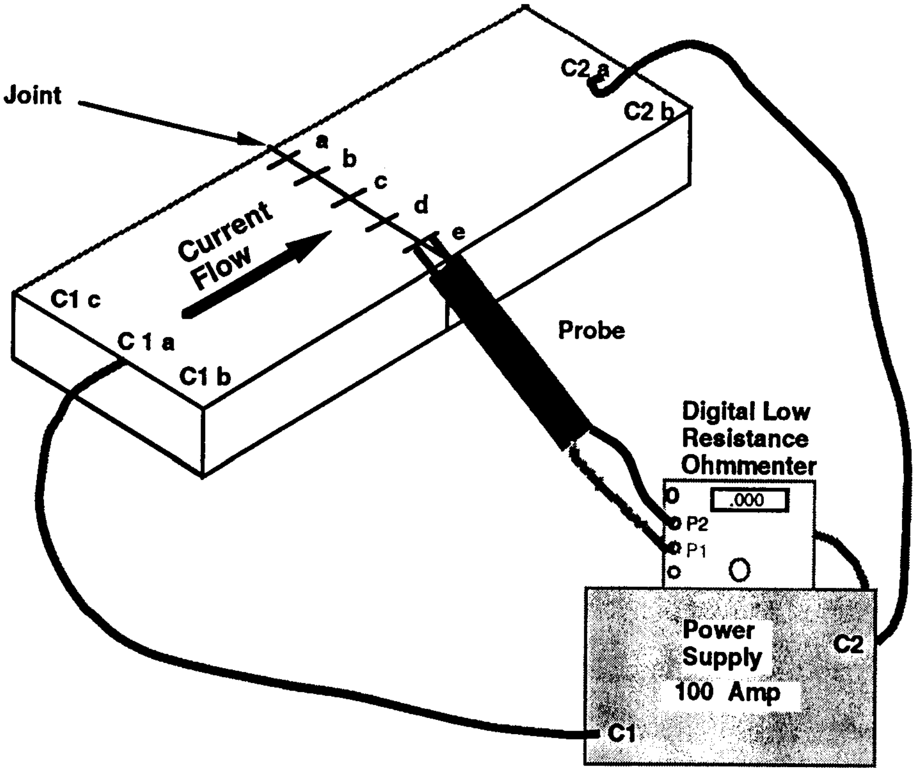


Table No. 5-12
1000 psi Joint Load/Bolt torque 90 In-Lbs.

Joint Resistance (Micro Ohms)

Test Point	Current Feed Terminals C1a/C2a	C1b/C2a	C1c/C2a	C1a/ C2b
a	0.9	0.9	0.8	0.7
b	0.9	0.9	0.9	0.7
c	1.0	0.9	0.9	0.8
d	1.1	0.9	0.9	0.8
e	0.9	0.9	0.9	0.8

5.2 Bare vs. Silver Plated Joint Test Results

Tests were performed to determine the effectiveness of an electrical joint which is bare vs. silver-plated. A full size TF joint model was used as the test stand with current flowing through the joint area. Resistance measurements were taken along the joint line and recorded.

Figure No. 5-12
Bare vs. Silver Plated Joint Test Specimen

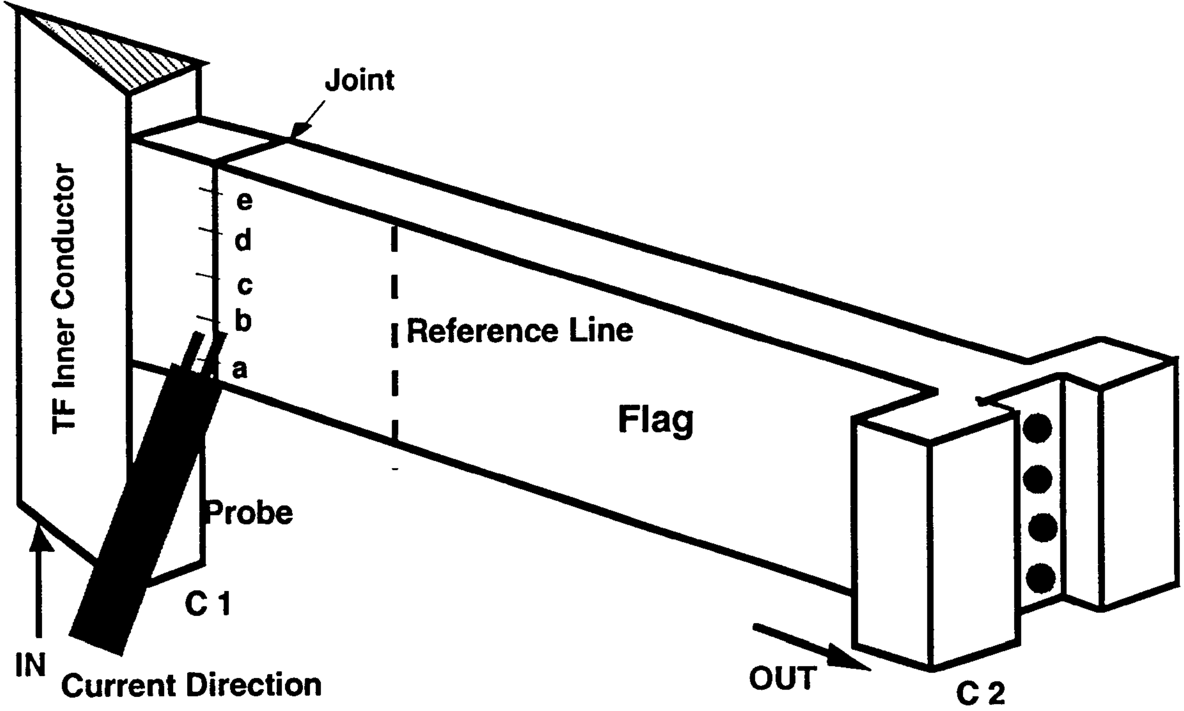


Table No. 5-13
Bare vs. Silver Plated Joint Test Results

	BARE COPPER JOINT Readings in micro Ohms			SILVER PLATED JOINT Readings in micro Ohms			
Test Point	1000 psi 60 amps	2000 psi 60 amps	2000 psi 100 amps	1000 psi 60 amps	1000 psi 100 amps	2000 psi 60 amps	2000 psi 100 amps
a	1.8	0.8	0.7	0.2	0.2	0.2	0.2
b	1.6	0.8	0.7	0.2	0.2	0.1	0.1
c	1.6	0.8	0.7	0.1	0.1	0.1	0.1
d	1.5	0.7	0.7	0.1	0.1	0.1	0.1
e	1.4	0.6	0.5	0.1	0.1	0.1	0.1

Reference measurements made at the reference line on the flag were 0.1 micro ohms.

Joint Load	Bolt Torque
1000 psi	90 in-lb
2000 psi	180 in-lb

5.3 Vertical Loading Test Results

Tests were performed to determine what effect a vertical load would have on the TF coil joint. A full size model of a TF joint was used as the test stand. 100 amperes of current was flowed through the model while varying loads were applied at the end of the bolted tee connector. Resistance measurements were taken along the joint line and recorded.

Figure No. 5-13
Vertical Load Test Specimen

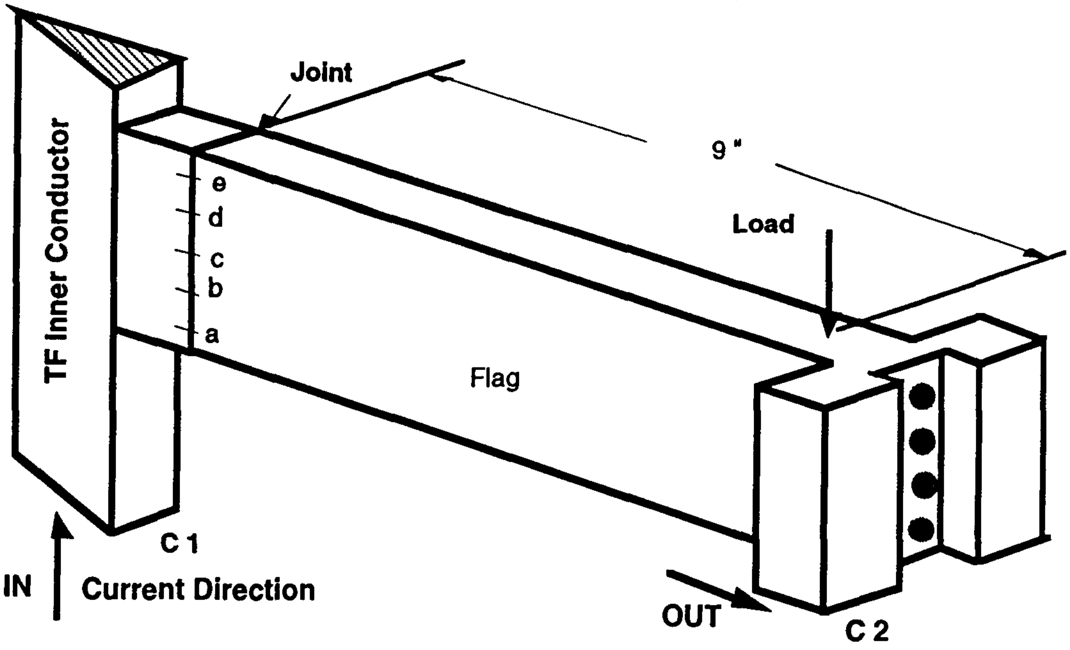


Table No. 5-14
Vertical Load Test Results

Load (Lbs.)	Joint Load 1000 psi/Bolt torque90 In-Lbs. Joint Resistance (Micro Ohms) a	b	c	d	e	Joint Load 2000 psi/Bolt torque 180 In-Lbs. Joint Resistance (Micro Ohms) a	b	c	d	e
3	0.2	0.2	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1
25	0.2	0.2	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1
50	0.2	0.2	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1
75	0.3	0.2	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1
100	0.3	0.2	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1
125	0.2	0.2	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1
150	0.2	0.2	0.1	0.1	0.15	0.2	0.1	0.1	0.1	0.1
175	0.2	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1
200	0.2	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.1

Table No. 5-15
Vertical Load Test Results

Load (Lbs.)	Front Joint Resistance (Micro Ohms)					Back Joint Resistance (Micro Ohms)				
	a	b	c	d	e	a	b	c	d	e
0	0.2	0.1	0.1	0.1	0.1	n/a	n/a	0.1	0.1	0.1
25	0.2	0.1	0.1	0.1	0.1	n/a	n/a	0.1	0.1	0.1
50	0.2	0.1	0.1	0.1	0.1	n/a	n/a	0.1	0.1	0.1
75	0.2	0.1	0.1	0.1	0.1	n/a	n/a	0.1	0.1	0.1
100	0.2	0.1	0.1	0.1	0.1	n/a	n/a	0.1	0.1	0.1
125	0.2	0.1	0.1	0.1	0.1	n/a	n/a	0.1	0.1	0.1
150	0.2	0.1	0.1	0.1	0.1	n/a	n/a	0.1	0.1	0.1
175	0.2	0.1	0.1	0.1	0.1	n/a	n/a	0.1	0.1	0.1
200	0.2	0.1	0.1	0.1	0.1	n/a	n/a	0.1	0.1	0.1
225	0.2	0.1	0.1	0.1	0.1	n/a	n/a	0.1	0.1	0.1
250	0.2	0.1	0.1	0.1	0.1	n/a	n/a	0.1	0.1	0.2
275	0.2	0.1	0.1	0.1	0.1	n/a	n/a	0.1	0.1	0.2
300	0.2	0.1	0.1	0.1	0.1	n/a	n/a	0.1	0.1	0.2
325	0.2	0.1	0.1	0.1	0.1	n/a	n/a	0.1	0.1	0.2
350	0.2	0.1	0.1	0.1	0.1	n/a	n/a	0.1	0.1	0.2
375	0.2	0.1	0.1	0.1	0.1	n/a	n/a	0.1	0.1	0.2
400	0.2	0.1	0.1	0.1	0.2	n/a	n/a	0.1	0.1	0.2
425	0.2	0.1	0.1	0.1	0.2	n/a	n/a	0.1	0.1	0.2
450	0.1	0.1	0.1	0.1	0.2	n/a	n/a	0.1	0.1	0.2
475	0.2	0.1	0.1	0.1	0.2	n/a	n/a	0.1	0.2	0.3
500	0.2	0.1	0.1	0.1	0.2	n/a	n/a	0.1	0.2	0.3
525	0.2	0.1	0.1	0.1	0.3	n/a	n/a	0.1	0.2	0.3
550	0.1	0.1	0.1	0.1	0.3	n/a	n/a	0.1	0.2	0.3
575	0.1	0.1	0.1	0.2	0.3	n/a	n/a	0.1	0.2	0.4
600	0.1	0.1	0.1	0.2	0.3	n/a	n/a	0.1	0.2	0.4
625	0.1	0.1	0.1	0.1	0.3	n/a	n/a	0.1	0.3	0.4
650	0.1	0.1	0.1	0.2	0.4	n/a	n/a	0.1	0.3	0.5
675	0.1	0.1	0.1	0.2	0.4	n/a	n/a	0.1	0.3	0.5
700	0.1	0.1	0.1	0.2	0.4	n/a	n/a	0.2	0.3	0.5

Table No. 5-16
Vertical Load Test Results

Load (Lbs.)	Front Joint Resistance (Micro Ohms)					Back Joint Resistance (Micro Ohms)				
	a	b	c	d	e	a	b	c	d	e
500	0.2	0.1	0.1	0.1	0.2	n/a	n/a	0.1	0.1	0.2
550	0.2	0.1	0.1	0.1	0.2	n/a	n/a	0	0.1	0.2
600	0.2	0.1	0.1	0.2	0.2	n/a	n/a	0.1	0.1	0.2
650	0.2	0.1	0.1	0.2	0.3	n/a	n/a	0.1	0.1	0.3
700	0.2	0.1	0.1	0.2	0.3	n/a	n/a	0.1	0.1	0.3
750	0.2	0.1	0.1	0.2	0.3	n/a	n/a	0.1	0.2	0.3
800	0.1	0.1	0.1	0.2	0.4	n/a	n/a	0.1	0.2	0.4
850	0.1	0.1	0.1	0.2	0.4	n/a	n/a	0.1	0.3	0.4
900	0.1	0.1	0.1	0.3	0.4	n/a	n/a	0.1	0.3	0.5
950	0.1	0.1	0.1	0.3	0.4	n/a	n/a	0.1	0.4	0.5
1000	0.1	0.1	0.1	0.3	0.5	n/a	n/a	0.2	0.4	0.5
1050	0.1	0.1	0.1	0.4	0.5	n/a	n/a	0.2	0.4	0.5
1100	0.1	0.1	0.1	0.4	0.5	n/a	n/a	0.2	0.5	0.6

5.4 Horizontal Loading Test Results

Tests were performed to determine what effect a horizontal load would have on the TF coil joint. A full size model of a TF joint was used as the test stand. 100 amperes of current was flowed through the model while varying loads were applied at the end of the bolted tee connector. Resistance measurements were taken along the joint line and recorded.

Figure No. 5-14
Horizontal Load Test Specimen

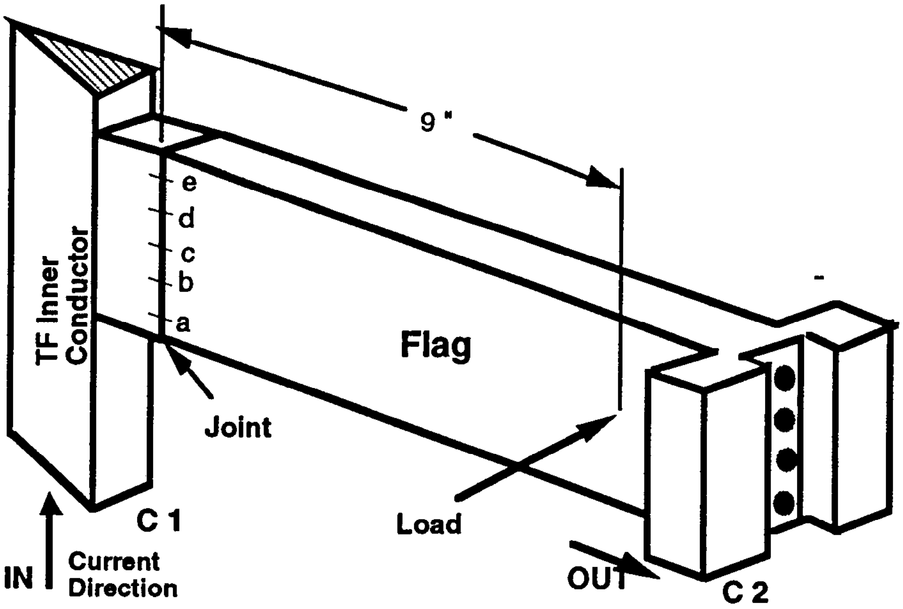


Table No. 5-17
Horizontal Load Test Results

FRONT BACK

Joint Load 1000 psi/ Bolt torque (90 In-Lbs.)

Load	Joint Resistance (Micro Ohms)					Joint Resistance (Micro Ohms)				
(Lbs.)	a	b	c	d	e	a	b	c	d	e
0	0.3	0.2	0.2	0.1	0.1	0.2	0.1	N/A	0.1	0.1
25	0.2	0.1	0.1	0.1	0.1	0.2	0.1	N/A	0.1	0.1
50	0.3	0.2	0.1	0.1	0.1	0.2	0.1	N/A	0.2	0.2
75	0.4	0.2	0.1	0.1	0.1	0.2	0.2	N/A	0.2	0.2
100	0.4	0.2	0.2	0.2	0.2	0.2	0.2	N/A	0.2	0.2
125	0.6	0.6	0.5	0.4	0.4	0.4	0.3	N/A	0.3	0.3
Joint Load 2000 psi/ Bolt torque (180 In-Lbs.)										
0	0.2	0.1	0.1	0.1	0.1	0.2	0.2	N/A	0.1	0.1
25	0.2	0.1	0.1	0.1	0.1	0.2	0.2	N/A	0.1	0.1
50	0.2	0.1	0.1	0.1	0.1	0.2	0.1	N/A	0.1	0.1
75	0.2	0.1	0.1	0.1	0.1	0.2	0.1	N/A	0.1	0.1
100	0.2	0.1	0.1	0.1	0.1	0.2	0.1	N/A	0.1	0.1
125	0.3	0.2	0.1	0.1	0.1	0.2	0.1	N/A	0.1	0.1
150	0.3	0.2	0.1	0.1	0.1	0.2	0.2	N/A	0.1	0.1
175	0.3	0.2	0.1	0.1	0.1	0.2	0.2	N/A	0.1	0.1
200	0.4	0.2	0.1	0.1	0.2	0.2	0.2	N/A	0.1	0.1

Tables No. 5-18
Horizontal Load Results

Load (Lbs.)	FRONT Joint Resistance (Micro Ohms)					BACK Joint Resistance (Micro Ohms)				
	a	b	c	d	e	a	b	c	d	e
0	0.2	0.1	0.1	0.1	0.1	0.2	0.1	n/a	0.1	0.1
25	0.2	0.1	0.1	0.1	0.1	0.1	0.1	n/a	0.1	0.1
50	0.2	0.1	0.1	0.1	0.1	0.1	0.1	n/a	0.1	0.1
75	0.2	0.1	0.1	0.1	0.1	0.1	0.1	n/a	0.1	0.1
100	0.3	0.2	0.1	0.1	0.1	0.1	0.1	n/a	0.1	0.1
125	0.3	0.2	0.1	0.1	0.1	0.1	0.1	n/a	0.1	0.1
150	0.4	0.2	0.1	0.1	0.1	0.1	0.1	n/a	0.1	0.1
175	0.3	0.2	0.1	0.1	0.1	0.2	0.1	n/a	0.1	0.1
200	0.4	0.3	0.1	0.1	0.1	0.2	0.1	n/a	0.1	0.1
225	0.4	0.3	0.2	0.1	0.2	0.2	0.2	n/a	0.1	0.1
250	0.5	0.5	0.4	0.3	0.2	0.3	0.2	n/a	0.2	0.2
275 *	0.6	0.5	0.4	0.4	0.4	0.3	0.3	n/a	0.2	0.3
300 *	0.6	0.5	0.4	0.4	0.4	0.3	0.3	n/a	0.3	0.3
325 *	0.7	0.6	0.5	0.4	0.4	0.3	0.3	n/a	0.2	0.2
350 *	0.7	0.6	0.5	0.4	0.4	0.3	0.3	n/a	0.3	0.3
375 *	0.6	0.6	0.5	0.4	0.4	0.4	0.3	n/a	0.3	0.3
400 *	0.7	0.6	0.5	0.4	0.4	0.4	0.4	n/a	0.3	0.3

Remarks: Gap in joint detected at these loads.
A 7 mil gap detected in joint at 400 Lbs.

Table 5-19
Load vs. Gap Results

Load (Lbs.)	Gap Size (mils)	Depth (in.)
275	1.5	0.125
300	1.5	0.5
325	3.0	0.125
350	4.0	0.125
375	6.0	0.125
400	7.0	0.125

6.0 TF JOINT INSERT PULL OUT TESTS

A test was performed to determine the pull out force of the threaded inserts being used for the TF coil electrical joints.

Materials Used:

Inserts :	"Keenserts" part number KNL-518 (303 stainless steel) 5/16-18 Internal Thread 7/16-14 External Thread
Copper:	CDA 104 (36-42 ksi)..equivalent yield strength to TF Center Stack copper conductor

Table 6-20
TF Joint Insert Pull Out Test Results

Sample No. 1 ....6460 lbs.
Sample No. 2 ....6720 lbs.

7.0 OH CONDUCTOR KEYSTONE TESTS

Trial windings were performed to determine the amount of keystoning which result during fabrication of the OH coil. The radial build tolerances on the OH coil are extremely critical. Any deformation of the copper conductor would result in a minimization of clearances between the OH and PF coils, thus making assembly of the Center Stack more difficult.

7.1 Test Setup

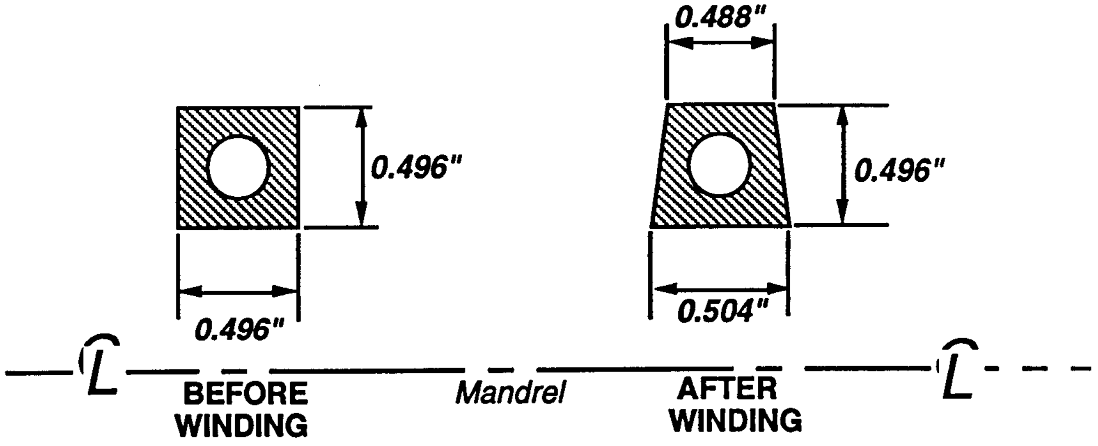
The trial windings were completed in the RESA building using a "Ransome" turn table and a manually controlled friction brake tension unit. The winding loads were monitored using a digital dynamometer. A mandrel of equivalent diameter as the OH coil was mounted to the turn table. (See figure 7-17)

7.2 Conductors

Two different conductors were used in these tests. Each had a different cross-section and hardness. Trial number 1 used an extruded square copper conductor with a coolant hole and a hardness of 64 on the Rockwell F-scale. The second winding was completed using a copper conductor which was machined to the correct OH conductor dimensions and a hardness of 85 on the Rockwell F-scale. This conductor was solid and did not have a coolant hole.

7.3 Winding Trial Results

Figure 7-15
Results From Trial Winding No. 1

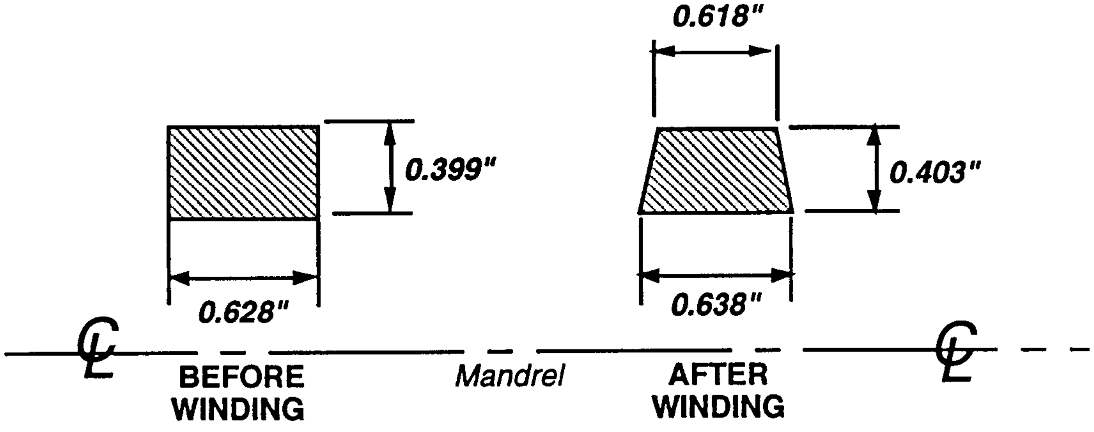


MATERIAL: **Copper (unknown CDA number)**

Rockwell Hardness:	Prior to winding	After winding
B-scale	13.0	19.0
F-Scale	64.5	68.0

NOTE: The above dimensions are average measurements taken along the length of the conductor prior to, and after winding.

Figure 7-16
Results From Trial Winding No. 2



MATERIAL: **Copper CDA 104**

Rockwell Hardness:	Prior to winding	After winding
B-scale	49.0	63.0
F-Scale	85.0	93.0

NOTE: The above dimensions are average measurements taken along the length of the conductor prior to, and after winding.

7.4 Trial Winding Preliminary Conclusions

It was observed in the 2nd trial winding (OH conductor cross-section) that the conductor not only changed cross-section from a rectangle to a trapezoid shape, but also grew in height due to a slight dishing of the conductor. From these results, it was decided to perform one additional trial winding. Using a conductor with the resulting keystone dimensions, it was wound onto a mandrel with the wide base of the trapezoid away from the mandrel. It was hoped that the conductor would return to its original cross-section.

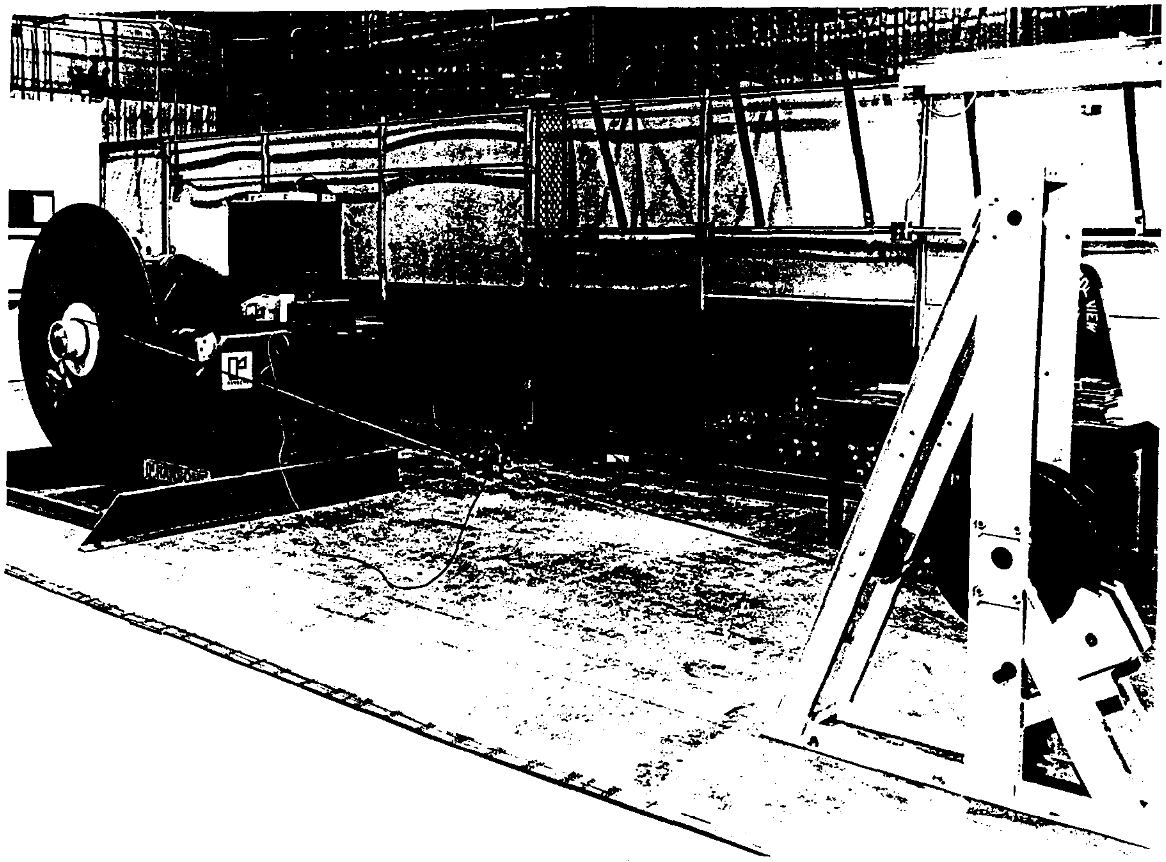


Figure No. 7-17
Trial Winding Station

7.5 Trial Winding No.3- Machined Conductor

A conductor was machined using CDA-104 with the dimensions obtained from the final keystoning cross-section. This conductor was then wound with the conductor in the opposite position, narrow side of the conductor facing the mandrel. The results from this trial winding showed that the conductor did return to a rectangular cross-section with the original OH conductor dimensions. Figures 7-18 and 7-19 show both the original OH conductor cross-section and the procured OH conductor cross-section with built-in keystone tolerances.

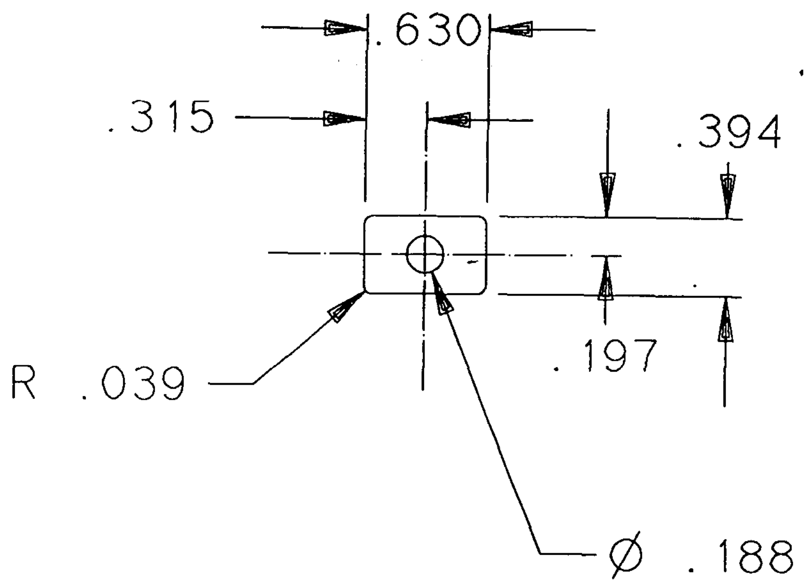


Figure No. 7-18
Original OH Copper Conductor

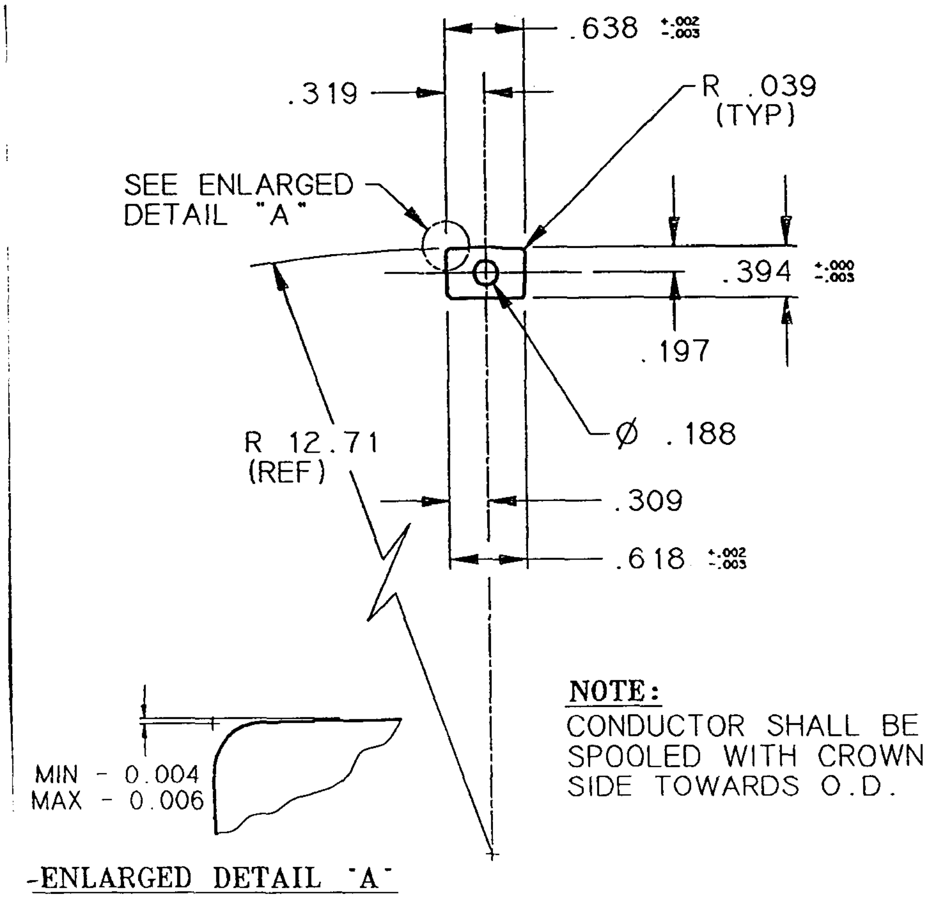
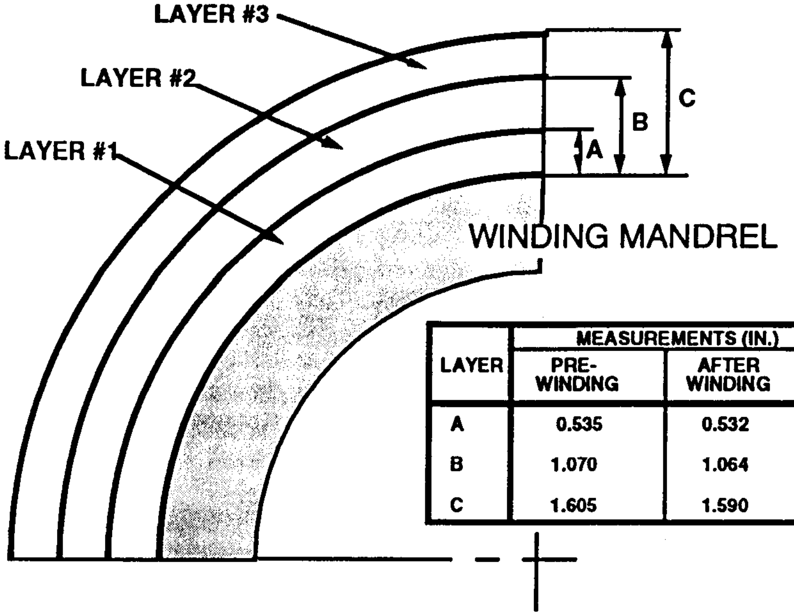


Figure No. 7-19
OH Copper Conductor With Keystone Cross-Section

7.6 Winding Tension vs. Insulation Compression

Additional winding trials were performed using copper conductors' insulated with two (2) half-lapped layers of B-stage insulation.. The purpose of these trials were to determine the winding tension which would be required to ensure a 10-12% compression of the B-stage insulation. The results are described in figure 7-20.



LAYER	MEASUREMENTS (IN.)		COMPRESSION		WINDING TENSION (psi)
	PRE-WINDING	AFTER WINDING	MEASURED (in.)	%	
A	0.535	0.532	0.003	12.5	1600
B	1.070	1.064	0.006	8.3	2000
C	1.605	1.590	0.015	12.5	2400

NOMINIAL INSULATION THICKNESS PER CONDUCTOR SIDE ~ 0.024 INCH

Figure 7-20
Winding Tension vs. Insulation Compression Results

8.0 CONCLUSIONS

The following conclusions have been made as a result of the activities described in this report, and will be included in the final design of the NSTX Center Stack.

a. The Insulation shear tests which were conducted at both PPPL and CMI conclude that the tested CTD-112 pre-impregnated insulation meets all of the minimum design criteria for the Inner TF coil bundle and is acceptable for use in the Center Stack fabrication (Section 2.0). A total of six (6) insulation specimens have been successfully been tested through 1,000,000 cycles with a 2400 psi shear load and 600 psi compressive load. CMI test results are in attached "CMI Final Report" (Appendix)

b. The Insulation shear tests which were conducted at both PPPL and CMI conclude that pre-impregnated insulation CTD-112P with Kapton meets all of the minimum design criteria for the OH and PF coils and is acceptable for use in the Center Stack fabrication (Section 2.0). A total of six (6) insulation specimens have been successfully tested through 300,000 cycles with a 1000 psi shear load and 600 psi compressive load. CMI test results are in attached "CMI Final Report" (Appendix)

c. The AC and DC electrical test results demonstrated that the CTD-112 insulation is a good dielectric insulator (420 volts/mil) and surpasses the dielectric requirements of the coils in the Center Stack. (Section 3.0)

d. The tensile and fatigue test results conclude that the Type VII OH coil joint design meets the minimum design requirements for the OH coil layer to layer joint. Three specimens were cycled through a minimum of 300,000 cycles under a maximum load of 20 ksi. This joint design combines two (2) methods for fabricating the joint. The conductor to conductor overlap which carries the current is a tin-silver soft solder join. The ends of the conductors are locked in place with a TIG braze tack at each end. This combination provides a reliable OH joint. (Section 4.0)

e. The results obtained from the load tests performed on the model TF coil joint were used in support of the final TF joint design. Results clearly demonstrated the importance of silver plated joints. Load tests (horizontal and vertical) showed the effect that external forces have on the TF joint design. The final data of load vs. joint resistance can be found in Section 5.0.

f. Trial winding tests were performed to investigate the effect that keystoning has on the radial build of the OH coil. The results from these tests proved the need for a specially designed conductor cross-section to compensate for the excessive keystoning. Figure 7-19 in Section 7 shows the final conductor cross-section which is included in the OH design.

e. Winding trials were used to determine the minimum winding tension required to ensure a 10%-12% compression of the pre-impregnated turn to turn insulation. This minimum compression is required to ensure a successful cure of the insulation system. The winding tension varies from 1600 psi to 2400 psi. As you increase the diameter with additional layer. (See Figure 7-20 of Section 7)

APPENDIX

NSTX Insulation Test Program

Final Report

Submitted by Cryogenic Materials Inc. (CMI)

PPPL Subcontract S-03989-F

March 17, 1997

NSTX Insulation Test Program

Final Report

PPPL Subcontract S-03989-F
13 December 1996

Richard P. Reed
Cryogenic Materials, Inc.
Boulder, Colorado

17 March 1997

Introduction

The purpose of this program was to evaluate the shear properties of candidate insulation systems for the NSTX fusion reactor project. The program was performed in three stages. The topics and delivery dates for the interim reports are listed below.

I. Short-Beam Shear Testing, 3 February 1997
II. Shear/Compression Testing (insulation systems 1 and 2), 26 February 1997
III. Shear/Compression Testing (insulation system 3), 17 March 1997

All the interim reports are included in this final report.

Cryogenic Materials, Inc.
2625 Iliff, Boulder, Colorado 80303
Telephone: 303/494-1852 Fax: 303/494-0134
e-mail: 72113.525@compuserve.com

March 17, 1997

NSTX Insulation Test Program

Interim Report: Shear/Compression Testing

Shear/compression tests were conducted on the last candidate NSTX insulation system:

> 3M 92 Kapton (silicone adhesive-backed Kapton, 0.06 mm thick) with CTD-112P preimpregnated S-2 glass (6781 satin weave), 0.19 mm thick per ply).

The sandwich-type specimen for this insulation system consisted of the following components (the dimension given is thickness):

copper chip - 3.5 mm
2 layers of 3M 92 Kapton tape (simulating 1 half-lap layer) - 0.12 mm
8 layers of CTD-112P/S-2 glass - 1.44 mm
2 layers of 3M 92 Kapton tape (simulating 1 half-lap layer) - 0.12 mm
copper chip - 3.5 mm

The total uncompressed thickness is 8.68 mm (1.68 mm for the insulation system); the thickness of the specimen after cure is 8.3 mm (1.3 mm for the insulation system).

The copper chips were degreased and cleaned, but were not sandblasted.

The cure schedule for the insulation system is

ramp to 177°C in 1 h
hold at 177°C for 2 h
ramp to 200°C in 1 h
hold at 200°C for 6 h
air cool (in mold) to room temperature

The results are summarized below:

> At both temperatures (295, 395 K), there was virtually no adhesive strength between the copper and the Kapton tape. To initiate sliding of this interface, loads up to 5 lb (< 1 MPa shear strength) were required. These loads were slightly less at 395 K than at 295 K. The texture of the silicone adhesive remained gumlike and did not show evidence of hardening. Therefore, the applied force was required only to slide the gumlike adhesive interface along the copper surface.

Cryogenic Materials, Inc.
2625 Iliff, Boulder, Colorado 80303
Telephone: 303/494-1852 Fax: 303/494-0134
e-mail: 72113.525@compuserve.com

February 3, 1997

NSTX Insulation Test Program

Interim Report: Short-Beam Shear Testing

Short-beam shear tests at 295 and 395 K were conducted on three candidate NSTX insulation systems:

1. CTD-112P (TGDM/amine) preimpregnated S-2 glass (6781 satin weave);
   thickness of one ply: 0.19 mm
2. IMI Fusa-Fab (76590P), polyester-preimpregnated E-glass cloth;
   thickness of one ply: 0.152 mm
3. Fusa-Fab (76590P)/3M 92 Kapton (silicone adhesive-backed Kapton);
   thickness of one ply: 0.152 + 0.060 = 0.21 mm

Specimens were cut from 3.2-mm (1/8-in) thick laminates. The laminates were produced by stacking individual plies into a mold about 150 mm (6 in) long × 25 to 50 mm wide. Pressure of about 280 kPa (40 psi) was applied, and the mold was heated to cure the resin system. The cure schedules for each insulation system are

1. ramp to 177°C in 1 h
   hold at 177°C for 2 h
   ramp to 200°C in 1 h
   hold at 200°C for 6 h
   air cool (in mold) to room temperature
2. ramp to 150°C in 1 h
   hold at 150°C for 1 h
   air cool (in mold) to room temperature
3. ramp to 150°C in 1 h
   hold at 150°C for 1 h
   air cool (in mold) to room temperature

Samples of each type of laminate are enclosed with this report.

Short-beam shear specimens were cut from laminates to the following dimensions:
3.2 mm (1/8 in) thick × 25 mm (1 in) long × 6.3 mm (1/4 in) wide

Tests were conducted in three-point bending at a thickness-to-span ratio of 5. Details of the test are provided on the accompanying sheet. Results were

Insulation System	SBS strength, MPa (ksi)		Flexural Modulus, GPa (Msi)		Failure Mode
	295 K	395 K	295 K	395 K	
1. CTD-112P	77 (11)	63 (9.2)	20 (28)	17 (2.5)	interlaminar shear
2. IMI Fusa-Fab	25 (3.6)	8 (1.1)	9 (1.4)	1 (0.1)	multiple interlaminar shear
3. IMI Fusa-Fab/3M 92 Kapton	0	0	—	—	Fusa-Fab/Kapton interface

Therefore, we recommend that the third insulation be changed for the shear/compression testing or that possible modifications be studied to improve the bonding of the Fusa-Fab to Kapton.

Short Beam Shear Test Results

Resin System:	CTD-112P		
Reinforcement:	S-2 Glass - 6580	Condition:	AR
Barrier:	None		
Specimen Type:	Short Beam Shear		
Material Reference #:	NA		
Load Rate:	0.0212 mm/s		
Strain Measurement:	MTS LVDT		
Test Fixture:	Short Beam Shear	Test Temperature:	295 and 395 K
Test Date:	1/30/97 and 1/31/97		

295 K

Specimen #	Thickness (mm)	Width (mm)	Length (mm)	Span (mm)	Span Ratio (T)	Flex. Modulus (GPa)	Load (kN)	Shear Strength (MPa)	Failure Mode
sb112-1	3.073	6.350	21.62	15.37	5.0	19.2	1.96	75.4	I
sb112-2	3.073	6.325	24.05	15.37	5.0	19.7	1.99	76.7	I
sb112-3	3.099	6.223	24.97	15.37	5.0	19.4	2.02	78.7	I
sb112-4	3.073	6.375	25.40	15.37	5.0	19.9	1.96	75.1	I
sb112-5	3.048	6.248	24.43	15.37	5.0	19.5	2.02	79.7	I

Average Shear Strength at Span Ratio of 5:	77.1 MPa
Standard Deviation:	2.0
Coefficient of Variation:	0.03

Average Flexural Modulus at Span Ratio of 5:	19.6 GPa
Standard Deviation:	0.3
Coefficient of Variation:	0.01

395 K

Specimen #	Thickness (mm)	Width (mm)	Length (mm)	Span (mm)	Span Ratio (T)	Flex. Modulus (GPa)	Load (kN)	Shear Strength (MPa)	Failure Mode
112hl-6	3.099	6.299	25.22	15.37	5.0	16.9	1.67	64.3	I
112-hl-7	3.048	6.274	24.36	15.37	5.0	17.6	1.64	64.2	I
112hl-8	3.073	6.299	24.51	15.37	5.0	17.1	1.61	62.2	I
112hl-9	3.048	6.350	24.56	15.37	5.0	17.4	1.62	62.8	I
112hl-10	3.048	6.325	25.58	15.37	5.0	17.1	1.62	63.2	I

Average Shear Strength at Span Ratio of 5:	63.3 MPa
Standard Deviation:	0.9
Coefficient of Variation:	0.01

Average Flexural Modulus at Span Ratio of 5:	17.2 GPa
Standard Deviation:	0.3
Coefficient of Variation:	0.02

Failure Modes:

I = Interlaminar Shear
MI = Multiple Interlaminar Shear
D = Diagonal Shear/Compression
C = Compressive Failure
T = Tensile Failure

Short Beam Shear Test Results

Resin System:	IMI - Fusitab-76590P		
Reinforcement:	Glass fabric	Condition:	AR
Barrier:	None		
Specimen Type:	Short Beam Shear		
Material Reference #:	NA		
Load Rate:	0.0212 mm/s		
Strain Measurement:	MTS LVDT		
Test Fixture:	Short Beam Shear	Test Temperature:	295 and 395 K
Test Date:	1/30/97 and 1/31/97		

295 K

Specimen #	Thickness (mm)	Width (mm)	Length (mm)	Span (mm)	Span Ratio (T)	Flex. Modulus (GPa)	Load (kN)	Shear Strength (MPa)	Failure Mode
fusi-1	3.734	6.299	26.01	19.18	5.1	9.8	0.65	27.0	MI
fusi-2	3.759	6.350	23.55	19.18	5.1	7.8	0.56	17.8	MI
fusi-3	3.861	6.299	24.66	19.18	5.0	8.9	0.84	25.9	MI
fusi-5	3.937	6.350	24.66	19.18	4.9	11.0	0.86	25.9	MI
fusi-6	3.962	6.325	24.64	19.18	4.8	9.8	0.89	26.5	MI

Average Shear Strength at Span Ratio of 5:	24.6 MPa
Standard Deviation:	3.9
Coefficient of Variation:	0.16

Average Flexural Modulus at Span Ratio of 5:	9.4 GPa
Standard Deviation:	1.3
Coefficient of Variation:	0.13

395 K

Specimen #	Thickness (mm)	Width (mm)	Length (mm)	Span (mm)	Span Ratio (T)	Flex. Modulus (GPa)	Load (kN)	Shear Strength (MPa)	Failure Mode
fushi-7	3.937	6.350	24.38	19.18	4.9	0.9	0.26	7.9	D
fushi-8	4.140	6.248	25.45	19.18	4.6	0.9	0.28	8.0	D
fushi-9	4.115	6.198	26.26	19.18	4.7	1.0	0.26	7.7	D
fushi-10	4.191	6.223	25.48	19.18	4.6	0.9	0.27	7.7	D
fushi-11	4.013	6.350	23.52	19.18	4.8	1.0	0.25	7.5	D

Average Shear Strength at Span Ratio of 5:	7.7 MPa
Standard Deviation:	0.2
Coefficient of Variation:	0.03

Average Flexural Modulus at Span Ratio of 5:	1.0 GPa
Standard Deviation:	0.0
Coefficient of Variation:	0.03

Failure Modes:

I = Interlaminar Shear
MI = Multiple Interlaminar Shear
D = Diagonal Shear/Compression
C = Compressive Failure
T = Tensile Failure

February 26, 1997

NSTX Insulation Test Program

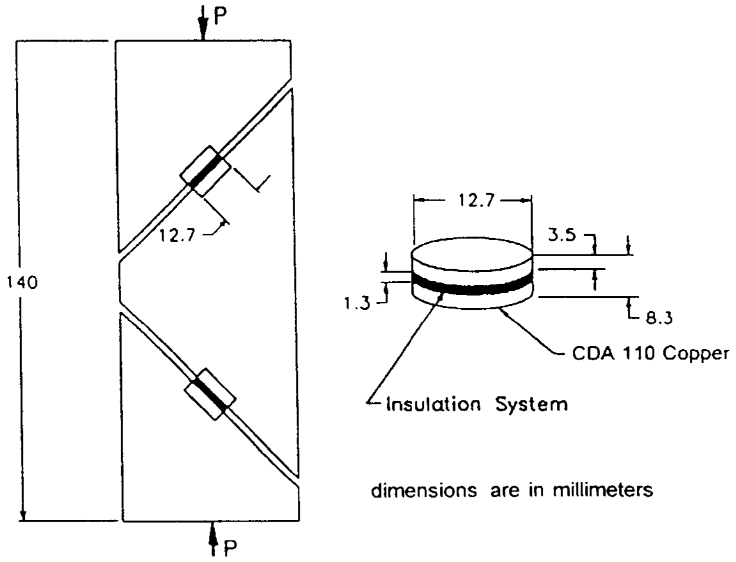
Interim Report: Shear/Compression Testing

Shear/compression tests were conducted on two of the three candidate NSTX insulation systems:

1. CTD-112P (TGDM/amine) preimpregnated S-2 glass (6580 satin weave); thickness of one ply = 0.18 mm
2. CTD-112P (TGDM/amine) preimpregnated S-2 glass (6580 satin weave); cowound with Kapton film, grade HA (0.06 mm thick); thickness of one ply = 0.24 mm.
3.[*] 3M 92 Kapton (silicone adhesive-backed Kapton); thickness of one ply = 0.06 mm.

For the CTD-112P preimpregnated material, glass contents of 49, 55, and 61 vol% were tested. In all but a few specimens, a primer (Ciba-Geigy DZ-80) was used on the copper surface.

The sandwich-type specimens and the loading fixture used for these tests are shown in Figure 1. Specimen dimensions are 13-mm diameter × 8-mm total thickness with 1.3-mm thick insulation.



dimensions are in millimeters

Figure 1. Loading arrangement and specimen for shear/compression test.

---

[*] to be tested.

The top and bottom portion are cold-drawn copper (CDA 110, 1/4 hard). After being cut and machined from copper bar, the chips were cleaned and degreased, sandblasted and air-blasted in dry nitrogen gas. A thin (about 0.025-mm) layer of primer (Ciba-Geigy DZ-80) was applied to the chip surfaces and cured at 80°C for 0.5 h.

The sandwich specimens were then prepared by using procedures and molds developed for the ITER program, which are described in the accompanying paper by Fabian and Reed (Appendix A). Test procedures and parameters are also described by Drexler et al. (Appendix A). Estimated amounts of compression on the insulation components of the specimens to obtain the final insulation through-thickness of 1.3 mm are listed below:

1. CTD-112P/S-2 glass with 8 layers (49 vol% glass)

prior to compression: 8 × 0.18 =	1.44 mm
after compression (in mold):	1.30 mm
compression:	10%

2. CTD-112P/S-2 glass with 9 layers (55 vol% glass)

prior to compression: 9 × 0.18 =	1.62 mm
after compression (in mold):	1.30 mm
compression:	20%

3. CTD-112P/S-2 glass with 10 layers (61 vol% glass)

prior to compression: 10 × 0.18 =	1.80 mm
after compression (in mold):	1.30 mm
compression:	28%

The cure schedule for insulation systems 1 and 2 with CTD-112P prepreg is
ramp to 177°C in 1 h
hold at 177°C for 2 h
ramp to 200°C in 1 h
hold at 200°C for 6 h
air cool (in mold) to room temperature

The results are summarized in the Table 1. Specific data sheets from Composite Technology Development are included in Appendix B.

Comments on Data:

- The use of the primer prevents adhesive-type failures and produces higher shear strengths.
- The glass volume percent is not effective in raising the shear strength, primarily because the primer/composite interface becomes slightly weaker. The reduction of this interfacial strength probably arises from the presence of less resin near the primer.
- Thus, any additional R&D to improve the shear strength of this insulation system must address the primer/composite interface. Possible variables that may increase the strength of this interface are (1) use of a more open glass weave, such as 6781 instead of 6580 satin weaves; (2) adjustment of the thickness of the primer layer, and (3) adjustment of the resin/hardener mix of the TGDM/aromatic amine hardener.
- It is important to remember that the TGDM (tetrafunctional epoxy) resin system was developed by the aerospace industry specifically for "high" temperature applications.

APPENDIX A

to

Interim Report: Shear/Compression Testing

Adv. Cry. Eng. - Mat.
42 (1996)

NEW COMBINED SHEAR AND COMPRESSION TEST METHOD

P. E. Fabian[1] and R. P. Reed[2]

[1]Composite Technology Development, Inc.
Boulder, CO 80301, USA
[2]Cryogenic Materials, Inc.
Boulder, CO 80303, USA

ABSTRACT

A new test method was developed to determine shear/compression properties of composite insulation systems used in superconducting magnets. It was developed specifically to enable in-situ testing (without warm-up) of insulation systems in a high flux neutron radiation and cryogenic (4 K) temperature environment at the Munich Research Reactor (FRM - Forschungsreaktor München).

The new shear/compression specimen consists of two sections of composite insulation bonded at a specific angle between three pieces of 316 stainless steel. During the test, the specimen is compressed between two loading platens. By varying the angle of the test specimen, different shear/compression ratios can be evaluated and a shear/compression envelope for various materials can be produced. This test method produces the same shear and compressive strengths found in other shear/compression tests, but the test fixture is smaller, and multiple test specimens are not required. The composite insulation systems were tested at 45° to demonstrate the feasibilty of the test. Specimens were produced from a vacuum pressure impregnation (VPI) resin system and a prepreg resin system. Design and fabrication of the test specimens and their shear and compressive properties are presented.

INTRODUCTION

The composite insulation to be used in the International Thermonuclear Experimental Reactor (ITER) fusion magnets will be subjected to both shear and compressive stresses at cryogenic temperatures throughout its operating lifetime. The shear and compressive stresses in the Toroidal Field (TF) coils and Central Solenoid (CS) coils will act on the insulation simultaneously; thus combined shear/compression tests are necessary in all magnet insulation characterization programs. A combined shear/compression test has been developed previously[1] and used extensively over the last several years to study and characterize insulation systems.[2-5]

Another condition of operation that both the TF and CS coils will encounter is high levels of radiation. As specified by ITER, the composite insulation in the TF coils must be capable of withstanding a fast (>0.1 MeV) neutron fluence of 2.5×10^{21} neutrons/m^2 with an associated gamma dose, while the CS coil insulation must withstand radiation that is an order of magnitude lower, at 2.5 X 10^{20} neutrons/m^2.[6] Previous shear/compression test specimens have been irradiated at temperatures below 6 K at the fission reactor in Garching, Germany at the Munich Research Reactor.[7] However, because of the specimen and test rig size, it was not possible to test these specimens without warming them to room temperature for shipment to the testing site. Thus, the effect of radiation on shear/compressive properties of organic composite insulators without warmup is currently an unknown but highly sought after material property.

It is surmised that shear/compressive stresses and a high radiation dose, combined with a cryogenic (4 K) operating temperature will heavily tax any organic insulation system; therefore a single test that can combine all three elements is most desirable. A new shear/compression test specimen was designed that enables specimens to be tested in-situ, without warmup, immediately after being irradiated in the Garching reactor. This paper describes the development, specimen production, and testing of these new in-situ shear/compression specimens; compares the new test method with the standard shear/compression test method; and compares the data produced by the two methods.

SPECIMEN DEVELOPMENT

The new shear/compression specimen was intended primarily for use in the Garching reactor, and therefore, it was designed to fit into the reactor's irradiation and testing cryostat and pressure cell. During irradiation, specimens are contained in aluminum capsules,[8] whose inner dimensions are 13 mm in diameter and 105 mm in length. Following irradiation, the specimens are transferred without warmup to a pressure cell, whose inner dimensions are 13.2 mm in diameter and 85 mm in length (see Figure 1). The pressure cell is designed to hold a single specimen, and it is set up to test only in compression.

In the actual magnet application, the insulation materials for the TF and CS coils are sandwiched between metallic components and, in most cases, bonded to them. AISI 316 stainless steel is used for the main structural components in the ITER magnets; Incoloy 908 is the material used for the superconducting coil conduits. Thus, insulation test specimens were bonded to AISI 316 stainless steel to evaluate their performance under combined shear and compressive forces.

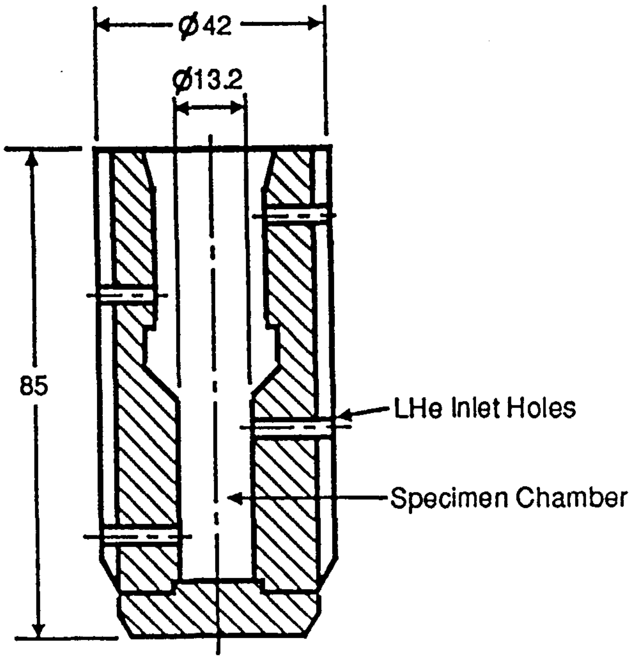


Figure 1. Cross-sectional view of the Munich Research Reactor's low-temperature pressure cell for in-situ testing. Dimensions are in millimeters.

The design of the in-situ shear/compression specimen is shown in Figure 2. The specimen is composed of three separate pieces of 316 stainless steel, 11 mm in diameter, cut at the desired test angle and bonded to two separate composite insulation sections, approximately 1.3 mm thick. The ratio of shear to compressive stress being studied determines the angle of the three steel specimen pieces. In-situ specimens to be used for the ITER program are to be fabricated to angles of 45° and 60°, which are shown in Figure 2. By changing the angle of the stainless steel specimen pieces, a shear/compression failure envelope can be developed. As seen in Figure 2, with a 11 mm diameter and 42 mm overall length, the in-situ shear/compression specimen fits easily into the pressure cell of the test cryostat.

The in-situ specimen, when compressed, is designed to behave exactly as the test fixturing behaves in the original combined shear/compression test. The original shear/compression test fixture and specimen are shown in Figure 3. The original specimen consists of flat, stainless steel discs, 12.7 mm in diameter that are bonded together by the composite insulation. The fixture is composed of three, angularly cut, high-strength steel pieces aligned vertically by two shear/compression specimens placed in circular recesses within the three pieces. When the test fixturing is compressed, both shear and compressive forces are applied to the test specimens; the center component of the test rig is free to move laterally, eliminating any shear constraint and ambiguity in the stresses within the insulating material.

The in-situ shear/compression specimen operates on the exact same principle. The specimen is composed of three separate, angular steel pieces, which, when compressed, apply both shear and compressive stresses to the insulating material. No side constraints are placed on the in-situ specimen, so that the center component of the specimen is free to move laterally, like the center component of the test rig described above.

The major difference in the two tests is that to change the shear-to-compression ratio in the in-situ test, the angle of the specimen's three stainless steel pieces must be changed. In the original shear/compression test, the angle of the entire test fixture must be changed, thus necessitating the construction of multiple test fixtures. A minor difference is that the in-situ shear/compression test requires only one test specimen to obtain a single data point; the original shear/compression test requires two specimens to achieve a single data point. -

SPECIMEN PRODUCTION

In-situ shear/compression specimens are produced in a four-part mold in which sixteen specimens are fabricated during the same specimen production run. The mold is modeled after the CTD ITER mold[4,9] and uses the same resin flow techniques that were successfully used to produce numerous original shear/compression specimens for ITER. As in the CTD ITER mold, the in-situ specimen mold can be used to produce both vacuum-pressure-impregnation (VPI) and pre-impregnated (prepreg) type specimens. The mold design also enables 45° or 60° specimens to be fabricated in the same mold,

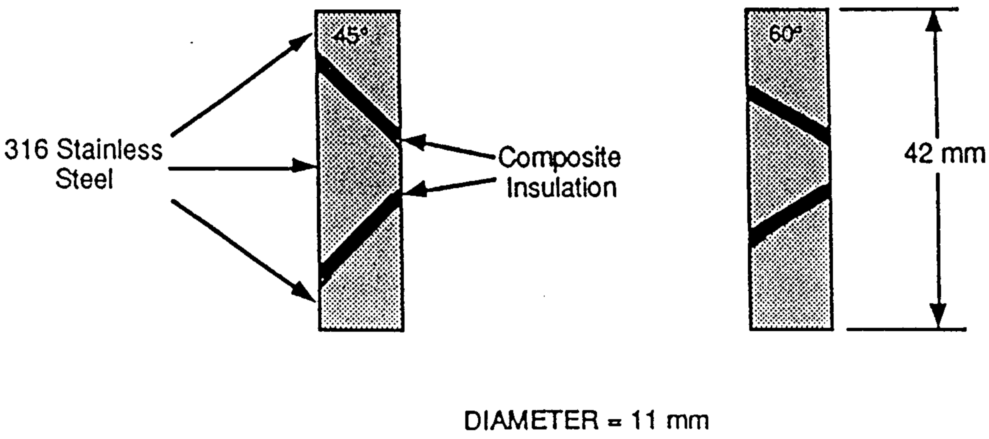


Figure 2. In-situ shear/compression test specimen with angles of 45° and 60°.

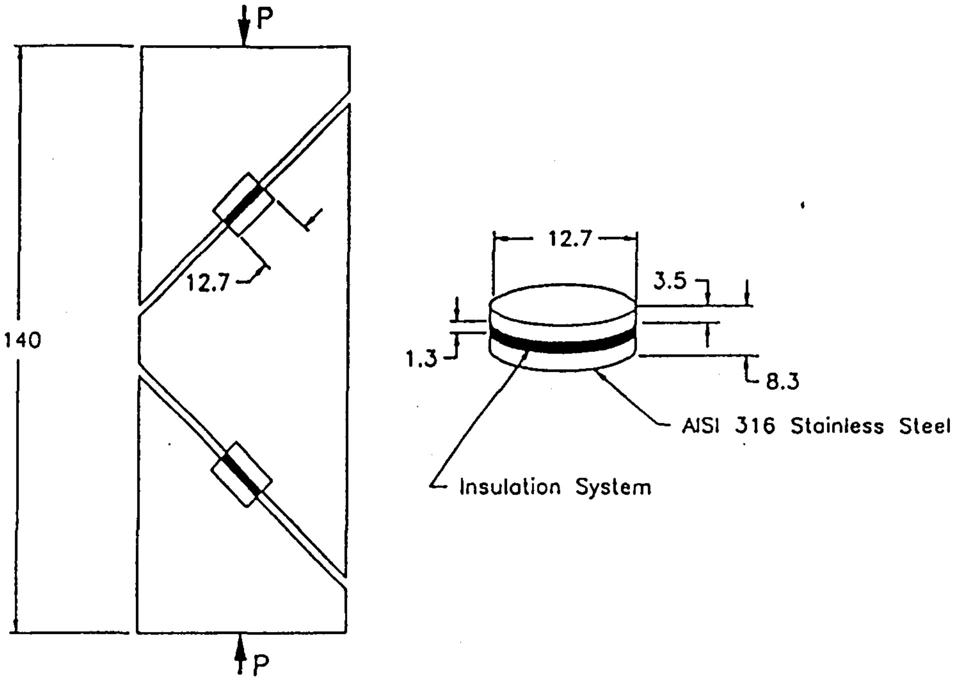


Figure 3. Original shear/compression test fixture and specimen. Dimensions in millimeters.

and, if desired, during the same specimen production run. A cut away view of the four-part mold and how it functions during a VPI production run is shown in Figure 4.

As noted in Figure 4, the mold consists of top and bottom sprue plates and two middle mold plates, one on top and one on bottom (as indicated by the T and B). The top and bottom sprue plates are designed to transfer the resin from the inlet through each of the sixteen specimens and to the mold outlet through the use of sprues that run along the horizontal plane of the sprue plates. The two middle mold plates maintain proper placement and alignment of the three stainless steel specimen pieces for each specimen. Vertical sprues that are cut next to the sixteen specimen holes enable the resin to flow to each specimen.

The specimen production process is thoroughly described below; however, before the stainless steel pieces are placed inside the mold, the surfaces to be bonded to the composite material must be prepared. To ensure proper bonding of the composite to the stainless steel, the surface of the stainless steel must be carefully prepared by ultrasonic

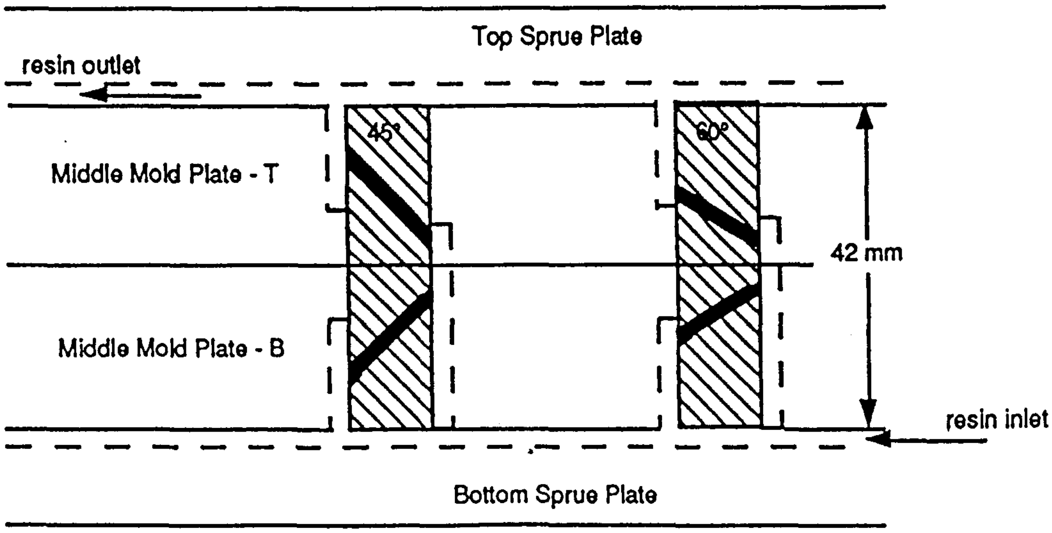


Figure 4. Four-part mold for in-situ VPI shear/compression specimen production.

cleaning in trichloroethane 1,1,1 (TCE); grit blasting of the bonding surface with 100 grit alumina; blasting with filtered, dry nitrogen gas to remove any embedded alumina particles; cleaning ultrasonically in TCE a second time; and vapor degreasing the bonding surface with clean TCE.

Once properly cleaned, the stainless steel pieces that make up each speceimen can be loaded into the mold. The middle mold plate - B is placed on top of the bottom sprue plate, and the bottom stainless steel specimen pieces are carefully lowered into the specimen holes (16 pieces total). The dry glass fabric plies or the prepreg fabric plies (cut to the proper elliptical size by using a punch and die set) are then placed on top of the bottom specimen piece. Next, the middle mold plate - T is placed on top of the bottom middle mold plate and the center stainless steel specimen pieces are lowered into the specimen holes in the correct orientation (16 pieces total). Then the second layer of dry glass plies or prepreg plies are placed on top of the center specimen pieces and the top stainless steel specimen pieces are lowered into the specimen holes in the correct orientation (16 pieces total). The last step is to place the top sprue plate on top of the top middle mold plate and clamp all mold plates together. Because the specimens must be vertically aligned to very close tolerances to give accurate test results, the four mold plates are held in alignment by two 3.2-mm-diameter pins that run through all four plates. To prevent resin leaks, all mating surfaces of the mold plates are vacuum-sealed with O-rings, which are placed along the perimeter of the plates.

The assembled mold is placed in a vacuum oven at approximately 10 to 40 Pa (0.1 to 0.4 mbar) for 2 h for VPI systems and 30 min for prepreg systems. At the same time, the mold is heated to the resin-processing temperature. After curing the composite material, the mold is allowed to cool before the specimens are removed. Because of the tight tolerances used in the molding of the in-situ shear compression specimens and the number of resin sprues located around the specimens, sometimes more than 10 kN of force is required to press the specimens out of the mold. An arbor or hydraulic press is usually required to accomplish this task. Resin sprues that remain attached to the specimen are gently sanded from the sides of the specimen.

TEST PROCEDURES AND RESULTS

A significan advantage of the in-situ shear/compression test is that complex test fixturing is not needed. The specimen is simply compressed between two loading platens to failure. To hold the specimen in place and stabilize it prior to its initial loading, a circular recess was machined into the bottom loading platen, approximately 3.2 mm in depth; however, this is not a necessary requirement for testing the in-situ specimen. Figure 5 illustrates the test setup.

To compare the in-situ shear/compression test with the original shear/compression test, two resin systems were tested: a flexibilized DGEBA epoxy VPI resin system (CTD-101K), and a TGDM epoxy pre-preg resin system (CTD-112P). Both systems were reinforced with an eight-harness satin weave S-2 glass, 6781 style with a nominal 0.50 fiber volume fraction. These systems were chosen because they had been extensively tested and characterized for ITER[4] with the original shear/compression test.

The bar graph in Figure 6 shows the results for both insulation systems and for both types of 45° shear/compression tests at 76 K. The shear strength of the VPI system found from the 45° in-situ shear/compression test is almost identical to those measured by the original shear/compression test. The VPI system (CTD-101K) exhibited a strength of 176.8 MPa when tested by the in-situ method at 76 K; the strength of the same system taken from the ITER characterization report is given as 175.8 MPa at 76 K.[4] The values for the prepreg system differ slightly, approximately 15% between the two test types. The shear strength of the prepreg resin system (CTD-112P) at 45° and 76 K is 140.9 MPa[4] from the original shear/compression test as compared to the 120.8 MPa shear strength found in the 45° in-situ shear/compression test. The test data scatter for this insulation system, from both types of shear/compression tests, is larger than that for the VPI system. The larger data scatter for the prepreg system can be attributed to its overall lower resin content than that of the VPI system, which would increase porosity in the composite material.

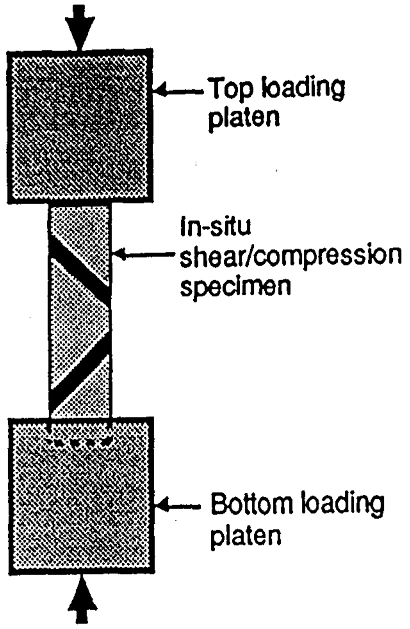


Figure 5. Testing procedure for in-situ shear/compression specimen.

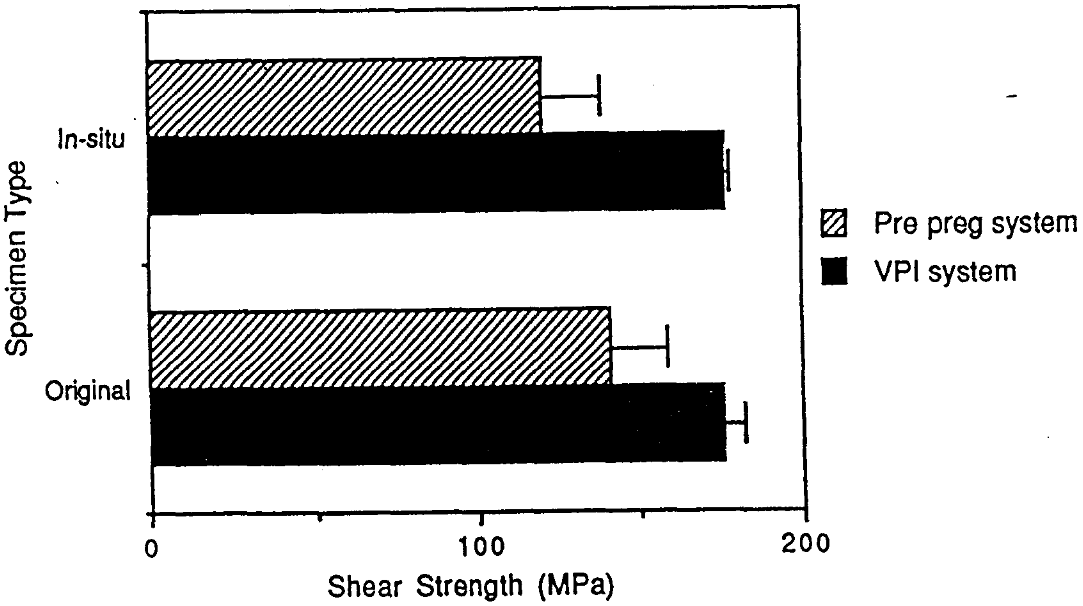


Figure 6. Comparison of 45° shear strengths measured by the original and in-situ shear/compression test methods at 76 K.

CONCLUSIONS

Comparison of data with those from the previous test method validates the new in-situ shear/compression tests. The new test method requires speceimens that are slightly more complicated to produce than the other test specimens; thus, each insulation system must be fully characterized prior to irradiation. The new in-situ shear/compression test method is currently the only one available for testing specimens in a high-neutron-radiation, cryogenic environment without warmup.

ACKNOWLEDGEMENTS

The authors wish to thank Trina S. Bauer-McDaniel for her contributions to this project and Robert Denis for his specimen production support. Research supported by Massachusetts Institute of Technology, Subcontract No. FT-S-549840.

REFERENCES

1. N.J. Simon, R.P. Reed, and R.P. Walsh, Compression and shear tests of vacuum-impregnation insulation systems, in: "Advances in Cryogenic Engineering," vol. 38, Plenum Press, New York (1992) pp. 363-370.
2. P.E. Fabian, J.B. Schutz, C.S. Hazelton, and R.P. Reed, Properties of candidate ITER vacuum impregnation insulation systems, in: "Advances in Cryogenic Engineering," vol. 40, Plenum Press, New York, (1994) pp. 1007-1014.
3. J.B. Schutz, and R.P. Reed, Inorganic and hybrid insulation materials for ITER, in: "Advances in Cryogenic Engineering," vol. 40, Plenum Press, New York, (1994) pp. 985-992.
4. P.E. Fabian, J.B. Schutz, C.S. Hazelton, and R.P. Reed, Candidate ITER insulation materials characterization report, report to MIT Plasma Fusion Center on contract numbers FCA 359063 and FCA-251317-003C, Composite Technology Development, Inc. and Cryogenic Materials, Inc., Boulder, Colorado (January 30, 1994).
5. P.E. Fabian, R.P. Reed, J.B. Schutz, and T.S. Bauer-McDaniel, Shear/compressive properties of candidate ITER insulation systems at low temperatures, to be published in *Cryogenics* 35 (1995).
6. C. Bushnell and R. Vieira, Memorandum N 11 MD 01 94-10-14 F, *2nd ICG Meeting* minutes, September 19-20, 1994, Oxford, UK (1994).
7. R.P. Reed, P.E. Fabian, T.S. Bauer-McDaniel, C.S. Hazelton, and N.A. Munshi, Effects of neutron/gamma irradiation at 4 K on shear and compressive properties of insulation, to be published in *Cryogenics* 35 (1995).
8. H. Gerstenberg, E. Krähling, and H. Katheder, Reactor irradiations at temperatures below 6 K, in: "Advances in Cryogenic Engineering," vol. 40, Plenum Press, New York, (1994) pp. 1161-1168.
9. P.E. Fabian, J.B. Schutz, C.S. Hazelton, and R.P. Reed, Screening of candidate insulation systems for ITER TF coils, report to MIT Plasma Fusion Center on contract numbers FCA 359063 and FCA-251317-003C, Composite Technology Development, Inc. and Cryogenic Materials, Inc., Boulder, Colorado (August 15, 1993).

SHEAR-COMPRESSIVE PROPERTIES OF VACUUM-IMPREGNATED INSULATION AT 76 K

ICMC - Kiev
1992

E. S. Drexler, N. J. Simon, and R. P. Reed*

National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80303, U.S.A.

Some electrical insulation for superconducting magnets is provided by a glass-fiber—reinforced, epoxy-based composites. A vacuum-impregnated epoxy insulation system experiences combined shear and compressive stresses and its shear strength is dependent on the applied compressive stress. The behavior of a vacuum-impregnated composite insulation system under simultaneous shear and compression stresses was investigated at 76 K. A test fixture was developed to characterize the shear-compression interactions by loading to failure at angles from vertical of 0 (pure shear), 15, 30, 45, 60, and 75°. The resolved shear and compressive strengths, when plotted against each other, result in a curve that defines a failure envelope. The failure modes have been identified and are discussed in relation to shear and compressive properties.

INTRODUCTION

In the conceptual design for the International Thermonuclear Experimental Reactor (ITER) an electrically insulating barrier surrounds the conductor conduits of the toroidal-field magnets. This barrier is expected to be a fiberglass-reinforced, epoxy-matrix composite bonded to the conduit walls. The composite insulation will experience combined shear and compressive forces at 4 K, and a combined neutron and gamma irradiation dose of about 5×10^7 Gy. A screening test program is needed to evaluate insulator candidates under loading and radiation conditions that simulate ITER requirements.

Several programs have been instituted to address the relationship between compressive and shear strengths of fiberglass-reinforced composites. Poehlchen et al. [1] investigated the shear properties at 295, 77, and 4.5 K of irradiated composite material bonded to a stainless steel. Currently, lap-shear tests are conducted *in situ* after 4-K fission-reactor irradiation. Okada et al. [2] devised an angled fixture that applied simultaneous resolvable shear and compressive forces. With this fixture the authors obtained shear-compressive strengths at 295 and 77 K for composite specimens without a bonded steel-composite interface. However, in both of these test approaches the specimen was constrained, introducing forces that could not be directly measured, or restricting specimen strain. McManamy et al. [3] also developed a test fixture to evaluate the shear-strength dependence on compressive stress for a composite sandwiched between metal (beryllium copper) plates for the Burning Plasma Experimental Device (BPX). With this fixture, a compressive load (capable of being varied) was applied to a specimen in one direction, and the perpendicular shear load necessary to cause the specimen to fail was measured. This design is not suitable for testing at 4 K, although it was adequate for tests at 77 K, the lowest operating temperature of the BPX.

The test fixture developed at the National Institute of Standards and Technology [4] (NIST) simulates ITER requirements and uses a specimen configuration that with minor modifications will permit 4-K irradiation in the limited geometries currently available [1]. Two specimens are loaded in series in the three-piece fixture (Figure 1). As an axial compressive load is applied, the inner wedge-shaped part of the fixture is free to move as the two specimens udergo deformation. The bottom fixture is rigidly attached to a base plate and the top is attached to a compressive push rod. Specimens can be tested while immersed in liquid nitrogen or liquid helium.

---

*Cryogenic Materials Inc., Boulder, CO 80303, U.S.A.

Changing the angle θ of the test fixture permits variations of the ratio of shear to compressive forces on the specimen.

PROCEDURES

The specimens are a sandwich type with fiber-reinforced composite between two small plates (12.7 × 12.7 × 3.40 mm) of 304 HN stainless steel. The composite consists of S-2-glass[†] cloth, layered to form nominal volume fractions of 0.52 and 0.64, and an epoxy resin (diglycidyl ether of bisphenol A with an anhydride curing agent). The fiberglass cloth used was a plain weave, style number 4533, with an areal density of 192 g/m^2. The number of bundles of fiber in the fill direction was equivalent to that in the warp direction (18 × 18). Nevertheless, the warp direction of the fiberglass was tracked during cutting, assembly, and testing. The fiberglass was cut in 12.7 × 12.7 mm squares with a punch-type die. The cleaned, sand-blasted, and vapor-degreased stainless-steel plates, and the fiberglass cloth were assembled into a mold. After assembly the mold was sealed, vacuum-impregnated, and cured for 5 h at 110 °C. The specimens were then removed and post-cured for 16 h at 125 °C. Excess epoxy was removed from the specimens prior to testing.

Fixtures were machined from a Ti alloy to enable tests at angles of 0, 15, 30, 45, 60, and 75°, measured from vertical. (The 0° fixture is a single-specimen lap-shear type.) The smaller angles correspond to tests with a larger shear component and the larger angles to tests with a larger compressive component. As the compressive component increased it was necessary to move to larger capacity machines. As a result, tests were conducted on three machines, two screw-driven machines of 35- and a 100-kN capacity and a servohydraulic machine of 250-kN capacity. All specimens were tested at 76 K with a crosshead velocity of ~0.01 cm/min.

RESULTS

A production lot of 66 specimens was generated with nominal fiber volume fractions of 0.52 and 0.64. Because of the specimen design it was not possible to test the composite material in pure compression, since the aspect ratio (length to width) was too low. Post-test analysis showed that the specimens exhibited one of six failure modes: (1) Type-A cohesive (Figure 2A), failure within the layers of fiberglass; (2) Type-B cohesive (Figure 2B), failure between the epoxy bonded to the stainless-steel and the outermost fiberglass layer; (3) Type-C mixed, a combination of Type-A and Type-B cohesive failures; (4) Type-D adhesive, failure at the stainless-steel/epoxy interface; (5) Type-E mixed, a combination of Type-A cohesive and Type-D adhesive failures; and (6) Type-F mixed, a combination of Type-B cohesive and Type-D adhesive failures. Surprisingly, in most of the Type-A cohesive failures the fracture path was not interlaminar, but instead jumped across layers. This more tortuous path resulted in considerable fiber breakage. A failure was designated to be Type-B cohesive failure if virtually no fiberglass adhered to the stainless-steel plate. In no case was an absolute Type-D failure observed.

In presenting the results we have chosen to use the term "strength," not "stress." The data represent failure strengths under simultaneously applied shear and compressive forces. The relationship between these resolved forces is established by the fixture loading angle ($P \cos\theta$ - shear force, $P \sin\theta$ - compressive force, where P is the applied axial load). Figures 3A and 3B present the relationship between the resolved shear- and compressive-strength components. These figures show the results of testing at six angles for specimens with a nominal volume fraction of fiberglass of 0.64 , and at five angles for specimens with a nominal volume fraction of 0.52.

DISCUSSION

The trend of shear-compressive strengths is similar for nominal volume fractions of fiberglass of both 0.52 and 0.64. Figures 3A and 3B show that shear strength increases with compressive load, through test angles of 75° (where 96% of the applied load is resoved as a compressive force and 25% is resolved as a shear force). This is in agreement with the relationship observed by Bushnell et al. [5] in the range of compressive loads that they investigated (up to an equivalent angle of 40° with the NIST test fixture).

A difference was observed in the failure modes of specimens with nominally 0.64 volume fraction from those with 0.52 volume fraction of fiberglass. Type-A failures (cohesive failures among the fiberglass layers) are considered the most desirable and Type-D (adhesive failure at the epoxy/steel interface) the least desirable mode of failure. Twenty-nine specimens with a nominallly 0.64 fiber volume fraction were tested to failure. Of those 29 specimens all but one failed in a cohesive (Types A, B and C) manner. Furthermore, all but three involved failures in the fiberglass reinforcement (Types A, C, or E). Type-A failures accounted for 66% of all the failures for this volume fraction. Eighteen specimens with a nominal fiber volume fraction of 0.52 were tested to failure. These specimens did not consistently fail in a cohesive manner as did the specimens with nominally 0.64 fiber volume fraction. Eight out of 18 specimens (less than half) exhibited cohesive-type failures (Types A, B, or C). Out of the same 18 specimens, nine involved failure in the fiberglass reinforcement. Only 17% of the failures were Type A.

The resolved failure strengths do not differ significantly for specimens with nominal volume fractions of fiberglass of 0.52 or 0.64. One would expect the strength to increase with increasing fiberglass content, but it appears that for this fiberglass cloth style and specimen type a plateau in strength ranges from a volume fraction of about 0.52–0.64. (Actual volume fractions determined from measured specimen thicknesses ranged from 0.525 to 0.558 and from 0.618 to 0.661.) It is not clear whether the plateau in strength extends beyond this range. However, in a preliminary study with these test fixtures and a similar method of specimen production, strengths for a volume fraction below 0.3 were ~35% lower than those seen in this study [4].

CONCLUSIONS

The results indicate that shear strength continues to increase with compressive stresses up to a loading angle of 75° where 96% of the applied load is resoved as a compressive force and 25% is resolved as a shear force. At all angles, the failure mode was primarily interlaminar shear. But at a loading angle of 90°, the applied force is compression and the failure must change to a compressive mode. Therefore, the relationship between shear and compression must change dramatically at loading angles between 75 and 90°.

Contrary to expectations, the maximum load for a given angle does not change with volume fraction in the range of 0.52–0.64. The mode of failure may be influenced by the volume fraction; from the limited test matrix more cohesive failure occurred in the specimens with higher (0.64) fiber-volume fraction.

[†] Trade names are furnished to identify the material adequately. Such identification does not imply recommendation or endorsements by NIST, nor does it imply that the material identified is necessarily the best available for the purpose.

ACKNOWLEDGEMENTS

We thank Composite Technology Development for producing the specimens discussed in this paper, and C. Bushnell of Princeton Plasma Physics Laboratory and T. J. McManamy of Oak Ridge National Laboratory for allowing us to use their mold. Additionally, R. P. Walsh and J. Shepic deserve our gratitude for helping us in the design, machining, and refinement of our procedure.

REFERENCES

1 Poehlchen, R., Salpietro, E., Vassiliadis, M., Rauch, J., Koenig, F., Claudet, G., Chabert, J. N., Marangos, J., Kraehling, E., and Soell, M., The Mechanical Strength of Irradiated Electric Insulation, Advances in Cryogenic Engineering--Materials. Vol. 36, pp. 893–900 (1990).

2 Okada, T., and Nishijima, S., Investigation of Interlaminar Shear Behavior of Organic Composites at Low Temperatures, Advances in Cryogenic Engineering--Materials. Vol. 36, pp. 811–817 (1990).

3 McManamy, T. J., Brasier, J. E., and Snook, P., Insulation Interlaminar Shear Strength Testing with Compression and Irradiation, Proc. of 13th Symposium on Fusion Energy, IEEE, New York, Vol. 1, pp. 342-347 (1990).

4 Simon, N. J., Reed, R. P., and Walsh, R. P., Compression and Shear Tests on Vacuum-impregnated Composites at Cryogenic Temperatures, Advances in Cryogenic Engineering--Materials. Vol. 38, pp. 363-370 (1992).

5 Bushnell, C., McManamy, T., Snook, P., BPX Insulation Tests--Post CDR Princeton Plasma Physics Laboratory, Princeton, NJ, Technical Report No. F-920221-PPL-03 (1991).

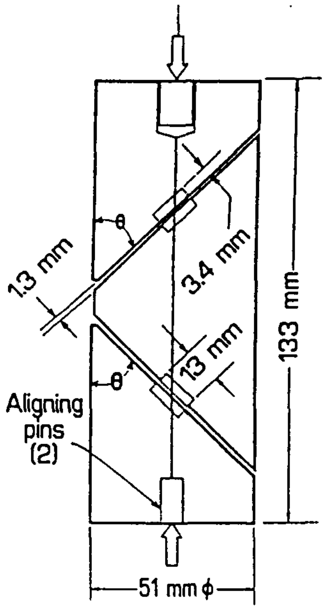


Figure 1 Schematic of the NIST angled fixture.

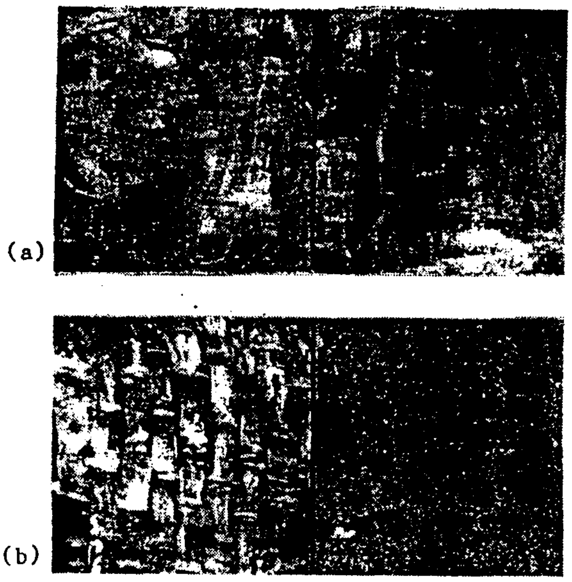


Figure 2 Photographs of typical examples of the two cohesive-type failure modes, (a) Type A and (b) Type B.

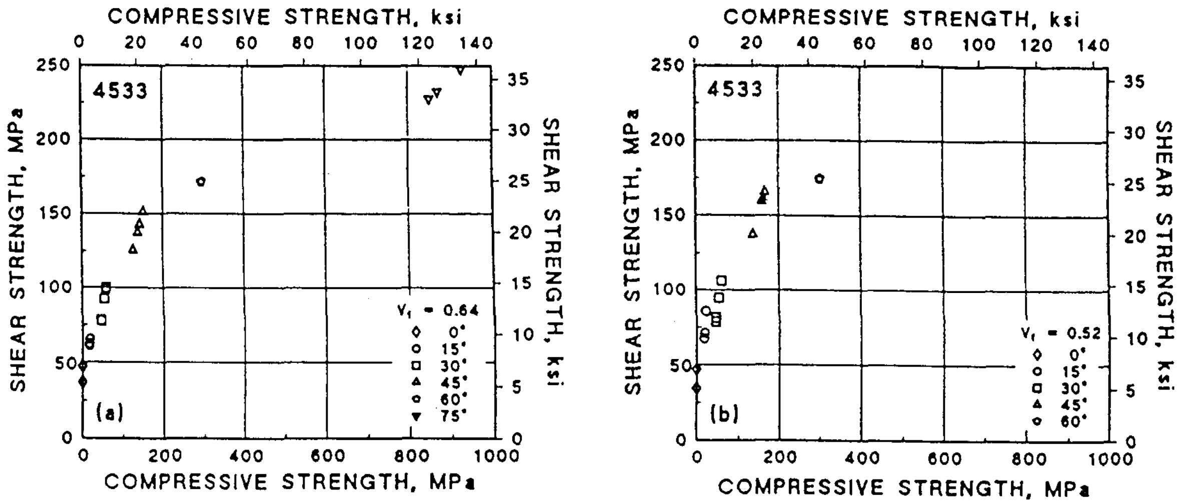


Figure 3 Relationship between the shear and compressive strengths for specimens containing nominally (a) 0.64 and (b) 0.52 fiberglass volume fraction tested at 76 K.

APPENDIX B

to

Interim Report: Shear/Compression Testing

CTD

COMPOSITE TECHNOLOGY DEVELOPMENT, INC.
1505 Coal Creek Drive • Lafayette, Colorado 80026

Phone: (303) 664-0394 • Fax: (303) 664-0392

Shear/Compression Test Results

Resin System:	CTD-112P (TGDM Epoxy)		
Reinforcement:	S-2 Glass - 6580	Condition:	AR
Barrier:	None		
Primer:	Ciba DZ-80		
Specimen Type:	S/C - Copper Chips		
Material Reference #:	Run #189		
Load Rate:	0.0018 mm/s		
Test Fixture:	15°	Test Temperature:	333 K
Test Date:	2/24/97		

primer
001
002
brass
40°C 1hr

49% Vf

Test #	Fixture Angle (Deg)	Top Specimen Number	Bottom Specimen Number	Specimen Failed (T or B)	Specimen Thickness (mm)	Ultimate Load (kN)	Spec. Dia. (mm)	Shear Strength (MPa)	Comp. Strength (MPa)	Failure Type
cm27c-1	15	A1	B1	T	8.15	3.6	12.65	28.0	7.5	C
cm27c-2	15	B2	B1	B	8.13	3.8	12.65	29.1	7.8	C

SHEAR STRENGTH		COMPRESSION STRENGTH	
AVERAGE (MPa):	28.56	AVERAGE (MPa):	7.65
STD.DEV. (MPa):	0.73	STD.DEV. (MPa):	0.19
CV:	0.03	CV:	0.03

55% Vf

Test #	Fixture Angle (Deg)	Top Specimen Number	Bottom Specimen Number	Specimen Failed (T or B)	Specimen Thickness (mm)	Ultimate Load (kN)	Spec. Dia. (mm)	Shear Strength (MPa)	Comp. Strength (MPa)	Failure Type
cm27c-3	15	A3	B3	B	8.13	3.7	12.65	28.4	7.6	C
cm27c-4	15	B4	A4	B	8.13	3.3	12.65	25.2	6.7	A/P
cm27c-5	15	B4	A3	B	8.13	3.6	12.65	27.4	7.3	C/P

SHEAR STRENGTH		COMPRESSION STRENGTH	
AVERAGE (MPa):	26.97	AVERAGE (MPa):	7.23
STD.DEV. (MPa):	1.64	STD.DEV. (MPa):	0.44
CV:	0.06	CV:	0.06

Failure Mode:

A/P - Adhesive failure at the metal/primer interface.
C/P - Cohesive failure in the primer.
C - Cohesive failure in the composite.

Shear/Compression Test Results

Resin System:	CTD-112P (TGDM Epoxy)		
Reinforcement:	S-2 Glass - 6580	Condition:	AR
Barrier:	None		
Primer:	Ciba DZ-80		
Specimen Type:	S/C - Copper Chips		
Material Reference #:	Run #189		
Load Rate:	0.0018 mm/s		
Test Fixture:	15°	Test Temperature:	333 K
Test Date:	2/24/97		

61% Vf

Test #	Fixture Angle (Deg)	Top Specimen Number	Bottom Specimen Number	Specimen Failed (T or B)	Specimen Thickness (mm)	Ultimate Load (kN)	Spec. Dia. (mm)	Shear Strength (MPa)	Comp. Strength (MPa)	Failure Type
cm27c-6	15	A6	B6	B	8.13	3.4	12.65	26.4	7.1	C/P
cm27c-7	15	A6	A7	B	8.13	3.3	12.65	25.7	6.9	C/P
cm27c-11	15	B2	A8	B	8.13	3.7	12.65	28.4	7.6	C

SHEAR STRENGTH		COMPRESSION STRENGTH	
AVERAGE (MPa):	26.83	AVERAGE (MPa):	7.19
STD.DEV. (MPa):	1.39	STD.DEV. (MPa):	0.37
CV:	0.05	CV:	0.05

55% Vf, without primer

Test #	Fixture Angle (Deg)	Top Specimen Number	Bottom Specimen Number	Specimen Failed (T or B)	Specimen Thickness (mm)	Ultimate Load (kN)	Spec. Dia. (mm)	Shear Strength (MPa)	Comp. Strength (MPa)	Failure Type
cm27c-8	15	B7	A8	T	8.13	2.7	12.65	20.7	5.6	A
cm27c-9	15	B8	A8	T	8.13	2.1	12.65	16.4	4.4	A
cm27c-10	15	A6	A8	B	8.13	2.9	12.65	22.4	6.0	A

SHEAR STRENGTH		COMPRESSION STRENGTH	
AVERAGE (MPa):	19.82	AVERAGE (MPa):	5.31
STD.DEV. (MPa):	3.09	STD.DEV. (MPa):	0.83
CV:	0.16	CV:	0.16

Failure Mode:

A/P - Adhesive failure at the metal/primer interface.
A - Adhesive failure at the insulation/metal interface.
C/P - Cohesive failure in the primer layer.
C - Cohesive failure in the composite.

CTD

COMPOSITE TECHNOLOGY DEVELOPMENT, INC.
1505 Coal Creek Drive • Lafayette, Colorado 80026
Phone: (303) 664-0394 • Fax: (303) 664-0392

Shear/Compression Test Results

Resin System:	CTD-112P (TGDM Epoxy)/Kapton		
Reinforcement:	S-2 Glass - 6580	Condition:	AR
Barrier:	Kapton 200 HA		
Primer:	Ciba DZ-80		
Specimen Type:	S/C - Copper Chips		
Material Reference #:	Run #188		
Load Rate:	0.0018 mm/s		
Test Fixture:	15°	Test Temperature:	295 and 395 K
Test Date:	2/23/97		

295 K

49v%

Test #	Fixture Angle (Deg)	Top Specimen Number	Bottom Specimen Number	Specimen Failed (T or B)	Specimen Thickness (mm)	Ultimate Load (kN)	Spec. Dia. (mm)	Shear Strength (MPa)	Comp. Strength (MPa)	Failure Type
cm27b-1	15	A1	B1	B	8.13	3.6	12.65	28.0	7.5	C
cm27b-2	15	B2	A2	B	8.13	3.9	12.67	29.9	8.0	C/P
cm27b-3	15	A1	B2	T	8.13	3.8	12.67	28.7	7.7	C

SHEAR STRENGTH		COMPRESSION STRENGTH	
AVERAGE (MPa):	28.91	AVERAGE (MPa):	7.75
STD.DEV. (MPa):	0.96	STD.DEV. (MPa):	0.26
CV:	0.03	CV:	0.03

395 K

49v%

Test #	Fixture Angle (Deg)	Top Specimen Number	Bottom Specimen Number	Specimen Failed (T or B)	Specimen Thickness (mm)	Ultimate Load (kN)	Spec. Dia. (mm)	Shear Strength (MPa)	Comp. Strength (MPa)	Failure Type
cm27b-10	15	A7	B7	B	8.15	2.9	12.65	22.7	6.1	C/P
cm27b-11	15	B8	A8	B	8.13	2.4	12.65	18.4	4.9	A/P
cm27b-12	15	B8	A7	B	8.13	2.4	12.65	18.7	5.0	C/P

SHEAR STRENGTH		COMPRESSION STRENGTH	
AVERAGE (MPa):	19.91	AVERAGE (MPa):	5.34
STD.DEV. (MPa):	2.40	STD.DEV. (MPa):	0.64
CV:	0.12	CV:	0.12

Failure Mode:

A/P - Adhesive failure at the metal/primer interface.
A/K - Adhesive failure at the Kapton.
C/P - Cohesive failure in the primer layer.
C - Cohesive failure in the composite.

Shear/Compression Test Results

Resin System:	CTD-112P (TGDM Epoxy)		
Reinforcement:	S-2 Glass - 6580	Condition:	AR
Barrier:	None		
Primer:	Ciba DZ-80		
Specimen Type:	S/C - Copper Chips		
Material Reference #:	Run #189		
Load Rate:	0.0018 mm/s		
Test Fixture:	45°	Test Temperature:	333 K
Test Date:	2/24/97		

49% Vf

Test #	Fixture Angle (Deg)	Top Specimen Number	Bottom Specimen Number	Specimen Failed (T or B)	Specimen Thickness (mm)	Ultimate Load (kN)	Spec. Dia. (mm)	Shear Strength (MPa)	Comp. Strength (MPa)	Failure Type
cm27c-14	45	A2	B2	B	8.13	7.5	12.65	42.3	42.3	C
cm27c-15	45	A2	B5	T	8.13	8.2	12.65	45.9	45.9	C

SHEAR STRENGTH		COMPRESSION STRENGTH	
AVERAGE (MPa):	44.13	AVERAGE (MPa):	44.12
STD.DEV. (MPa):	2.57	STD.DEV. (MPa):	2.57
CV:	0.06	CV:	0.06

55% Vf

Test #	Fixture Angle (Deg)	Top Specimen Number	Bottom Specimen Number	Specimen Failed (T or B)	Specimen Thickness (mm)	Ultimate Load (kN)	Spec. Dia. (mm)	Shear Strength (MPa)	Comp. Strength (MPa)	Failure Type
cm27c-12	45	B4	A5	B	8.13	9.0	12.65	50.8	50.8	C
cm27c-13	45	B5	B4	B	8.10	8.6	12.65	48.6	48.6	C/P

SHEAR STRENGTH		COMPRESSION STRENGTH	
AVERAGE (MPa):	49.72	AVERAGE (MPa):	49.72
STD.DEV. (MPa):	1.52	STD.DEV. (MPa):	1.52
CV:	0.03	CV:	0.03

Failure Mode:

A/P - Adhesive failure at the metal/primer interface.
C/P - Cohesive failure in the primer.
C - Cohesive failure in the composite.

CTD
COMPOSITE TECHNOLOGY DEVELOPMENT, INC.
1505 Coal Creek Drive • Lafayette, Colorado 80026
Phone: (303) 664-0394 • Fax: (303) 664-0392

Shear/Compression Test Results

Resin System: CTD-112P (TGDM-Epoxy)/Kapton
Reinforcement: S-2 Glass - 6580
Condition: AR
Barrier: Kapton 200 HA
Primer: Ciba DZ-80
Specimen Type: S/C - Copper Chips
Material Reference #: Run #188

Load Rate: 0.0018 mm/s

Test Fixture: 45°
Test Temperature: 295 and 395 K
Test Date: 2/23/97

295 K

497004

Test #	Fixture Angle (Deg)	Top Specimen Number	Bottom Specimen Number	Specimen Failed (T or B)	Specimen Thickness (mm)	Ultimate Load (kN)	Spec. Dia. (mm)	Shear Strength (MPa)	Comp. Strength (MPa)	Failure Type
cm27b-4	45	A3	B3	B	8.13	8.9	12.65	50.2	50.2	C/K
cm27b-5	45	B4	A4	B	8.13	8.6	12.67	48.0	48.0	C
cm27b-6	45	B4	A3	B	8.13	9.1	12.65	51.2	51.2	C/K

SHEAR STRENGTH

AVERAGE (MPa):	49.80
STD.DEV. (MPa):	1.66
CV:	0.03

COMPRESSION STRENGTH

AVERAGE (MPa):	49.79
STD.DEV. (MPa):	1.66
CV:	0.03

395 K

497006

Test #	Fixture Angle (Deg)	Top Specimen Number	Bottom Specimen Number	Specimen Failed (T or B)	Specimen Thickness (mm)	Ultimate Load (kN)	Spec. Dia. (mm)	Shear Strength (MPa)	Comp. Strength (MPa)	Failure Type
cm27b-7	45	A5	B5	T	8.13	5.2	12.65	29.1	29.1	C/P
cm27b-8	45	B6	A6	B	8.13	5.2	12.65	29.3	29.3	A/P
cm27b-9	45	B5	B6	B	8.13	5.4	12.65	30.6	30.6	C/P

SHEAR STRENGTH

AVERAGE (MPa):	29.68
STD.DEV. (MPa):	0.82
CV:	0.03

COMPRESSION STRENGTH

AVERAGE (MPa):	29.67
STD.DEV. (MPa):	0.82
CV:	0.03

Failure Mode:

A/P - Adhesive failure at the metal/primer interface.
A/K - Adhesive failure at the Kapton.
C/P - Cohesive failure in the primer.
C/K - Cohesive failure at the Kapton; tearing of the Kapton.
C - Cohesive failure in the composite.

CTD

COMPOSITE TECHNOLOGY DEVELOPMENT, INC.
1505 Coal Creek Drive • Lafayette, Colorado 80026
Phone: (303) 664-0394 • Fax: (303) 664-0392

Shear/Compression Test Results

Resin System:	CTD-112P (TGDM Epoxy)		
Reinforcement:	S-2 Glass - 6580	Condition:	AR
Barrier:	None		
Primer:	Ciba DZ-80		
Specimen Type:	S/C - Copper Chips		
Material Reference #:	Run #187		
Load Rate:	0.0018 mm/s		
Test Fixture:	15°	Test Temperature:	295 and 395 K
Test Date:	2/18/97		

295 K

Test #	Fixture Angle (Deg)	Top Specimen Number	Bottom Specimen Number	Specimen Failed (T or B)	Specimen Thickness (mm)	Ultimate Load (kN)	Spec. Dia. (mm)	Shear Strength (MPa)	Comp. Strength (MPa)	Failure Type
cm27-7	15	A5	B5	B	8.10	3.8	12.65	28.9	7.8	C
cm27-8	15	B6	A6	T	8.10	4.0	12.65	31.1	8.3	C
cm27-9	15	A6	A5	T	8.10	3.9	12.67	30.2	8.1	C

SHEAR STRENGTH		COMPRESSION STRENGTH	
AVERAGE (MPa):	30.07	AVERAGE (MPa):	8.06
STD.DEV. (MPa):	1.07	STD.DEV. (MPa):	0.29
CV:	0.04	CV:	0.04

395 K

Test #	Fixture Angle (Deg)	Top Specimen Number	Bottom Specimen Number	Specimen Failed (T or B)	Specimen Thickness (mm)	Ultimate Load (kN)	Spec. Dia. (mm)	Shear Strength (MPa)	Comp. Strength (MPa)	Failure Type
cm27-10	15	A7	B7	T	8.08	3.0	12.67	23.0	6.2	A/P
cm27-11	15	B7	A8	T	8.08	2.8	12.67	21.2	5.7	C/P
cm27-12	15	B8	A8	T	8.08	3.6	12.65	27.4	7.3	C

SHEAR STRENGTH		COMPRESSION STRENGTH	
AVERAGE (MPa):	23.87	AVERAGE (MPa):	6.40
STD.DEV. (MPa):	3.18	STD.DEV. (MPa):	0.85
CV:	0.13	CV:	0.13

Failure Mode:

A/P - Adhesive failure at the metal/primer interface.
A/K - Adhesive failure at the Kapton.
C/P - Cohesive failure in the primer layer.
C - Cohesive failure in the composite.

CTD
COMPOSITE TECHNOLOGY DEVELOPMENT, INC.
1505 Coal Creek Drive • Lafayette, Colorado 80026
Phone: (303) 664-0394 • Fax: (303) 664-0392

Shear/Compression Test Results

Resin System: CTD-112P (TGDM Epoxy)
Reinforcement: S-2 Glass - 6580 Condition: AR
Barrier: None
Primer: Ciba DZ-80
Specimen Type: S/C - Copper Chips
Material Reference #: Run #187

Load Rate: 0.0018 mm/s

Test Fixture: 45° Test Temperature: 295 and 395 K
Test Date: 2/17/97

295 K

Test #	Fixture Angle (Deg)	Top Specimen Number	Bottom Specimen Number	Specimen Failed (T or B)	Specimen Thickness (mm)	Ultimate Load (kN)	Spec. Dia. (mm)	Shear Strength (MPa)	Comp. Strength (MPa)	Failure Type
cm27-1	45	A1	B1	T	8.13	8.9	12.67	49.6	49.6	C
cm27-2	45	B2	A2	B	8.08	9.2	12.65	52.0	52.0	C
cm27-3	45	B1	B2	T	8.10	9.4	12.65	53.1	53.1	C

SHEAR STRENGTH		COMPRESSION STRENGTH	
AVERAGE (MPa):	51.58	AVERAGE (MPa):	51.57
STD.DEV. (MPa):	1.77	STD.DEV. (MPa):	1.77
CV:	0.03	CV:	0.03

395 K

Test #	Fixture Angle (Deg)	Top Specimen Number	Bottom Specimen Number	Specimen Failed (T or B)	Specimen Thickness (mm)	Ultimate Load (kN)	Spec. Dia. (mm)	Shear Strength (MPa)	Comp. Strength (MPa)	Failure Type
cm27-4	45	A3	B3	T	8.08	7.4	12.65	41.8	41.8	C
cm27-5	45	B4	A4	T	8.13	6.8	12.65	38.2	38.2	C
cm27-6	45	B3	A4	T	8.05	7.3	12.65	40.9	40.9	A/P

SHEAR STRENGTH		COMPRESSION STRENGTH	
AVERAGE (MPa):	40.30	AVERAGE (MPa):	40.30
STD.DEV. (MPa):	1.91	STD.DEV. (MPa):	1.91
CV:	0.05	CV:	0.05

Failure Mode:

A/P - Adhesive failure at the metal/primer interface.
A/K - Adhesive failure at the Kapton.
C/K - Cohesive failure at the Kapton; tearing of the Kapton.
C - Cohesive failure in the composite.