UCRL-CR-121739-V01.5

TPX Insulation & Impregnation R&D - 3x3 Test Report Electrical Insulation

J. F. Roach and W. M. Urban
Advanced Electromechanical Systems Department

D. Hartman
Everson Electric Company

August 4, 1995

TPX 14-950630-WEC-FRoach-02

APPROVED:

P. A. Sanger
Westinghouse TPX Chief Scientist

APPROVED:

D. R. Potter
Westinghouse TPX Engineering Manager

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Westinghouse Electric Corporation
Electronic Systems Group

MASTER

401 East Hendy Avenue, Sunnyvale, California 94088-3499

CONTENTS

LIST OF FIGURES v

LIST OF TABLES vii

ABSTRACT ix

1. OBJECTIVES 1-1

2. SCOPE 2-1

3. CANDIDATE INSULATION APPROACHES 3-1

4. TEST PROGRAM 4-1

4.1 SAMPLE AND MOLD DESIGNS 4-1

4.2 MATERIALS AND VENDORS 4-3

4.3 FABRICATION AT EVERSON ELECTRIC 4-4

4.4 ELECTRICAL TEST EQUIPMENT 4-4

4.5 ELECTRICAL TESTING PROCEDURES 4-8

5. TEST RESULTS 5-1

5.1 TEST MATRIX 5-1

5.2 SAMPLE DIMENSIONAL ANALYSIS 5-1

5.3 DC ELECTRICAL PERFORMANCE 5-5

5.4 AC PARTIAL DISCHARGE PERFORMANCE 5-10

5.5 DC HIPOT TO FAILURE TESTS 5-13

5.6 OBSERVATIONS OF SAMPLE CROSS SECTIONS 5-20

5.7 MANUFACTURING LESSONS LEARNED 5-23

6. CONCLUSIONS 6-1

7. ACKNOWLEDGMENTS 7-1

8. APPENDICES 8-1

8.1: CTD101K AND CTD112P SPECIFICATION SHEETS 8.1-1

8.2: QA MEASUREMENTS OF TTI S-2 GLASS PLAIN WEAVE TAPE 8.2-1

8.3: FABRICATION AND IMPREGNATION PROCEDURES 8.3-1

8.4: POST CURE DIMENSIONS OF SAMPLES CA AND D 8.4-1

LIST OF FIGURES

Page

Figure 3.1 — Conduit insulation configuration for 1x2 Samples A-Baseline. Sketch not to scale....3-3

Figure 3.2 — Conduit insulation configuration for 1x2 Samples B-Interleaved Kapton/Dry Glass design. Sketch not to scale....3-4

Figure 3.3 — Conduit insulation configurations for 1x2 Sample C-Kapton Slip/Dry Glass. Sketch not to scale....3-5

Figure 3.4 — Conduit insulation configuration for 1x2 Sample CA-Adhesive Kapton Slip/Dry Glass. Sketch not to scale....3-6

Figure 3.5 — Conduit insulation configuration for 1x2 Sample D-Interleaved KaptonPrepreg Glass. Sketch not to scale....3-7

Figure 4.1 — Nominal design of 1x2 samples based on a 1.626 mm insulation build between conductors after impregnation process....4-2

Figure 4.2 — Typical A-Baseline samples as received from Everson Electric with electrical lead posts screwed into top and bottom conduits....4-5

Figure 4.3 — Typical B-Kapton/Glass samples as received from Everson Electric with electrical lead posts screwed into top and bottom conduits....4-6

Figure 4.4 — Typical C-Kapton/Slip samples as received from Everson Electric with electrical lead posts screwed into top and bottom conduits....4-7

Figure 5.1 — Electrostatic field plot shown for a quarter section a 1x2 sample for the A-Baseline insulation design....5-9

Figure 5.2 — Comparison of partial discharge for Shell 826 (1-) and CTD-101K (2-)-2A samples under liquid nitogen after thermal cycling....5-15

Figure 5.3 — Comparison of partial discharge for Shell 826 (1-) and CTD-101K (2-) 1B samples under liquid nitrogen after thermal cycling....5-16

Figure 5.4 — Comparison of partial discharge for Shell 826 (1-) and CTD-101K (2-) 2B samples under liquid nitrogen after thermal cycling. 5-17

Figure 5.5 — Polished longitudinal cross sections of sample 1-1B. Upper photograph for the turn-turn insulation and lower photograph for the conduit insulation only. 5-21

Figure 5.6 — Polished cross sections of sample 3-3CA. Upper photograph for the turn-turn insulation and lower photograph for the corner region showing the roving void filler. 5-22

LIST OF TABLES

Page

Table 3.1 — Summary of insulation configurations as fabricated at Everson Electric for the 1x2 program. 3-2

Table 5.1 — Summary of 1x2 configurations and test plan. 5-2

Table 5.2 — Test matrix for 1x2 insulation samples. 5-3

Table 5.3 — Dimensional characteristics of TPX 1x2 samples as received. 5-4

Table 5.4 — Dielectric characteristics of TPX 1x2 insulation samples. 5-6

Table 5.5 — Estimated relative dielectric constants for TPX 1x2 insulation samples. 5-7

Table 5.6 — Summary of partial discharge measurements for 1x2 samples before and after thermal cycles. 5-11

Table 5.7 — Partial discharge as function of voltage after thermal cycles for samples under oil. 5-12

Table 5.8 — Partial discharge as function of voltage under liquid nitrogen after thermal cycles. 5-14

Table 5.9 — Failure Hipot testing in air for TPX 1x2 samples. 5-19

ABSTRACT

TPX Insulation & Impregnation R&D test results are reported for 1x2 samples designed for screening candidate conduit insulation systems for TPX PF and TF coils. The 1x2 samples were fabricated at the Everson Electric Company in Allentown, PA and the electrical test program was carried out at the Westinghouse Science & Technology Center, Pittsburgh, PA. The test program evaluating the electrical performance of the TPX CDR fully bonded baseline epoxy/glass insulation system and three proposed alternate insulation systems employing Kapton, was evaluated in as received post cure sample condition and after 10 thermal cycles in liquid nitrogen. Two DGBA impregnation systems, Shell 826 and CTD101K were investigated. Square Incoloy 908 and 316 LN stainless hollow conduits were used for 1x2 sample fabrication. No mechanical tests were conducted on the 1x2 samples. Samples were tested in as received post cure condition and after 10 thermal cycles in liquid nitrogen. Capacitance, dielectric loss (tan δ), and insulation resistance (IR) dielectric characteristics were measured for all samples. Partial discharge performance was measured for samples either in air, under silicon oil, or under liquid nitrogen up to 10 kVrms at 60 Hz. Hipot screening was performed at 10 kVdc. After completion of all screening tests a final Hipot to failure test was performed up to 40 kVdc. The samples were cross sectioned and evaluated for impregnation quality. The implications of the test results on the TPX preliminary design decision are discussed.

1. OBJECTIVES

The focus of the TPX 1x2 R&D program was to explore Kapton/Epoxy/Dry Glass and Kapton/Epoxy/Prepreg Glass design options to the Barrier/Epoxy/Dry Glass fully bonded CDR baseline design for both TF and PF winding pack electrical insulation. The electrical performance was measured for 75 mm long, 1x2 PF conduit samples of the baseline and optional designs in as received condition and after thermal cycling in liquid nitrogen. The major objectives of the 1x2 electrical testing program were to:

- Compare electrical performance of the baseline and optional designs
- Explore Shell 826 and CTD101K resin systems for impregnation system
- Assess bonding to Incoloy 908 and 304LN stainless steel conduits
- Assess electrical performance discriminators for design change decisions
- Assess manufacturing issues of baseline and optional designs
- Recommend designs for 3x3 R&D program follow-up

2. SCOPE

The 1x2 program was designed as a preliminary screening test for insulation and impregnation system options. The test matrix consisted of (18)-1x2 samples as follows: (4) Samples A-Baseline, (4) Samples B-Interleaved Kapton/Dry Glass, (4) Samples C-Kapton Slip/Dry Glass, (3) Samples CA- Kapton Slip/Dry Glass, and (3) Samples D-Interleaved Kapton/Prepreg Glass. Samples A, B, and C each consisted of (2) samples of Shell 826 and (2) samples of CTD101K resins. Samples CA and D were all impregnated with CTD101K resin. The test program focused on dielectric performance of the (18) samples in as received condition and after thermal cycling in liquid nitrogen. There were no mechanical tests performed on the 1x2 samples, and all electrical tests were conducted without mechanical loading.

The 1x2 samples were fabricated and impregnated at the Everson Electric Company (EE) in Allentown, PA under the supervision of Mr. Doug Hartman of EE. The completed samples were then shipped to the Westinghouse Science & Technology Center (W-STC) in Pittsburgh, PA. The dielectric testing, sample cross sectioning, and data analysis was performed at W-STC under the direction of Dr. Frank Roach.

The 1x2 sample testing included measurements in laboratory air of capacitance and dielectric loss tangent as a function of frequency, insulation resistance (IR), and dc Hipot. Partial discharge measurements were made at 60 Hz voltage either in air, silicon oil, or in liquid nitrogen. Partial discharge onset/offset voltages as well as average/peak discharge levels were measured. Following the electrical testing, selected samples were cross sectioned and the epoxy impregnation condition was qualitatively assessed from microscope observations of polished cross sections.

Finally, the 1x2 samples were designed to test the basic insulation between adjacent turns within a winding pack stacked one on top of the other. The 1x2 samples, therefore, did not include groundwrap insulation. Also, Samples A, B, and C did not incorporate any void filler in the two corners of the conductors. Void filler was subsequently used for Samples CA and D.

3. CANDIDATE INSULATION APPROACHES

The candidate CDR baseline and optional Kapton insulation configurations investigated in the 1x2 program are summarized in Table 3.1 and Figures 3.1 through 3.5. The CDR Baseline design labeled A-Baseline for sample identification is given in Figure 3.1. The four optional approaches, which employ Kapton insulation are presented in Figures 3.2 through 3.5. These Kapton options are labeled for sample identification as follows: B-Kapton/Dry Glass, C-Kapton Slip, CA-Adhesive Kapton Slip, and D-Kapton/Prepreg.

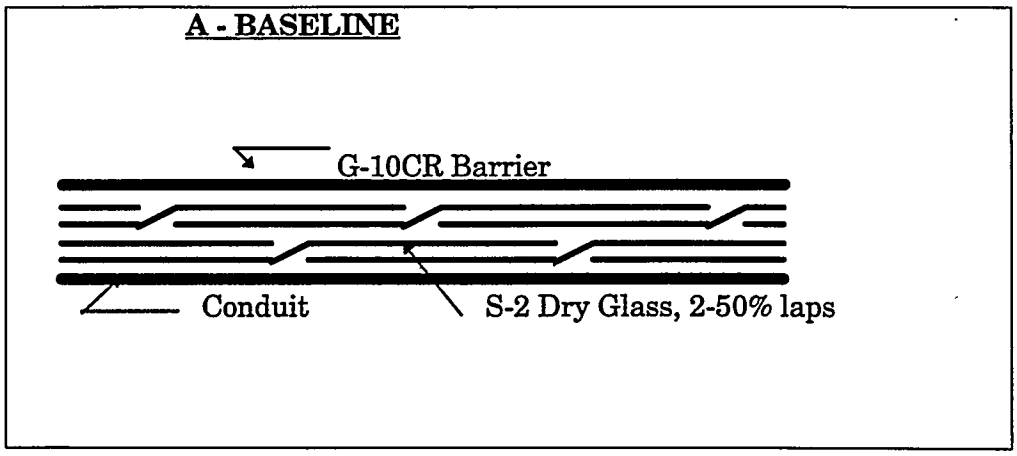
Kapton options B-Kapton/Dry Glass, Figure 3.2 and D-Kapton/Prepreg, Figure 3.5 were envisioned to be fully bonded to the conduit at the glass/conduit interface. The Kapton film insulation is interleaved with dry glass in the B-option and bonding to the conduit achieved by epoxy impregnation through the 0.178 mm dry glass tape wicking path to the conduit wall. The taping scheme is designed such that the Kapton is essentially 50%-lapped and the dry glass 67% lapped. This taping method puts the dry glass on both the outside and conduit wall side of the interleaved Kapton/glass taping providing for direct wicking paths. To ensure full bonding to the conduit, the Kapton is slightly offset relative to the dry glass tape edge to prevent Kapton from contacting the conduit.

In the case of the D-option, Kapton is interleaved with prepreg glass in the same way as the B-option. The dry glass is wrapped directly over the Kapton/prepreg taping and is cured simultaneously with the impregnating epoxy resin during the epoxy vacuum pressure impregnation (VPI) process. In practice the VPI process must be tailored to prevent prepreg from fully curing until sufficient pressure is applied to the epoxy resin to ensure the prepreg. The 1x2 program did not explore optimization of such a "hybrid" curing process. The vacuum processing

Table 3.1 — Summary of insulation configurations as fabricated at Everson Electric for the 1x2 program.

SAMPLE TYPE	KAPTON WRAP (DuPont Type H, 0.051 mm thickness)	GLASS WRAP (TTI, S-2, 0.223 mm 4-Harness Satin Finish Weave)	BARRIER (G-10)	EPOXY SYSTEMS	CONDUIT
A- Baseline	None	2-50%	0.36 mm G-10 Sheet	CTD-101K & Shell 826	Incoloy 908
B- Kapton/ Dry Glass	Interleaved with S-2 glass 1-50% wraps	1-67% interleaved with Kapton on top	None	CTD-101K & Shell 826	Incoloy 908
C- Kapton Slip	2-50% wraps on conduit	2-50% overwraps	None	CTD-101K & Shell 826	Incoloy 908
CA- Adhesive Kapton Slip	2-50% counter wraped on conduit	1-50% & 1-Butt overwraps	None	CTD-101K	Incoloy 908 & 304LN
D- Kapton/ Prepreg	1-50% wrap centered on top of prepreg	1-50% ITER wet prepreg prototype, 0.229 mm	None	CTD-101K & CTD-112P (Prepreg resin)	Incoloy 908 & 304LN

temperature was limited to below the prepreg cure temperature during the VPI process. However, the 1x2 samples were not pressurized during the epoxy curing which took place at essentially atmospheric pressure only.



A - CDR Baseline Design (*Fully Bonded*)

Conduit Wrap:

2-50% lapped S-2 dry glass 19.0 mm wide, 0.178 mm thick registered so that second wrap is lapped half-way between inner wrap overlaps. S-2 glass is 4 harness Satin finish weave, Silane finish purchased from Textile Technologies Industries (TTI), Hatboro, PA

Barrier:

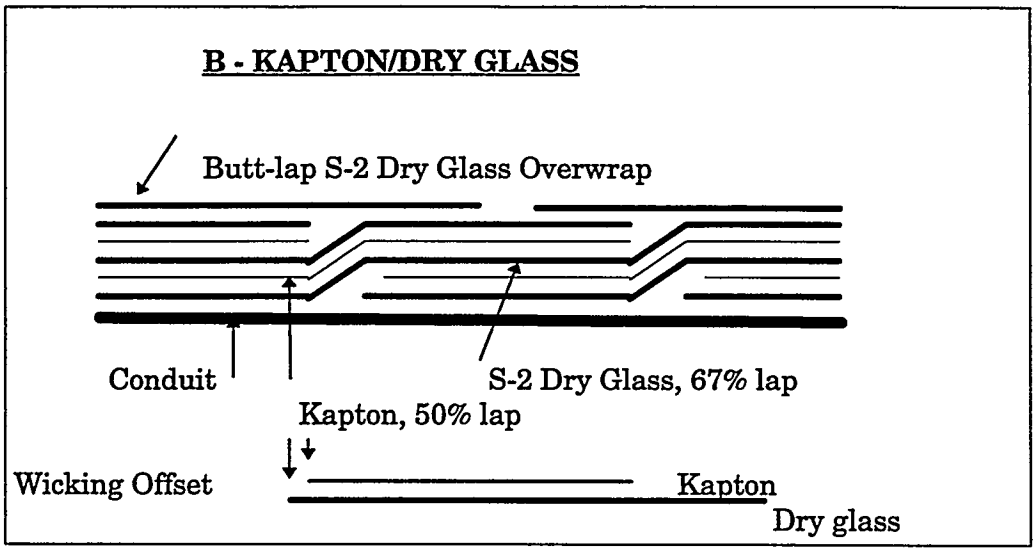
0.356 mm G10 sheet available at EE with sandblast surface preparation; sheet edges flush with conductor sides

Insulation Build Metal to Metal:

Nominal build without compression is 8x0.178 + 0.356 = 1.778 mm

Assume 9% compression of build in 1x2 mold to achieve 1.626 mm build design goal

Figure 3.1 — Conduit insulation configuration for 1x2 Samples A-Baseline. Sketch not to scale.



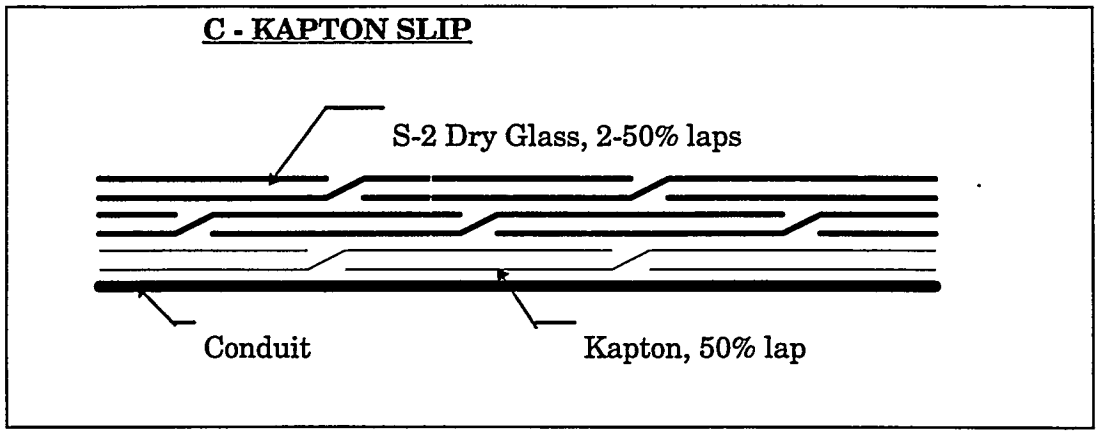
B - Interleaved Kapton/Dry Glass (*Fully Bonded with Elimination of Layer Barrier*)

Conduit Wrap:
12.7 mm wide 0.051 mm Type H Kapton on 19.0 mm wide 0.178 mm TTI S-2 dry glass 1-67% lapped layer with approximately 1.6 mm wicking offset

Glass Overlap:
19.0 mm wide 0.178 mm TTI S-2 dry glass 1-butt lap over conduit Kapton/glass wrap

Insulation Build Metal to Metal:
Nominal build (4x0.178 + 2x0.051)x2 = 1.626 mm without mold compression

Figure 3.2 — Conduit insulation configuration for 1x2 Samples B- Interleaved Kapton/Dry Glass design. Sketch not to scale.



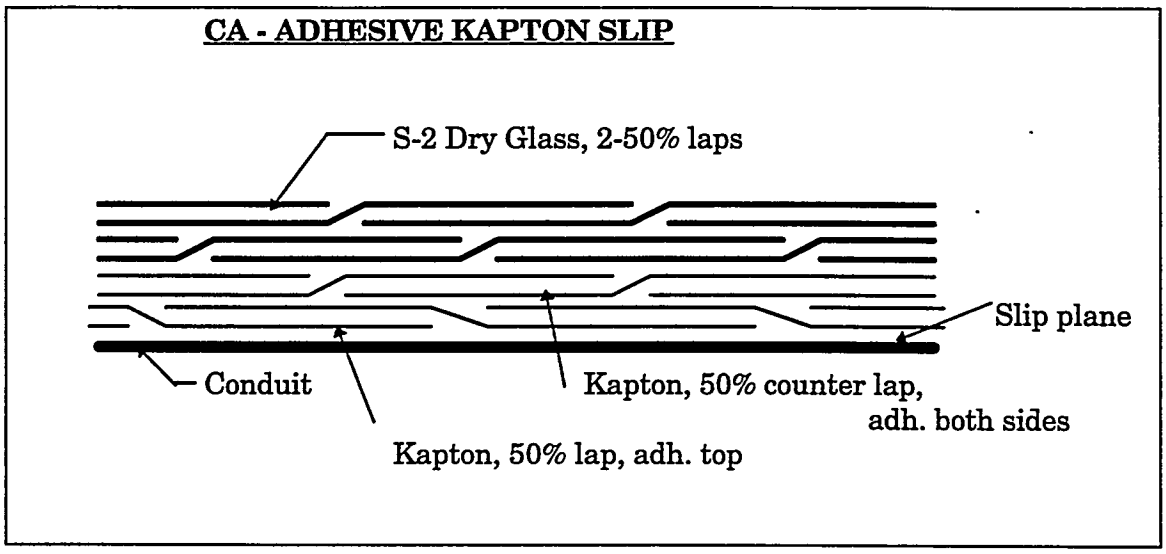
C - Kapton Slip/Dry Glass (*Kapton Slip on Conduit with Elimination of Layer Barrier)*

Conduit Wrap:
19.0 mm wide 0.051 mm Type H Kapton 1-50% lapped layer

Glass Overlap:
19.0 mm wide 0.178 mil TTI S-2 dry glass 2-50% laps over Kapton wrap

Insulation Build Metal to Metal:
Nominal build (4x0.178 + 2x0.051)x2 = 1.626 mm without mold compression

Figure 3.3 — Conduit insulation configurations for 1x2 Sample C-Kapton Slip/Dry Glass. Sketch not to scale.



CA - Adhesive Kapton Slip/Dry Glass (Adhesive Kapton with Slip on Conduit and Elimination of Layer Barrier)

Conduit Wrap:

12.7 mm wide 0.025 mm Type HN Kapton with 0.005 mm adhesive one side, 1-50% lapped layer

19.0 mm wide 0.025 mm Type HN Kapton with 0.005 mm adhesive each side, 1-50% counter lapped

(Actually used two counterlapped 25.4 mm wide, .051 mm Kapton layers without any adhesive on the Kapton)

Glass Overlap:

19.0 mm wide 0.178 mm TTI S-2 dry glass 2-50% laps over Kapton wrap

(Actually used 1-50% layer and 1 butt layer of dry glass)

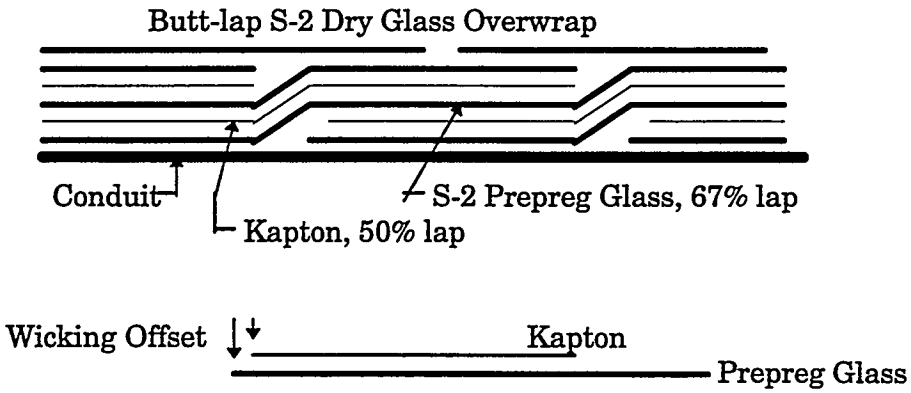
Insulation Build Metal to Metal:

Nominal build (4x0.178 + 2x0.065)x2 = 1.684 mm without mold compression

(Actual build (3x0.229 + 2x0.051)x2 = 1.578 mm)

Figure 3.4 — Conduit insulation configuration for 1x2 Sample CA-Adhesive Kapton Slip/Dry Glass. Sketch not to scale.

D - KAPTON/ PREPREG



D - Interleaved Kapton/Prepreg Glass (Fully Bonded Hybrid Epoxy/Prepreg Cure with Elimination of Layer Barrier)

Conduit Wrap:

12.7 mm wide 0.051 mm Type H Kapton on 19.0 mm wide 0.178 mm S-2 prepreg glass 1-67% lapped layer *(Actually used 19.0 mm wide 0.051 mm Type H Kapton centered on 25.4 mm wide 0.229 mm S-2 prepreg glass 1-50% lapped layer. Prepreg obtained from ITER program.)*

Glass Overlap:

19.0 mm wide 0.178 mm S-2 dry glass 1-butt lap over conduit Kapton/glass wrap

Insulation Build Metal to Metal:

Nominal build (4x0.178 + 2x0.051)x2 = 1.628 mm without mold compression *(Actual build (2x0.229 + 2x0.051 + 1x0.178)x2= 1.476 mm without mold compression)*

Figure 3.5 — Conduit insulation configuration for 1x2 Sample D-Interleaved Kapton/Prepreg Glass. Sketch not to scale

The D-option design was implemented in a slighly different configuration from that described in Figure 3.5. Because prepreg tape was available from the ITER development program, it was decided to adapt the D-option to use the ITER prepreg tape which is 25.4 mm wide and nominally 0.229 mm thick. Therefore, the D-option replaced the 50% 12.7 mm Kapton by 67% 19.1 mm prepreg interleaved wrap original design with a 50% lap of interleaved 19.1 mm Kapton centered on the 25.4 mm ITER prepreg tape. This modification was believed adaquate for screening D-option without having to develop and obtain the 0.178 mm prepreg tape.

The D-option is a Hybrid of the ITER baseline insulation approach. It was selected for screening tests because of the maturing state of the ITER design and the potential for synergism between the two programs. In the ITER conduit insulation design the interleaved Kapton/prepreg glass taping is fully cured before final dry glass overwrapping and epoxy impregnation. In this way the cured Kapton/prepreg insulation can be tested for electrical insulation integrity before final assembly and full impregnation of the ITER coils. The ITER design employing nested solenoid coils makes it practical to use the Kapton/Prepreg approach as baselined for ITER. For TPX, however, the full implementation of the ITER concept is made very difficult by the general complexity of the TPX winding pack designs with spiral windings, pancake layers, and multiple joggled turn transitions.

The C-option, Figure 3.3 and CA-option, Figure 3.4 are non-bonded approaches where Kapton is wrapped directly on the conduit resulting in slip plane at the Kapton/conduit interface. In the C-option the Kapton tape is dry, that is, has no adhesive. Therefore, for the C-option there is the potential for epoxy to find its way through the Kapton laps and to the conduit surface Even with tight wrapping of multiple Kapton layers, 2-50% laps in the 1x2 samples, epoxy is expected to get to the conduit, particularly in real coils where Kapton wraps around 3-dimensional elements of the winding pack structure will likely result in wicking channels.

The proposed CA-option explores using cureable adhesives on the Kapton conduit wraps such that the wrap adjacent to the conduit has adhesive only on the top side of the film away from the conduit while adhesive is applied to both sides of

the outer Kapton overwrap. It was proposed to counter wrap the inner and outer Kapton films to reduce the probablity of impregnating resin getting to the conduit through the adhesive Kapton wraps. The Kapton adhesive system must be compatible with the epoxy VPI process such that the adhesive bond is fully cured. The CA alternative proposed using Kapton tapes developed for the adhesive Kapton system used in the RHIC program by Grumman Aerospace and supplied for the 1x2 program by teaming partner Northrup-Grumman. The RHIC insulation system used the all polyimide XMPI adhesive on Type HA Kapton developed by DuPont during the Super Collider program. The XMPI adhesive bonds when the temperature is 185^{0}C and requires no curing time. In the CA-option it was proposed to set-off the Kapton adhesive by heating the Kapton insulated conduits prior to wrapping with dry glass. In this way the Kapton-Kapton interfaces would be bonded together before epoxy impregnation, significantly reducing the risk of getting epoxy to the Kapton/conduit slip interface.

The CA-option as proposed was not implemented during the 1x2 program as planned, but was deferred to the 3x3 program due to schedule constraints in obtaining adhesived Kapton materials. The CA samples actually fabricated in the 1x2 program simulated the CA configuration but did not use adhesived Kapton wraps.

4. TEST PROGRAM

4.1 SAMPLE AND MOLD DESIGNS

The 1x2 sample design layout is shown in Figure 4.1. The conductors were hollow Incoloy 908 or 304LN stainless steel cut in 75 mm lengths. The dummy conductors were supplied by LLNL and were PF prototypes nominally 22.3 mm square with 5.1 mm radiused corners. The conductor edges were deburred and slightly rounded after cutting. The insulation wraps were applied by hand with insulation extending just over the conductor edges for insulation. Adhesive Kapton tape, 6.35 mm wide was used as an assembly aid to hold insulation at the conductor end where necessary to prevent telescoping. The two insulated conductors were then stacked on top of one another with about a 10 mm electrical creep stress offset. The sample was then held together with one 50% wrap of Tedlar mold released tape.

For Samples A, B, and C copper plates were placed over the hollow ends of the conductors and RTV used to seal the plates to end surfaces. The purpose of the plates was to prevent resin from filling the inside of the conductors. This procedure proved to be less than satisfactory for vacuum end sealing and was abandoned for Samples CA and D which were allowed to resin fill and totally encapsulate the exposed conductor bare metal ends in resin.

The mold design and fabrication was carried out at Everson Electric. The aluminum mold cavity dimensions were based upon 0.813 mm of insulation build on each conduit with allowance for 0.203 mm of Tedlar mold release tape per mold side. The 559 mm mold cavity length was designed to be able to mold six 1x2 samples at a time in either the Shell 826 or CTD101K resin systems.

Sketch of 1x2 Insulation Screening Samples

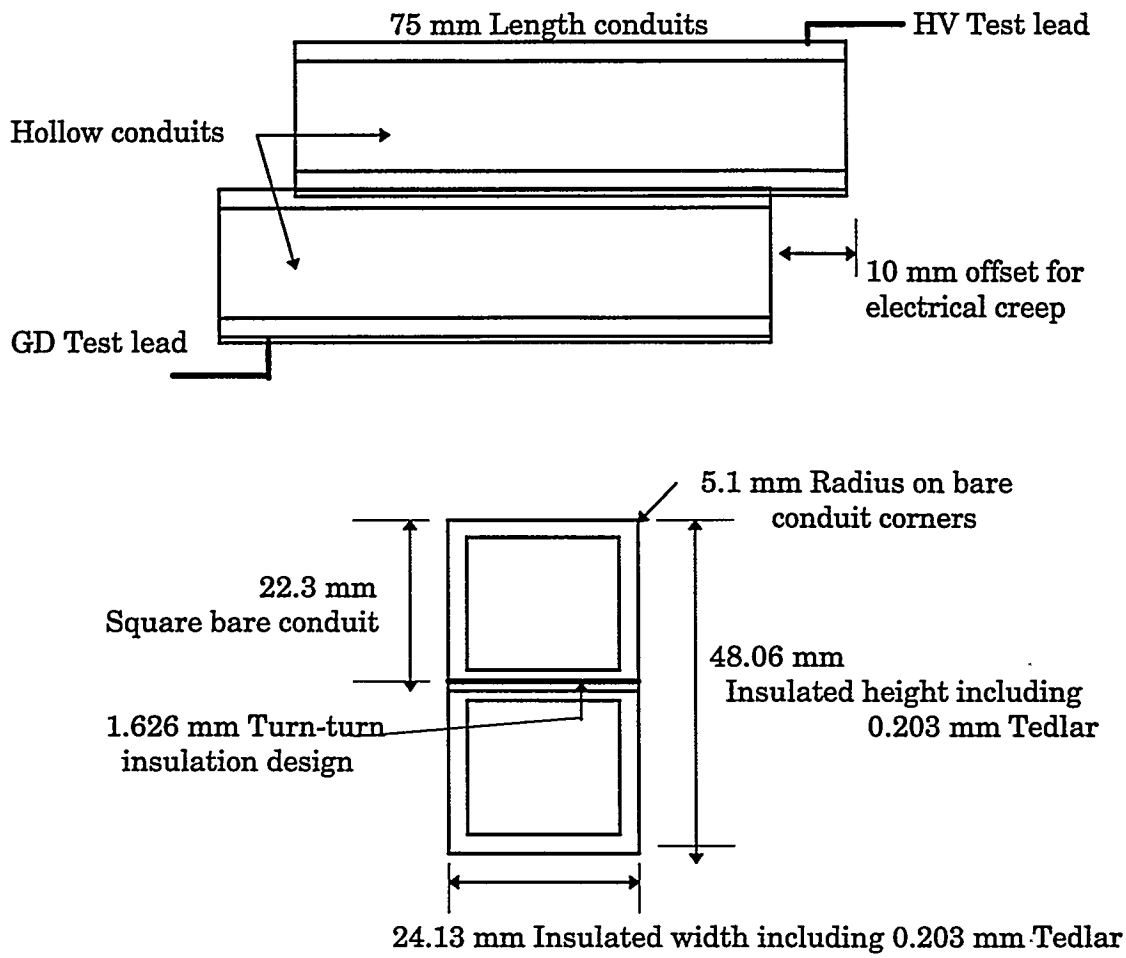


Figure 4.1 — Nominal design of 1x2 samples based on a 1.626 insulation build between conductors after impregnation process.

4.2 MATERIALS AND VENDORS

All Type H or HN Kapton tapes in the required widths were readily available from Kapton distributors. The barrier material for the A-Baseline samples was available at Everson Electric in the form of G10CR sheets. The Shell 826 and CTD101K resin systems were supplied directly or purchased by Everson Electric.

As previously discussed, the D-Kapton/Prepreg option was implemented using ITER prepreg tape supplied by Composite Technology Development for evaluation in the TPX program. The ITER prepreg is 25.4 mm wide, 0.229 mm thick and the prepreg resin is CTC112P. This prepreg is a "wet" prepreg which required refrigerated storage which was available at Everson Electric.

Data sheets provided by Composite Technology Development on the CTD-101K flexiblized epoxy system and CTD-112P prepreg epoxy system developed for ITER are found in Appendix 8.1.

The S-2 dry glass was purchased from Textiles Technology Industries, Hatboro, PA. The specification was for S-2 Glass Tape, 19.0 mm wide, 0.178 mm thick, 4-harness Satin finish weave, Silane treated. The product delivered by TTI was nominally 0.216 mm thick in the middle of the 19.0 mm width and about 0.25 mm on the tape ends which had broad end loops. Although the TTI S-2 glass product was disappointedly thicker than the nominal 0.178 mm design goal, it was decided to make the A, B, and C 1x2 samples with the TTI tape rather than risk schedule delays. In view of the fact that the 1x2 samples were for insulation performance screening and comparison to the baseline design, it was concluded that increase insulation builds expected using the TTI product were tolerable.

In order to resolve the S-2 glass manufacturing problems with TTI, an order was placed with TTI for additional glass tape with the following specification: 19.0 mm wide, 0.178 mm thick, C150 equivalent plain weave, with cold cleaning and Silane treatment. This product was considered acceptable with measured thickness of 0.190 mm in the middle of the width and not more than 0.229 mm thickness at the tape ends. Appendix 8.2 contains the QA measurements of the new TTI tape

dimensions from incoming inspection. The excessive looping experienced with the 4-harness Satin weave was eliminated and the weave was nearly uniform across the tape width. This tape was held in reserve for the TPX 3x3 insulation and mechanical test program.

4.3 FABRICATION AT EVERSON ELECTRIC

Fabrication, assembly, VPI process, and post cure sizing of 1x2 samples was carried out on the factory floor at Everson Electric. Appendix 8.3 contains the Everson Electric Manufacturing Process Outlines for the 1x2 sample fabrication and the VPI process. These processes were used in the manufacture of A, B, and C samples. They were modified during the manufacture of the CA and D samples as follows: (1) the copper plate end seals were eliminated and the ends completely encased in resin, (2) the vacuum prebake temperature was reduced to avoid curing the CTD112P prepreg before the VPI process.

Photographs of typical 1x2 samples as received from Everson Electric are shown in Figures 4.2, 4.3, and 4.4. The photographs show six samples impregnated in Shell 826, two samples each for the A, B, and C insulation configurations. Electrical leads were attached to the screws run into the upper and lower conduits. The copper seal plates which were RTV'ed to the ends of the A, B, and C samples were removed at Everson Electric. The copper plates did not work well and the hollow conduits were typically filled with resin.

4.4 ELECTRICAL TEST EQUIPMENT

The following test equipment was employed at W-STC in the electrical evaluation of the 1x2 samples:

TEST EQUIPMENT	MEASUREMENT
4274A Multi-frequency LCR Meter	Capacitance, loss tangent to 100 kHz
1864 Megohm Meter, General Radio	Insulation resistance (IR) to 1000 V
100 kV Hipot Facility	DC withstand and leakage current
50 kV Biddle Instruments Partial Discharge Detector, Model 66/5700	Peak and average partial discharge, 60 Hz
40 kV Biddle DC/AC Hipot Tester	DC withstand and leakage current

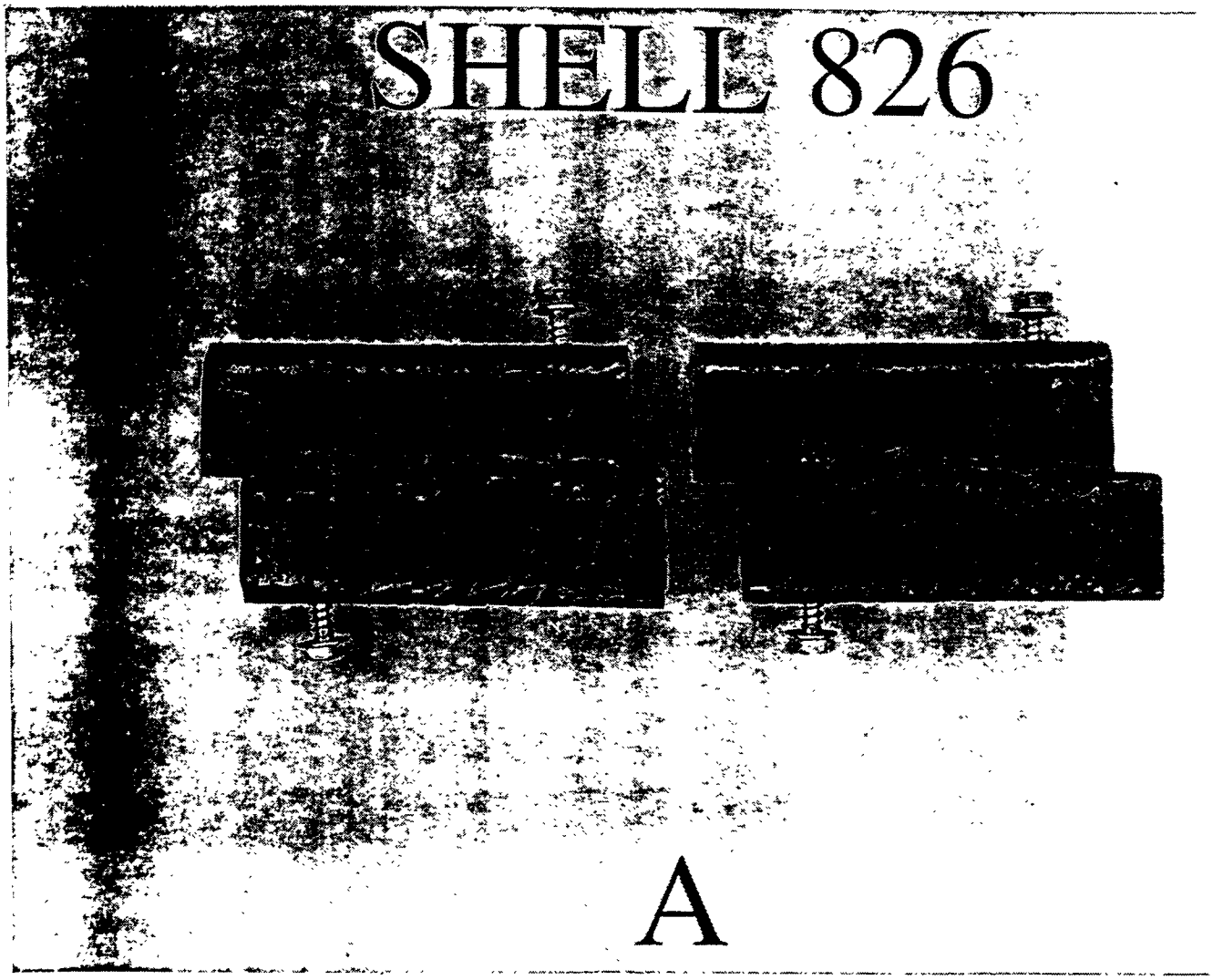


Figure 4.2 — Typical A-Baseline samples as received from Everson Electric with electrical lead posts screwed into top and bottom conduits.

RM-34134

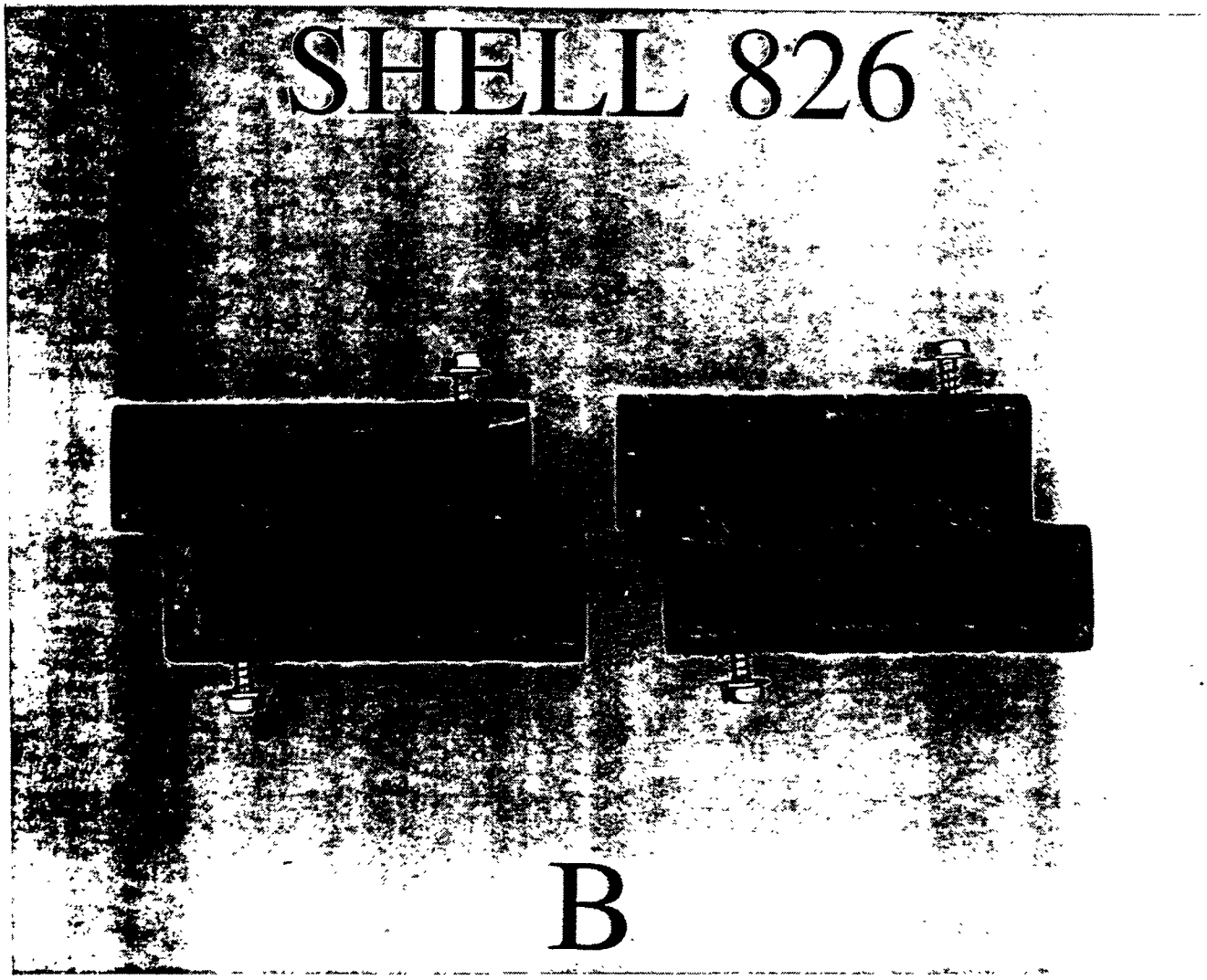


Figure 4.3 — Typical B-Kapton/Glass samples as received from Everson Electric with electrical lead posts screwed into top and bottom conduits.

RM-34131

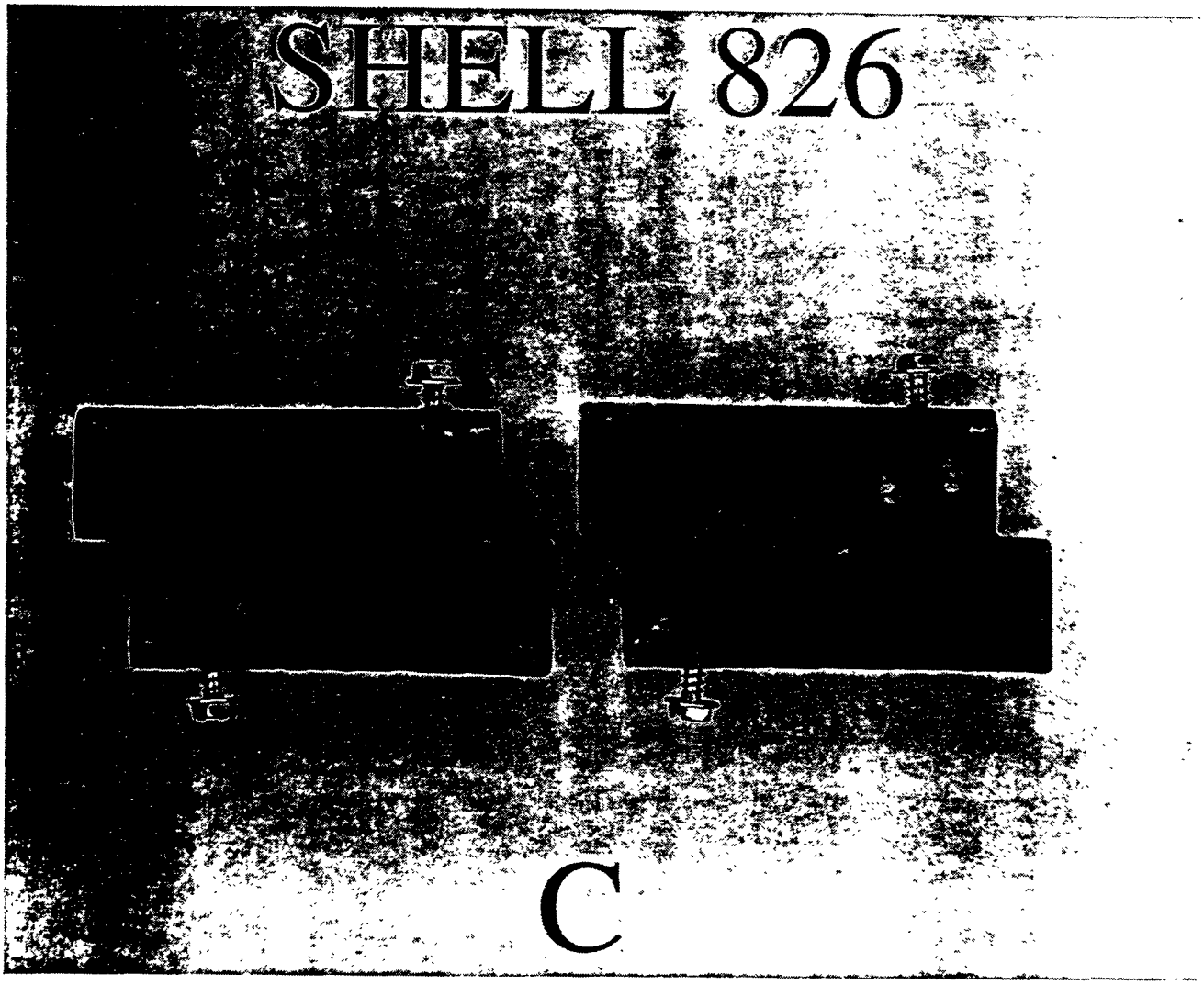


Figure 4.4 — Typical C-Kapton/Slip samples as received from Everson Electric with electrical lead posts screwed into top and bottom conduits.

RM-34130

4.5 ELECTRICAL TESTING PROCEDURES

All 1x2 samples were electrically tested as received, and for selected samples after thermal cycling. Samples A, B, and C were subjected to 10 thermal cycles by batch processing of all 12 samples simultaneously. Samples CA and D were not subjected to thermal cycling tests.

Dimensional characterization of the samples was made as received from Everson Electric and the turn-turn capacitance estimated by calculation. The average dielectric constant was deduced from actual capacitance measurements. The as received sample capacitance and loss tangent was measured from 100 to 10 kHz, and the IR measured at 500 and 1000 V. DC Hipot was performed up to 10 kV and leakage currents measured using an electrometer. Dielectric properties were checked after Hipot to look for changes (this step being eliminated in later testing as redundant since samples all pass the 10 kVdc withstand). AC partial discharge testing was performed at 60 Hz up to 10 kVrms. Partial discharge onset/offset voltage and average/peak dischage levels in pC were measured. This test procedure was repeated for samples A, B, and C after thermal cycling.

Following completion of all electrical characterization testing selected samples were cross sectioned, polished, and examined under a microscope for impregnation quality to assess insulation taping layups. The remaining uncut samples were then subjected to DC Hipot testing to failure or to 40 kVdc withstand.

5. TEST RESULTS

5.1 TEST MATRIX

The 1x2 sample configurations and general test plan are summarized in Table 5.1. The CA-option using adhesive Kapton was not implemented as planned. The three CA samples fabricated did not use adhesive Kapton and represented simulations of the proposed CA-option discussed in Section 3. The full CA-option was, however, implemented in the 3x3 program where one CA-option 3x3 model was fabricated and tested.

The electrical testing performed on the 1x2 samples before thermal cycling as received and after thermal cycling is summarized in Table 5.2. Samples are designated by the impregnation batch number 1, 2, or 3 followed by the sample number in that batch 1, 2, or 3 and by the running test sequence #1 through #28. For example, 2-1B / 9 represents B-option sample 1 for impregnation batch 2 and testing sequence #9, performed as received.

5.2 SAMPLE DIMENSIONAL ANALYSIS

The dimensions of the post cured, as received samples were measured either at W-STC or Everson Electric. Based upon the measured outside dimensions the turn-turn insulation build between conductors and effective stressed length of the turn-turn space estimated. As received dimensions for A, B, and C samples were measured at W-STC. The post cure dimensions for CA and D samples were measured at Everson Electric, and the results are found in Appendix 8.4.

Table 5.3 presents a summary of the dimensional analysis for all the 1x2 samples. The design goal for the turn-turn insulation build was 1.626 mm.

Table 5.1 — Summary of 1x2 configurations and test plan.

VPI BATCH	SAMPLE NUMBERS	CONDUIT MATERIAL	INSULATION SYSTEM Taping, Resin	THERMAL L-Nitrogen Shocks	TESTING Electrical(E) Sectioning(CS)
1	1,2	I-908(2)	A, CTD-101K	√	E, CS
1	1,2	I-908(2)	B, CTD-101K	√	E, CS
1	1,2	I-908(2)	C, CTD-101K	√	E, CS
2	1,2	I-908(2)	A, SHELL 826	√	E, CS
2	1,2	I-908(2)	B, SHELL 826	√	E, CS
2	1,2	I-908(2)	C, SHELL 826	√	E, CS
3	1,2,3	I-908(2) 304LN(1)	CA, CTD-101K	-	E,CS
3	1,2,3	I-908(2) 304LN(1)	D, CTD-101K	-	E, CS

The average A-Baseline insulation build was 1.963 mm, and the B- Kapton/Dry Glass and C-Kapton Slip options averaged 1.771 mm. The increase in the sample builds from the design goal was due to the fact that the S-2 glass tape purchased from TTI was nominally 0.229 mm and the design was predicated on 0.178 mm glass tape, so that a growth of about 0.203 mm was expected. In building the CA-Kapton/Slip and D-Kapton/Prepreg samples the same TTI S-2 glass product was used but the outer glass wrap was made a butt lap to effectively reduce the insulation build by 0.229 mm for these models. The insulation builds for the CA and D models averaged 1.559 mm in good agreement with the expected reduction in insulation build.

In the case of the A, B, and C samples, the increased insulation did not in all likelihood allow the 1x2 mold to be totally closed, whereas in the case of the CA and D samples the mold was closed. Since the impregnation process for the 1x2 samples did not involve pressurization of the mold, the RTV sealant used on the mold was adequate for vacuum processing even when the mold was not completely closed. In the case of the 1x2 mold closure was accomplished by a set of C-clamps hand-

Table 5.2 —Test matrix for 1x2 insulation samples

TPX 1X2 INSULATION SAMPLES TEST MATRIX							
Sample/ Test ID	Test #1	Test #2	Test #3	Test #4	Test #5	Test #6	Test #7
Before cold cycle							
1-1A / 1	X	X	X	X	X	x	X
1-2A / 2	X	X	X	X	X	xc	
1-1B / 3	X	X	X	X	X	xc	
1-2B / 4	X	X	X	X	X	xc	
1-1C / 5	X	X	X	X	X	Xa	
1-2C / 6	X	X	X	X	X	xc	
2-1A / 7	X	X	X	X	X	xc	
2-2A / 8	X	X	X	X	X	xc	
2-1B / 9	X	X	X	X	X	xc	
2-2B / 10	X	X	X	X	X	xc	
2-1C / 11	X	X	X	X	X	Xa	
2-2C / 12	X	X	X	X	X	xc	
3-2CA / 25	X	X	X	X	X	X	X
3-3CA / 26	X	X	X	X	X	X	X
3-2D / 27	X	X	X	X	X	X	X
3-3D / 28	X	X	X	X	X	X	X
After cold cycle							
1-1A / 13	X	X	X	X	X	xa	X
1-2A / 14			X	X	X	Xab	X
1-1B / 15			X	X	X	Xab	X
1-2B / 16			X	X		Xab	X
1-1C / 17			X	X	X	Xa	X
1-2C / 18			X	X	X		
2-1A / 19			X	X	X	Xb	X
2-2A / 20			X	X	X	Xab	X
2-1B / 21			X	X	X	Xab	X
2-2B / 22			X	X	X	Xab	X
2-1C / 23			X	X	X	Xa	X
2-2C / 24			X	X	X		

TEST #1 Dimensional characteristics
TEST #2 Calculated turn-to-turn capacitance
TEST #3 Dielectric properties
TEST #4 DC hipot
TEST #5 Dielectric properties after hipot
TEST #6 AC partial discharge
TEST #7 Dielectric properties after partial discharge

NOTE: a = in silicon oil
b = in LN2
c = in air

Table 5.3 — Dimensional characteristics of TPX 1x2 samples as received

SAMPLE	WIDTH mm	HEIGHT mm	STRESSED LENGTH mm	TURN-TURN INSULATION BUILD mm
1-1A	23.978	48.006	73	1.880
1-2A	24.308	48.158	71	1.956
2-1A	24.384	48.260	70	2.007
2-2A	24.409	48.260	69	2.007
1-1B	24.257	48.082	71	1.740
1-2B	24.003	47.777	70	1.588
2-1B	24.206	48.158	68	1.780
2-2B	24.003	47.981	67	1.690
1-1C	24.384	48.184	68	1.793
1-2C	24.384	48.260	68	1.830
2-1C	24.282	48.336	67	1.868
2-2C	24.257	48.362	67	1.882
3-1D	24.206	47.727	-	1.562
3-2D	24.011	47.701	-	1.549
3-3D	24.155	47.761	-	1.579
3-1CA	24.037	47.625		1.511
3-2CA	24.155	47.752	-	1.575
3-3CA	24.096	47.752	-	1.575
AVERAGE	24.195 +/- 0.216	48.008 +/- 0.369	69	1.963(A) 1.771(B&C) 1.559(D&CA)
MOLD SIZE	24.054 +/- 0.127	47.879 +/- 0.127		1.626 (DESIGNGOAL)

tightened alternately on the adjacent sides of the mold. In any event the mold clamps were not over-tightened in an effort to compress the insulation and achieve closure if possible since excessive pressure on the 1x2 sample walls could impede impregnation and lead to "white spots", i.e., dry glass areas. In fact, some of the A, B, and C samples did exhibit some "white spot" areas indicating that the mold

pressure may have been too great in some areas. Since the focus of the 1x2 screening was on achieving through impregnation in the turn-turn space for electrical evaluation, any lack of impregnation on the outside surface of the models was considered tolerable.

5.3 DC ELECTRICAL PERFORMANCE

A compilation of the DC voltage characteristics of the 1x2 samples as received and after thermal cycling is presented in Table 5.4. The measurements of capacitance in pF and loss tangent in % were made at frequencies of 100, 200, 1000, and 10,000 Hz, and the results are shown only for 1,000 Hz. In general, over this frequency range the capacitance decreases by about 2%, and for most samples the loss tangent tended to increase several percent peaking around 1 kHz before falling off at 10 kHz. There was no significant change in the capacitance or loss tangent after thermal cycling of the samples. The IR or insulation resistance was measured at 1000 V and was in the 10 MΩ to >50 MΩ range, and measured generally higher after thermal cycling. All samples passed a 10 kVdc Hipot before and after thermal cycling and the leakage currents measured during the Hipot tests presented in the Table 5.4. The leakage current at 10 kVdc ranged from about 0.2 nA to <9 nA, with calculated IR in the 50 MΩ to 1 MΩ range in fair agreement with the 1000 V IR meter readings.

The results of the DC electrical tests indicate that the A-Baseline and B, C, CA, and D Kapton options have similar electrical characteristics. There were no clear discriminators between the CDR Baseline and the Kapton options based upon the results of the DC electrical measurements. All insulation systems had acceptable DC turn-turn dielectric performance for TPX magnets based upon room air measurements without mechanical loads or mechanical load cycling.

The capacitance measurements were used to deduce the effective dielectric constant of the impregnated S-2 glass insulation. The results of this dielectric constant analysis are shown in Table 5.5. The glass insulation dielectric constant was deduced from the following equations.

Table 5.4 — Dielectric characteristics of TPX 1x2 insulation samples

TPX 1X2 INSULATION SAMPLES
DIELECTRIC CHARACTERISTICS TEST DATA

Sample	Measured								Calculated	
	C pF(1kHz)		Loss %(1kHz)		IR MΩ(1kv)		Leakage nA(10kvdc)		IR MΩ(10kv)	
	Start	End	Start	End	Start	End	Start	End	Start	End
1-1A	30.17	30.39	0.4	0.34	15	50	1.7	8.8	5.9	1.1
1-2A	28.73	28.69	0.38	0.31	30	30	8.5	0.36	1.2	27.8
1-1B	28.66	28.56	0.26	0.28	30	35	0.35	0.3	28.6	33.3
1-2B	31.44	30.45	0.26	0.23	17	45	0.53	0.35	18.9	28.6
1-1C	29.39	29.51	0.26	0.22	40	50	0.5	0.16	20.0	62.5
1-2C	30.13	29.98	0.27	0.27	10	40	0.54	0.43	18.5	23.3
2-1A	30.39	30.17	0.35	0.33	27	40	0.34	0.37	29.4	27.0
2-2A	28.19	28.13	0.32	0.3	35	50	0.2	0.3	50.0	33.3
2-1B	29.39	29.33	0.23	0.19	17	50	0.38	0.32	26.3	31.3
2-2B	30.28	30.21	0.7	0.6	12	35	0.5	0.3	20.0	33.3
2-1C	28.7	28.61	0.35	0.22	13	40	0.53	0.35	18.9	28.6
2-2C	29.18	29.01	0.61	0.58	21	45	0.37	0.3	27.0	33.3
3-2CA	31.92	31.36	0.29	0.26	>50		0.52		19.0	
3-3CA	31.89	31.3	0.42	0.4	>50		0.56		17.9	
3-2D	31.16	30.61	0.41	0.42	>50		0.87		11.5	
3-3D	31.92	31.42	0.42	0.43	>50		0.55		18.2	

Table 5.5 — Estimated relative dielectric constants for TPX 1x2 insulation samples

Sample	Measured Capacitance pF/mm	Percent Kapton %	Turn-Turn Insulation Spacing mm	Average Relative Dielectric Constant	Epoxy/Glass Relative Dielectric Constant
A	0.426	0 (16.7% G10 Barrier)	1.96	5.1	5.1
B	0.435	11.5	1.70	4.7	4.8
C	0.431	10.5	1.84	5.0	5.1
CA	0.469	5.6	1.56	4.7	4.8
D	0.463	11.5	1.55	4.6	4.7
C-Option Baseline	0.474	12.5	1.6256	4.75	4.85

(1) $\text{Cmeas} = \varepsilon_{av}\, \varepsilon_0\, (1+\eta_E)\, (W - 2R) / d$

where Cmeas is the measured capacitance per unit length, W=22.3 mm is the conduit width, R=5.1 mm is the conduit corner radius, and d is the measured turn-turn insulation thickness. The parameter η_E is a correction factor accounting for the contribution to the capacitance from the curved ends; η_E was estimated based on calculations the capacitance of 1x2 configurations. For the purpose of the dielectric constant analysis, the end contribution to the 1x2 sample capacitance was estimated using the following empirical expression for η_E.

(2) $\eta_E = (2R/(W-2R)) / (1+1.37/d)$

Equations 1 and 2 are used to calculate ε_{av}, the average dielectric constant of the turn insulation. The dielectric constant of the impregnated glass, ε_{epoxy} is then calculated from

(3) $\varepsilon_{epoxy} = [\varepsilon_{av} - \varepsilon_1\, \eta_1] / (1-\eta_1)$

where η_1 is the fraction of Kapton or barrier in turn-turn insulation through thickness given by $n_1 d_1 / d$ where n_1 is the number layers and d_1 the layer thickness of Kapton or barrier insulation. Based on this method the average dielectric constant of the impregnated S-2 glass for all the 1x2 samples is

(4) $\varepsilon_{epoxy} = 4.9 +\backslash- 4\%$

An electrostatic field calculation for the for the A-Baseline 1x2 sample configuration performed using the WETMAP code version of WEMAP (Westinghouse proprietary codes) is presented in Figure 5.1. The field plot shows equipotential lines for a quarter section of the 1x2 sample. The conduit insulation wrap is assumed to be 0.822 mm thick and is indicated by the dashed line around the conduit wall. The G10 barrier is assumed to have a half thickness of 0.178 mm and is shown as the dashed line located above the midplane through the turn-turn insulation build. The triangular corner void region is assumed to be filled with pure resin. The vertical dashed line is the boundary between the 1x2 sample and air. The relative dielectric constants are assumed to be 5.0 for both the barrier and the conduit wrap and 3.5 for the corner void area. The predicted capacitance per unit length of the 1x2 sample predicted by the WETMAP code is 0.509 pF/mm. The average stress across the uniform field region of the sample is 1.00 kV/mm per kV drop across the 0.822 mm quarter section gap, i.e., across half the total turn-turn insulation build. The maximum stress on the surface of the conduit occurs just as the conduit wall curves away from the uniform field region and is 1.02 kV/mm per kV drop across the quarter section gap. Therefore, the maximum stress enhancement factor on the conduit wall is only 2% greater than the average stress. Therefore, the 1x2 samples represent essentially uniform field test samples in the 2-D cross section. The longitudinal end fields were not evaluated.

The predicted capacitance per unit length, 0.432 pF/mm is in excellent agreement with the average measured value of 0.426 pF/mm for the A-Baseline samples.

HOTMAP 3-D POST-PROCESSOR Ver:071095DEV 07/18/95 11:04:51 modela.sln_6

The Plotted Values are :

2.	0.5000E+02
3.	0.1000E+03
4.	0.1500E+03
5.	0.2000E+03
6.	0.2500E+03
7.	0.3000E+03
8.	0.3500E+03
9.	0.4000E+03
10.	0.4500E+03
11.	0.5000E+03
12.	0.5500E+03
13.	0.6000E+03
14.	0.6500E+03
15.	0.7000E+03
16.	0.7500E+03
17.	0.8000E+03
18.	0.8500E+03
19.	0.9000E+03
20.	0.9500E+03

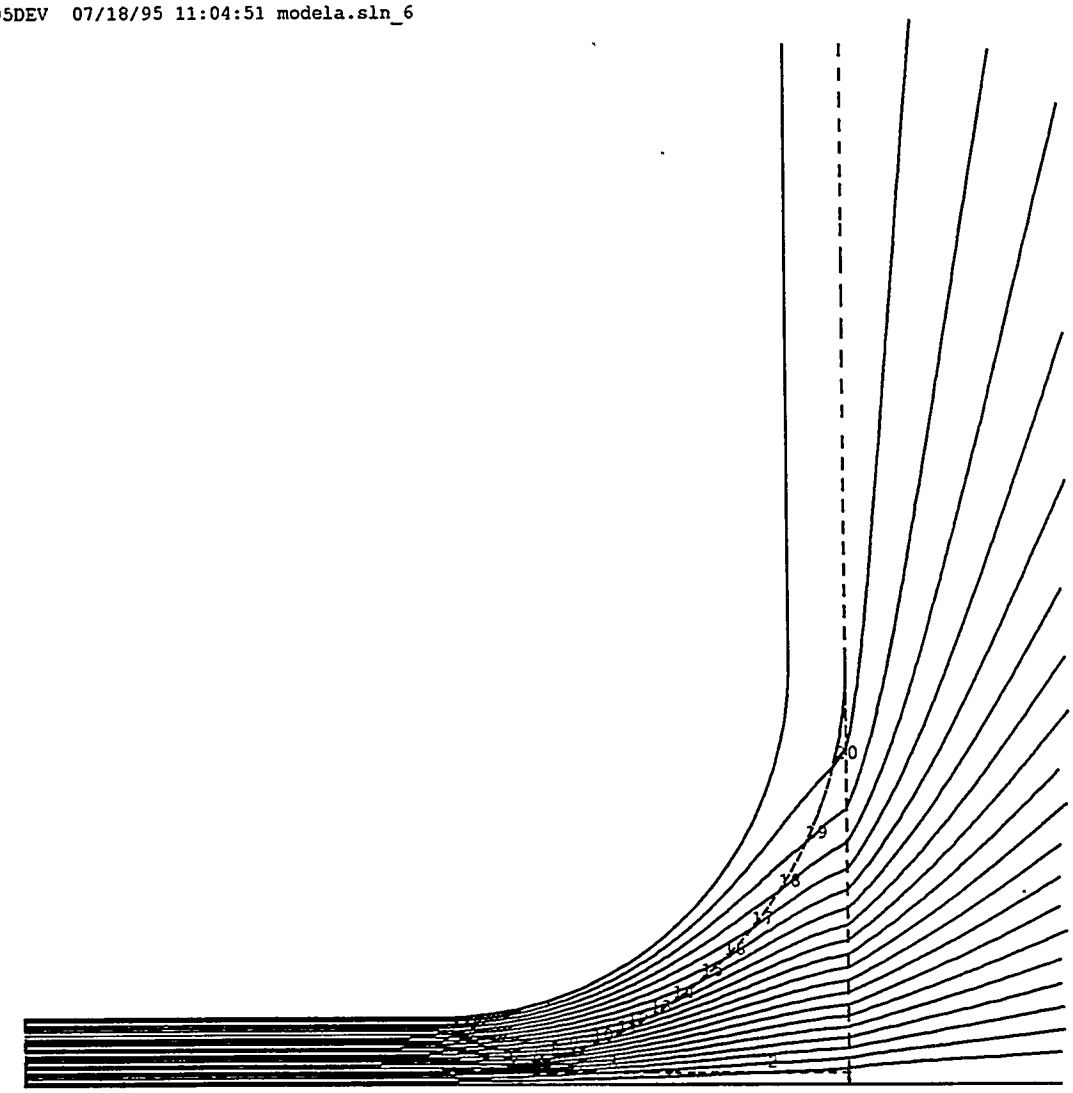


Figure 5.1 — Electrostatic field plot shown for a quarter section a 1x2 sample for the A-Baseline insulation design.

5.4 AC PARTIAL DISCHARGE PERFORMANCE

Table 5.6 presents a summary of the AC partial discharge (PD) performance of the 1x2 samples. PD measurements were performed up to 10 kVrms at 60 Hz before and after thermal cycling for selected samples. Table 5.6 gives the measured PD onset/offset voltages and average/peak PD levels in units of pC at 10 kVrms. Because the ends of the conduits of the A, B, and C samples were exposed bare metal, limited PD measurements were performed in air and only in the as received condition. Air PD testing was done after coating the exposed metal ends with silicon grease in an effort to limit edge discharge activity and early PD voltage onset. Only two samples 1-1C and 2-1C were tested under silicon oil in the as received condition to check the effectiveness of the silicon grease used in air testing. In both cases the air onset was less, and it was decided to perform the PD testing after thermal cycling under silicon oil to limit PD activity at the sample ends. Some PD testing was performed under liquid nitrogen on A and B samples to compare the A-Baseline to the B-Kapton/Glass fully bonded systems. The CA and D samples were only tested in air and had large average and peak PD levels at 10 kVrms. Cross sections of the D-Kapton/Pregreg sample indicated poor impregnation and curing of the interleaved Kapton/prepreg laps, which qualitatively correlated with the high PD activity in the D samples. Based on the poor CA and D sample as received PD performance, no further PD testing was performed on these samples.

The PD onset/offset voltages presented in Table 5.6 were determined for when peak partial discharge level was greater/less than 20 pC. In general, a more rapid increase in discharge activity began at > 100 pC peak level. Using 20 pC, therefore, for PD onset/offset may reflect high stress edge PD whereas the rapid increases observed beyond 100 may be a truer indication of void activity in the bulk of the turn-turn insulation, that is to say that voids within the turn-turn insulation are higher.

The PD data was taken in voltage steps of 500 Vrms up to 10 kVrms and then back down in 500 or 1000 Vrms steps. Summaries of the peak pC levels samples tested after thermal cycling are shown in Table 5.7 for tests under silicon

Table 5.6 —Summary of partial discharge measurements for 1x2 samples before and after thermal cycles.

TPX 1X2 INSULATION SAMPLES
AC PARTIAL DISCHARGE TEST DATA

Sample	Before cold cycle						After cold cycle								
	PD in air			PD in silicon oil			PD in silicon oil			PD in LN_2			PD in silicon oil (2nd time)		
	kvrms	pC(10kvrms)		kvrms	pC(10kvrms)		kvrms	pC(10kvrms)		kvrms	pC(10kvrms)		kvrms	pC(10kvrms)	
	Onset/Offset	Avg	Peak	Onset/Offset	Avg	Peak	Onset/Offset	Avg	Peak	Onset/Offset	Avg	Peak	Onset/Offset	Avg	Peak
1-1A	1.8/-	-	[1]75				1.8/1.9	na	150						
1-2A	3.6/-	-	[1]50				4.9/4.5	8	750	3.8/3.0	0	80			
1-1B	4.8/-	-	[1]100				4.8/4.0	4.5	400	6.3/4.0	0	100	3.8/4.0	4.2	400
1-2B	4.5/-	-	[1]100				2.9/4.0	6	300	7.5/4.5	<1	80	4.5/4.5	4.1	300
1-1C	4.5/-	-	[1]100	4.7/3.5	-	750	3.0/2.5	7.5	4000						
1-2C	5.0/-	-	[1]40												
2-1A	4.5/-	-	[1]20							6.2/6.7	0	80			
2-2A	5.0/-	-	[1]2				4.5/3.5	3	200	8.5/7.0	0	60			
2-1B	4.4/-	-	[1]10				4.0/4.2	2.8	150	2.8/2.8	4	1000	4.5/3.5	3.3	400
2-2B	3.7/-	-	[1]50				3.1/3.0	8	3000	3.0/2.6	2.3	2000	3.7/3.7	3.3	400
2-1C	3.3/-	-	[1]500	5.0/5.0	-	100	5.5/6.0	4.25	600						
2-2C	4.1/-	-	[1]10												
3-2AC	3.5/3.0	22	5000												
3-3AC	3.5/4.5	14	1700												
3-2D	2.0/3.0	58	10,000												
3-3D	2.5/3.0	72	4000												

NOTE: [1] Peak partial discharge level just after PD onset

Table 5.7 — Partial discharge as function of voltage after thermal cycles for samples under oil

	Voltage, kVrms															
	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10
Sample	Peak Partial Discharge Level, pC															
1-1B up	0	0	0	0	175	175	200	300	300	300	300	300	300	300	400	400
1-1B down	0	0	0	0	200	250		300		300		300		400		400
2-1B up	0	0	0	12	40	60	80	100	110	120	140	160	180	180	180	150
2-1B down	0	0	0	0	20	40		80		60		100		100		150
1-2B up	0	0	12	25	50	75	100	140	200	200	200	200	300	300	300	300
1-2B down	0	0	0	0	0	50		180		200		250		300		300
2-2B up	0	10	13	30	90	100	110	150	200	1000	1000	1000	1000	1000	1000	3000
2-2B down	0	0	10	12		40		80		800		1000		1200		3000
1-1C up	0	20		40	50	180	220	260	320	1000	1400	3200		4000		
1-1C down	0	0		20		100		200		400		1000		4000		
2-1C up	0	0	0	0	0	0	50	100	500	600	600	600	600	600	600	600
2-1C down	0	0	0	0	0	0	0	0	160	200		400		600		600
1-2A up	0	0	0	0	0	70	500	750	750	750	750	750	750	750	750	750
1-2A down	0	0	0	0	10	100		300		500		500		750		750
2-2A up	0	0	0	0	10	60	80	80	120	125	120	120	120	180	200	200
2-2A down	0	0	0	15		20		20		25		80		100		200

All data is Partial Discharge in oil after cold cycle

oil and in Table 5.8 for tests under liquid nitrogen. The PD onset/offset voltages as judged from the discrete voltage steps are highlighted.

An analysis of all the under oil and under liquid nitrogen PD data performed after thermal cycling showed that the Shell 826 epoxy and CTD-101K resin systems generally performed about the same for the fully bonded A-Baseline samples, but the Shell 826 had poorer PD performance than the CTD-101K for Kapton options. This was particularly true in the case of the PD data for the two fully bonded A-Baseline and B-Kapton/Glass samples for PD under liquid nitrogen, shown in Figures 5.2, 5.3, and 5.4. Figure 5.2 shows that all A samples for both epoxy resin systems had very low discharge levels < 40 pC all the way to 8 kVrms indicating good impregnation quality and performance after cold shocking. On the other hand the PD data for the B samples in Figures 5.3 and 5.4 clearly show that Shell 826 performs poorer than CTD-101K for interleaved Kapton/Glass after cold shocking. PD levels for Shell 826 samples, for example, are > 150 pC at 6 kVrms with onset voltage < 4 kVrms while for CTD-101K the discharge activity at 6 kVrms is negligible and onset is at 7 kVrms. This data suggests that bonding at Kapton/impregnated glass layers in the B samples is better with CD-101K with less voids than for Shell 826 under liquid nitrogen conditions. The lower viscosity of CTD-101K probably resulted in more complete impregnation of the interleaved Kapton/glass wraps than in the case of the more viscous Shell 826.

5.5 DC HIPOT TO FAILURE TESTS

After completion of all electrical testing before and after thermal cycling the samples were Hipot tested again in laboratory air to 40 kVdc. The exposed metal ends of the conduits for samples A, B, and C were insulated with RTV to prevent premature end flashovers; the ends of samples D and CA were encapsulated in epoxy resin during the impregnation process. The Hipot tester trip current was set at 50 μA and sample failure was assumed if the power supply tripped at the 50 μA leakage current limit.

Table 5.8 — Partial discharge as function of voltage under liquid nitrogen after thermal cycles

									Voltage, kVrms								
Sample		2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10
									Partial Discharge Level, pC								
1-2A up		0	0	0	0	10	10	12	12	15	16	20	30	50	50	60	80
1-2A down		2	5	5	8	10	10		15		30		40		50		80
2-2A up		0	0	0	0	0	0	0	0	0	0	0	0	30	50	60	60
2-2A down		0	0	0	0	0	0	0	0	0	0	0	0		60		60
1-1B up		0	0	0	0	0	0	0	0	0	1	25	40	50	70	100	100
1-1B down		0	0	0	0	5	7		20		30		50		100		100
2-1B up		0	6	12	20	50	150	150	200	500	600	800	800	1000	1000	1000	1000
2-1B down		0	2	10	30		400		700		700		700		1000		1000
1-2B up		0	0	0	0	0	0	0	0	0	0	40	40	50	60	70	80
1-2B down		0	0	0	0	0	30		40		50		50		60		80
2-2B up		0	0	20	30	40	70	100	150	150	150	180	200	1500	1500	1500	2000
2-2B down		0	0	20	25	50	500		1000		1000		1500		1500		2000
2-1A up		0	0	0	0	0	0	0	15	15	15	25	30	40	60	80	80
2-1A down		0	0	0	0	0	0	0	0	0	5		10		50		80
All data is Partial Discharge in Liquid Nitrogen																	

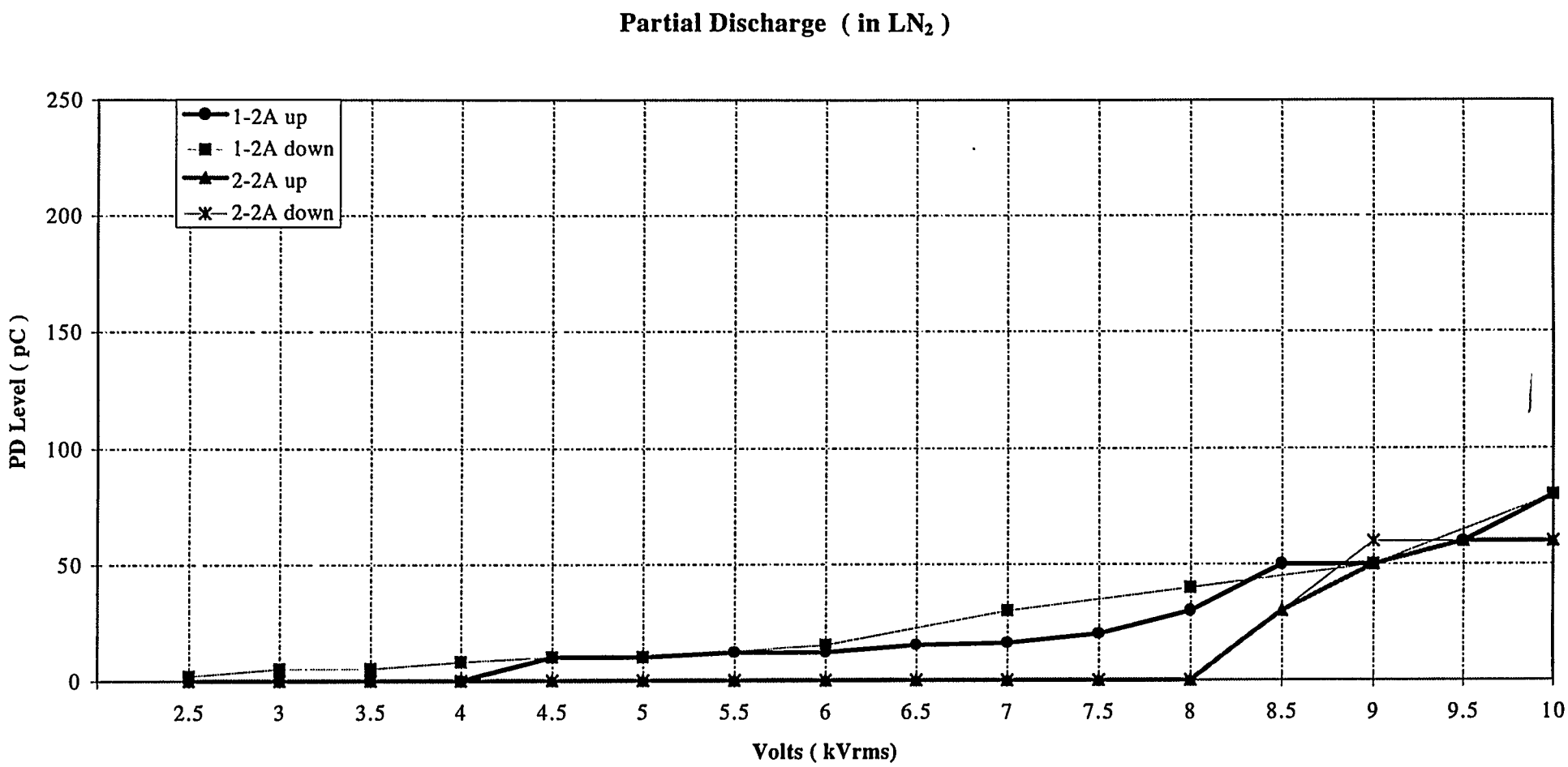


Figure 5.2 — Comparison of partial discharge for Shell 826 (1-) and CTD-101K (2-) 2A samples under liquid nitrogen after thermal cycling.

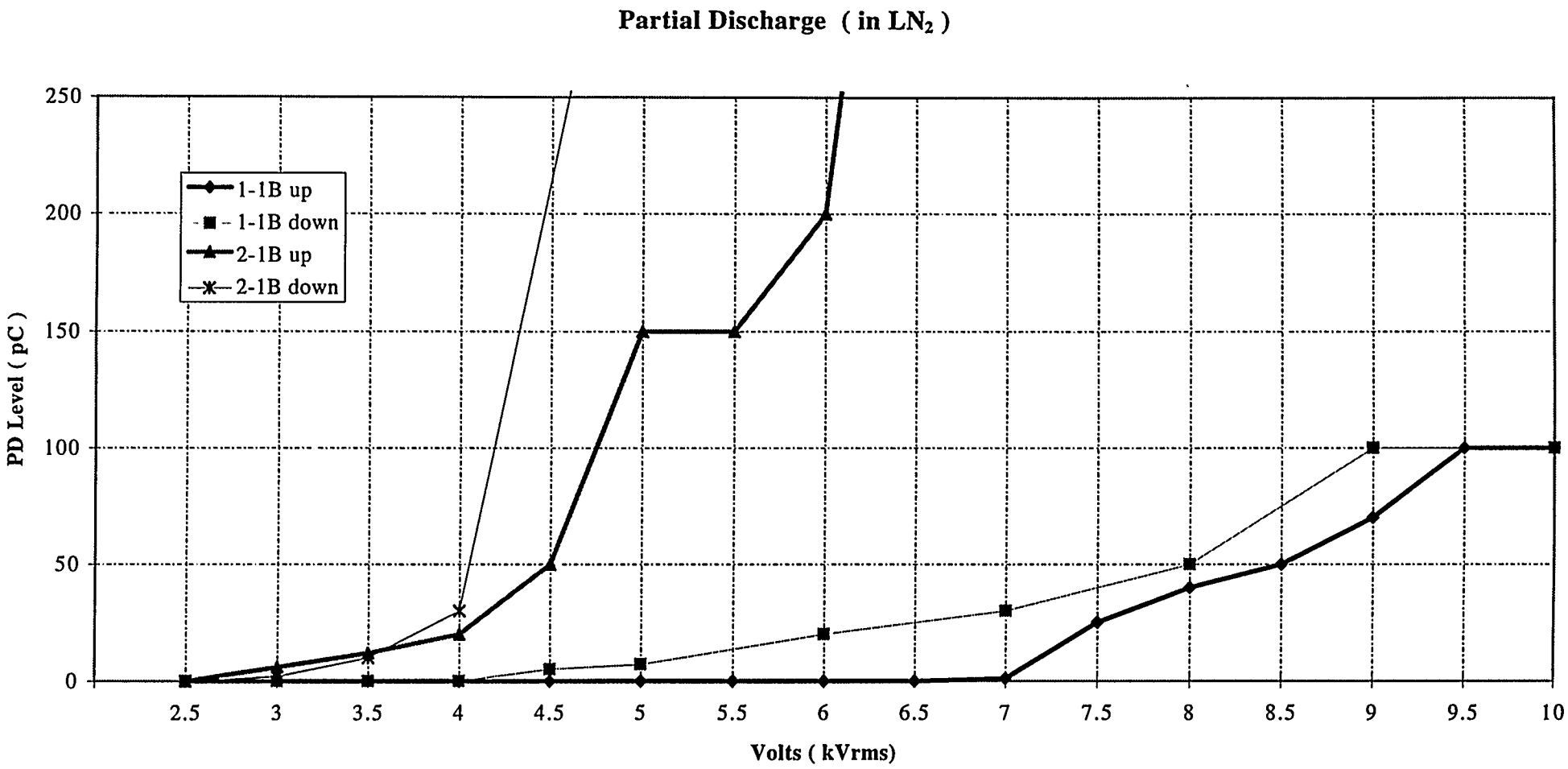


Figure 5.3 — Comparison of partial discharge for Shell 826 (1-) and CTD-101K (2-) 1B samples under liquid nitrogen after thermal cycling.

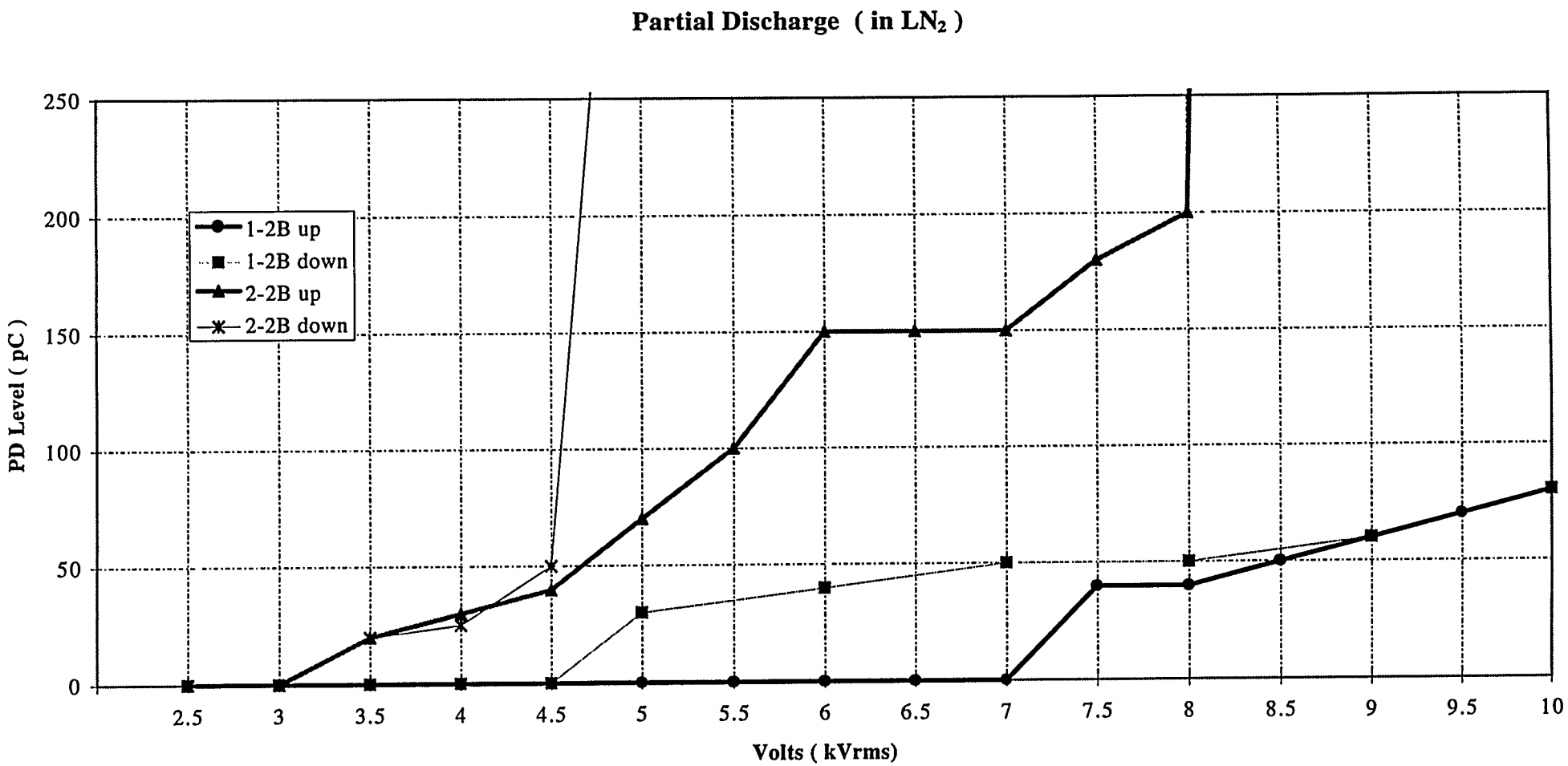


Figure 5.4 — Comparison of partial discharge for Shell 826 (1-) and CTD-101K (2-) 2B samples under liquid nitrogen after thermal cycling.

The 40 kVdc Hipot failure results are presented in Table 5.9. The failures were of several types as indicated in the table. Faults were classified as internal (I), external side (S), or external end (E) where external faults S and E were either audible with visible turn-turn tracking or in the case of end faults silent visible discharge within the end insulation observed. Also, S type failures were all associated with punctures and tracking (P) of the conduit corner insulation. Samples A, B, and C, which were thermally cycled, failed at voltages > 33 kVdc and average turn-turn stress > 19 kV/mm. Samples D and CA, which were not thermally cycled, failed at voltages > 34 kVdc and average turn-turn stress > 22 kV/mm. One of the CA samples had a withstand at the 40 kVdc test voltage limit upon first voltage application; some samples withstood 40 kVdc after a second or third voltage application following internal I type faults. Samples #1 in for each insulation option had been previously cross sectioned for impregnation observation and were therefore, not available for failure testing.

Only internal failures are considered indicative of the turn-turn insulation performance. External faults are due to the short sample conduit end conditions as well as external conditions of the corner insulation exposed to air. The external turn-turn faults on the sides of the samples were generally due to poor impregnation of the corner void and shrinkage of the corner void resin fill away from the conduit edges, often leaving an air pocket where puncture and tracking sites were located.

The A-Baseline samples had the lowest average breakdown stress of 19.3 kV/mm compared to all the Kapton options. However, this difference in failure stress is considered small since the B and C samples had average breakdown stresses of 22.3 kV/mm and 19.8 kV/mm, respectively, which were only slightly better than for the A samples. Given the limited number of samples of each type, there was insufficient data to statistically discriminate between the A-Baseline and Kapton options with respect to Hipot failure. The higher average breakdown stresses for the D and CA samples were in the as received condition only with the Kapton/Slip CA samples having the highest failure stress at 25.1 kV/mm with one sample having a 40 kVdc withstand. The D samples all failed on the external sides

Table 5.9 — Failure Hipot testing in air for TPX 1x2 samples

SAMPLE NUMBER	INSULATION SPACING mm	HIPOT FAILURE VOLTAGE (40 kV max ; 50 μA Trip) kVdc		
		1 st Test	2 nd Test	3 rd Test
1-1A	1.880	-	-	-
1-2A	1.956	37.5 (E)	11.0 (E)	10.0 (E)
2-1A	2.007	38.5 (S,P)	-	-
2-2A	2.007	39.2 (I)	40 (WS)	-
Models A	Av Failure Stress,	19.3 kV/mm		
1-1B	1.740	-	-	-
1-2B	1.588	38.0 (I)	38.5 (I)	38.5 (I)
2-1B	1.780	38.0 (E)	30.0 (E)	19.8 (I)
2-2B	1.690	36.7 (I)	32.7 (I)	36.0 (S,P)
Models B	Av Failure Stress	22.3 kV/mm		
1-1C	1.793	-	-	-
1-2C	1.830	38.0 (I)	37.8 (I)	40 (WS)
2-1C	1.868	38.5 (E)	18.0 (E)	16.0 (E)
2-2C	1.882	33.8 (E)	22.5 (E)	-
Models C	Av Failure Stress	19.8 kV/mm		
3-1D	1.562	-	-	-
3-2D	1.549	37.0 (S,P)	12.0 (S,P)	-
3-3D	1.579	34.0 (S,P)	6.0 (S,P)	-
Models D	Av Failure Stress	22.7 kV/mm		
3-1CA	1.511	-	-	-
3-2CA	1.575	40 (WS)	-	-
3-3CA	1.575	39.0 (E)	-	-
Models CA	Av Failure Stress	25.1 kV/mm		

WS - Withstand
I - Internal fault
P - Puncture of turn insulation

S - External side fault
E - External end fault

with puncture of the conduit corner insulation. This failure was due in part to poor impregnation and expected high void content in the prepreg which was observed in sample cross sections.

5.6 OBSERVATIONS OF SAMPLE CROSS SECTIONS

Typical 1x2 sample cross sections for the Kapton options B and CA are presented in Figures 5.5 and 5.6. In Figure 5.5 the interleaving of Kapton and impregnated glass is shown for a polished longitudinal cross section for sample 1-1B with Shell 826 resin. Views are shown for the insulation between the two conduits and at the top of one of the conduits. The microphotographs show that the Kapton/glass interleaving and registration is close to the design, but far from perfect. It is clear that the Kapton film is a "wavy wall" conforming to glass tape movements during the molding process. The Kapton lapping is less than the 50% design, leading to larger area of a single layer of Kapton instead of two layers per conduit, and to turn-turn spaces which have only two layers of Kapton between turns instead of at least three layers on average. This resulted in the "candy stripe" appearance of the outside of the B samples, such as can be seen in Figure 4.3. From detailed observations of the glass impregnation between Kapton layers it appears that good wicking was achieved all the way to the conduit surface, and that bonding to the conduit looks good. This is very important to the success of the B-option which is predicated on achieving full bonding at the conduit/insulation interface. In the as received condition the Kapton/glass interfaces seem to be bonded and voids are not observed at the interfaces.

Figure 5.6 shows a polished cross section cut perpendicular to the longitudinal direction for sample 3-3CA with CTD-101K resin. The CA sample is a Kapton/Slip option using two counter lapped dry Kapton (instead of adhesive Kapton) layers wrapped directly on to the conduit. Figure 5.6 shows cross sections normal to the longitudinal direction for the turn-turn insulation in the flat area between conduits and at the conduit corners. The Kapton layers on the conduit are seen as the dry black band around the conduit. In the corner region one can

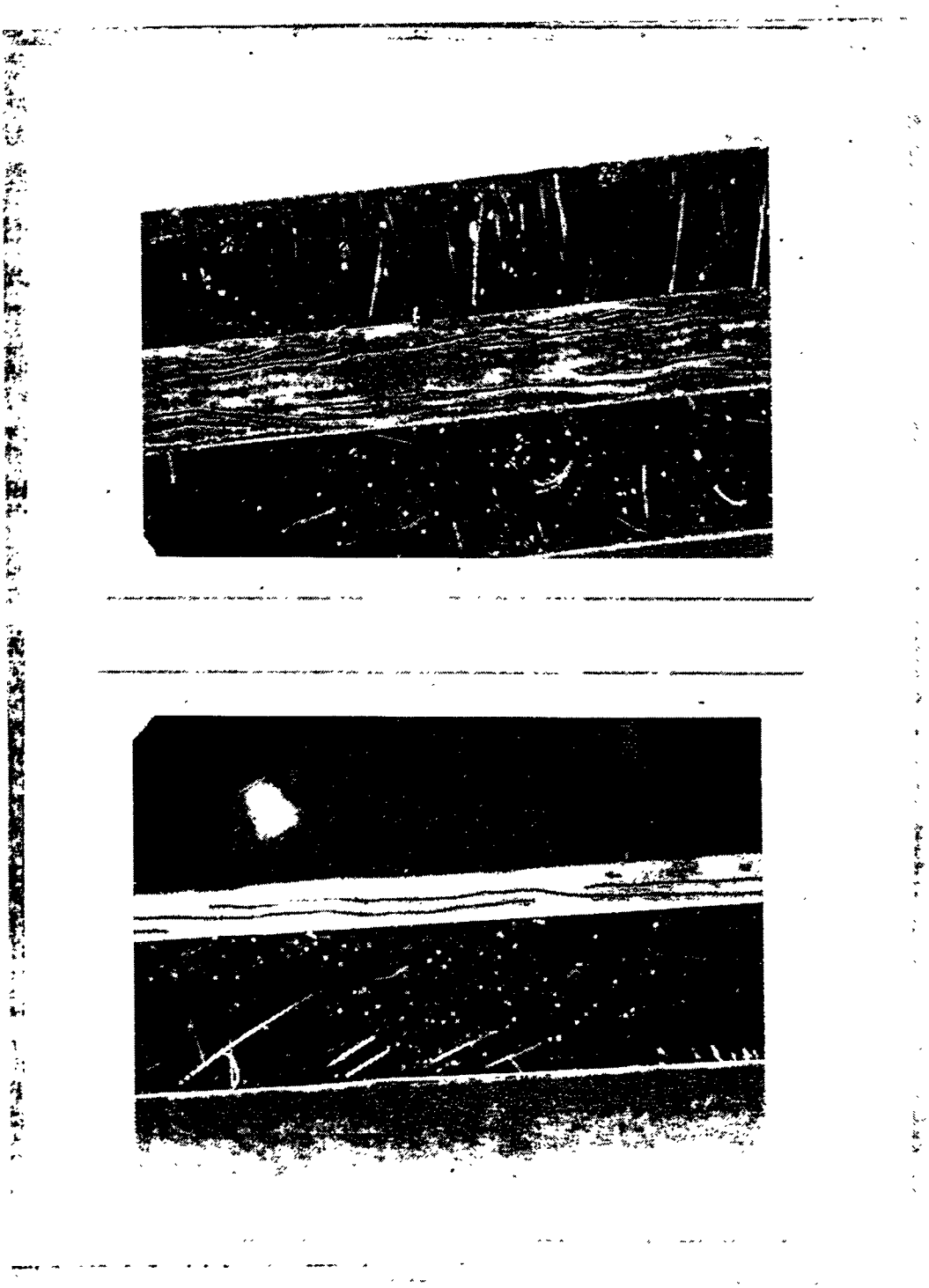


Figure 5.5 — Polished longitudinal cross sections of sample 1-1B. Upper photograph for the turn-turn insulation and lower photograph for the conduit insulation only.

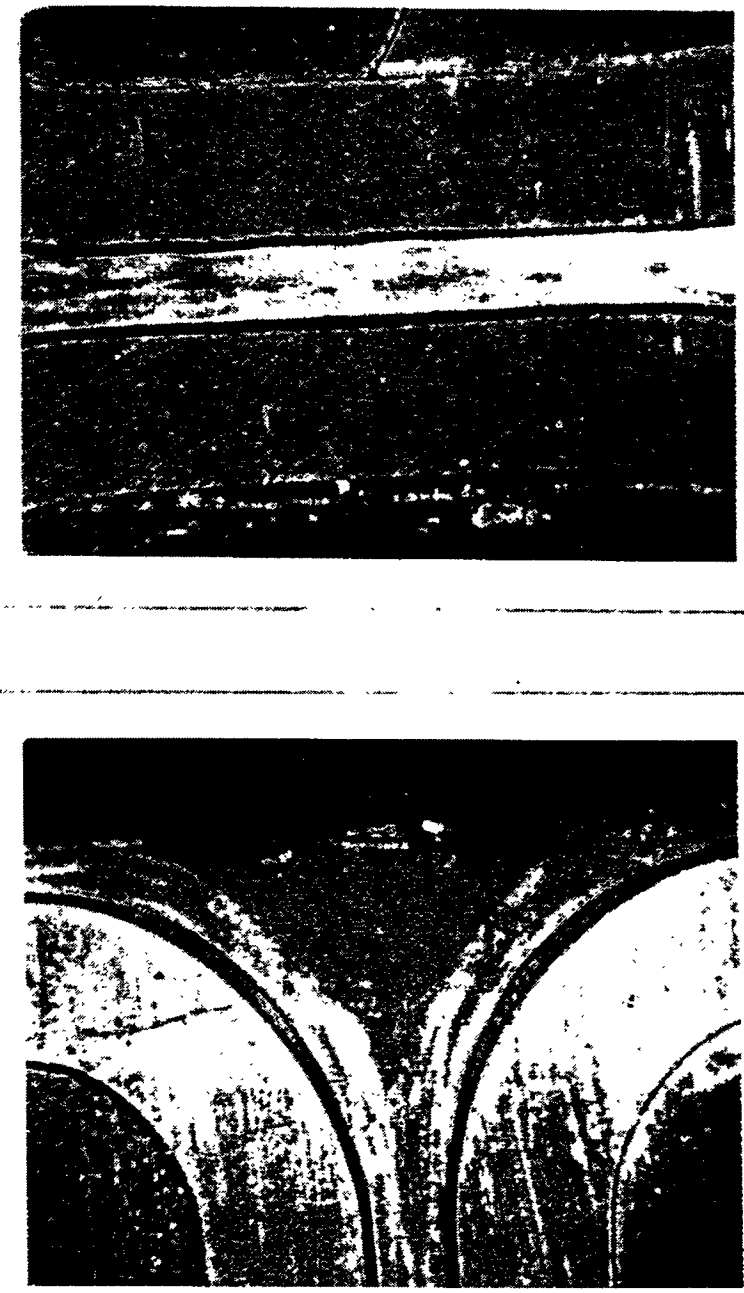


Figure 5.6 — Polished cross sections of sample 3-3CA. Upper photograph for the turn-turn insulation and lower photograph for the corner region showing the roving void filler.

actually see the two lapped layers separated, due to movement of the Kapton into the corner region during mold compression. Also, the glass roving void filler used in the CA (and D) samples is clearly visible. The glass beween the Kapton layers as well as the corner void area appeared to impregnate well.

5.7 MANUFACTURING LESSONS LEARNED

The manufacturing of the 1x2 samples was performed under real factory environment at Everson Electric. Experienced personnel were employed to perform the conduit preparations, insulation taping, and VPI processing. The factory experience in fabricating the 1x2 samples led to several lessons learned which are summarized as follows:

- ***Insulating Operations***: Controlling hand taping layup of the insulating tapes was difficult for the short 75 mm 1x2 samples. Kapton tape had to be used to hold the start and finish ends to prevent telescoping and unravelling. This was especially difficult for the interleaved Kapton/ Glass and Kapton/Prepreg samples B and D where control of the registration of the Kapton relative to the dry glass and prepreg. In the B samples it was discovered that the Kapton tended to slip on the glass as the winding progressed so that the 50% Kapton and 67% glass wraps could not be consistently achieved. This was clearly demonstrated by trying to wind the B-option on a large curve TPX conductor section with the same 12.7 mm Kapton and 19.0 mm glass tapes. Even when an experienced wrapper had lots of conductor in which to get the interleaved wrapping going at a steady pace, it was very difficult to control the tensions on the two-inhand taping such that the Kapton stayed registered relative to the glass. Some of these problems could be minimized in a practical design by using wider Kapton and glass tapes.

  The ITER prepreg taping was frustrating to work with since it became tacky as it warmed up after refrigeration and it was hard to keep the Kapton register on the prepreg. Again, the short sample made it difficult to achieve the ideal

insulation configuration over the active length of the effective 65 mm turn-turn insulation space of the sample.

- ***Conduit End Sealing***: Using copper plates sealed to the conduit ends with RTV was not an effective vacuum seal and did not prevent resin from filling the hollow conduits during VPI. Dummy conductor would have been easier to seal, and could have been used with out any sealing since the resin volume entering the dummy conductor bundle would not have been enough to effect the resin supply during VPI.
- ***Sample End Insulation***: The sample ends were deburred and rounded but the ends of the A, B, and C samples had bare conductors. This proved to be a problem for high voltage evaluation of the samples since flashover of the bare metal ends along the 10 mm creep path does not test the quality of the turn insulation designs. In retrospect, the 1x2 samples should have had fully epoxied ends with the impregnating resin so that end failure effects would be minimized. Also, dry glass and Kapton insulation could have been placed over the ends and fully impregnated to provide even better end insulation.
- **VPI Process**: Only atmospheric pressure was applied to the mold during the final stages of cure following vacuum filling of epoxy. For interleaved Kapton/Glass options to be effective it is believed that pressure is essential for filling all voids and ensuring that resin wicks effectively down to the conduit surface through the Kapton/glass interfaces.

6. CONCLUSIONS

The following conclusions may be drawn from the TPX 1x2 insulation screening program:

1. The proposed Kapton optional insulation approaches performed electrically as well as or better than the CDR baseline based upon as received condition and limited thermal cycling under liquid nitrogen. Mechanical stesses were not applied during the 1x2 screening tests. Therefore, this conclusion is only relative to the basic insulation integrity on a comparative basis without consideration to mechanical loads expected in the TPX system.
2. On the basis of AC partial discharge measurements at 60 Hz in air and under silicon oil and liquid nitrogen, the Shell 826 epoxy system performed poorer than the CTD-101K resin system for interleaved Kapton/glass insulation configuration B. However, for the fully bonded A-Baseline samples both the Shell 826 and CTD-101K had excellent partial discharge performance under liquid nitrogen conditions.
3. No clear discriminators were found between the baseline and the Kapton options with respect to Hipot performance. All samples passed the 1x2 initial acceptance test of 10 kVdc withstand. All samples had an average turn-turn Hipot failure stress of > 19 kV/mm as measured at the end of all electrical testing and thermal cycling. The Kapton/Slip samples CA had the greatest average failure stress at 25 kV/mm with two 50% laps of 1 mil Kapton per conduit.
4. Option B-Interleaved Kapton/Dry Glass, which is in principle fully bonded, performed well. In spite of difficulties in achieving the design goals of the interleaved Kapton and dry glass wrapping scheme, the program showed that it is possible to wick through the interleaved glass layers and bond the inner glass

layer to the conduit. The principle issue is whether or not the Kapton/Glass bonding is strong enough for mechanical performance in the TPX system.

5. Kapton/Slip options C and CA performed well electrically. Observations of cross sections of the samples shows that the Kapton wraps adhere to the conduit and are judged to be bonded to the impregnated glass/Kapton interface. For 1x2 samples the Kapton laps tend to separate from the conduit in the conductor corners due to molding forces. In a winding pack such relatively large extrusions of Kapton over the conduit corners would be expected to be minimal. However, such separations of Kapton wraps would lead to large voids and enhanced partial discharge activity.
6. Kapton/Prepreg option D was only tried using a Hybrid cure approach which tries to cure the prepreg during the epoxy VPI process. In the ITER approach, upon which option D is based, the prepreg is first fully cured and even electrically tested before VPI of the windings. In the TPX 1x2 program prototype ITER prepreg tape based on CTD-112P resin was used. The Hybrid cure approach using CTD-101K resin did not appear to work well as judged from sample cross sections which revealed lack of impregnation and full curing of the prepreg. This situation led to voids and very high partial discharge activity.
7. No discriminators were found between Incoloy 908 and 304LN stainless steel conduits for the CA and D samples. Only Incoloy 908 conduits were used for the A, B, and C samples.
8. Based on the 1x2 program results it was concluded that the 3x3 program should down select to explore only the A-Baseline and the CA-Adhesive Kapton/Dry Glass option for the first two 300 mm long samples. Focus of the program will be on the effect of mechanical and thermal loads on the insulation performance of the 3x3 samples. Insulation design of the 3x3 samples will explore options for corner void filler including glass roving bundles and epoxy resin putty. Although the fully bonded B-Interleaved Kapton/Dry Glass option showed promise, it is recommended that this option be dropped from the 3x3 program. The principle reasons for this decision are the potential manufacturing difficulties in

cowrapping Kapton and dry glass tapes without slip, tension, and registration problems as well as concerns with achieving good impregnation through the Kapton/glass wrapping and Kapton to glass bonding for a full TPX winding pack. The initial experience with the D-Kapton/Prepreg option was not favorable since the Hybrid curing approach as tried at Everson Electric was not successful and resulted in voids and high partial discharge activity. A final decision on further exploration of this ITER based insulation approach will be deferred until later in the 3x3 program.

7. ACKNOWLEDGMENTS

The Everson Electric participation was guided by Mr. Greg Naumovich, TPX Project Manager at EE. The authors wish to thank Mr. Naumovich for his cooperation in using EE factory facilities. The EE factory personnel who performed the manufacturing of the 1x2 samples were very dedicated and cooperative, and the authors wish to personally thank them. Much of the dielectric testing was conducted in the Dielectrics Laboratory at W-STC with the cooperation of Dr. Lyon Mandelcorn, Manager, Ceramics & Coatings Department. Mr. R. W. Lancaster of the Ceramic & Coatings Department who performed many of the measurements is thanked for his hard work and advice during the program. Finally, the authors wish to thank Dr. P. A. Sanger, TPX Project Manager at W-STC for his many suggestions and technical direction during the performance of the 1x2 program.

8. APPENDICES

(Attachments 8.1 - 8.4)

— 8.2

CTD

CTD-101K Flexiblized Epoxy System

Radiation Resistant Electrical Insulation for Superconducting Magnets

Developed for the

International Thermonuclear Experimental Reactor (ITER)

- An anhydride cured epoxy system that was developed and tested for vacuum impregnation of very large superconducting magnets requiring impregnation of long tortuous paths.
- Sets the performance standard in cryogenic and high radiation applications and is backed by performance data that meet all applicable test specification.
- Excellent handling and processing characteristics: long pot life and low viscosity
- Non-carcinogenic resin system with very low toxicity. It is a non-solvent based system, and will not give off volatiles on cure.
- Excellent cryogenic fatigue performance to strss levels as high as 80% of ultimate.

Chemical Description Diglycidyl Ether of Disphenol-A (DGEBA) with anhydride curing agent.

Cure: 1 1/2 hours at 135°C; No Post Cure or
5 hours at 110°C with a post cure of 16 hours at 125°C

Pot Life: 15 hours at 60°C
60 hours at 40°C

Process Compatabilities

* Filament winding (FW)
* Resin Transfer Molding (RTM)
* Resin Injection Molding (RIM)
* Vacuum Pressure Impregnation (VPI)
* Casting

Advantages

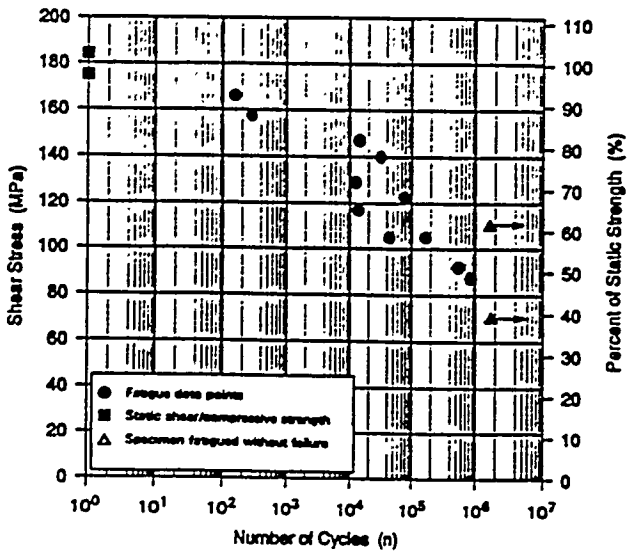
* Excellent wetting of fibers and other surfaces
* Strong adhesion to fibers and fillers
* Non-Carcinogenic
* Low Toxicity
* Specific Gravity < 1.2 g/cc
* Mixing Temperature 40-60°C

Disclaimer: The information and recommendations contained herein are based upon data believed to be accurate. However, no guarantee or warranty of any kind expressed or implied is made with respect to the information contained herein.

COMPOSITE TECHNOLOGY DEVELOPMENT, INC
2400 Central Avenue, Suite H, Boulder, CO 80301. (303) 447-2226 (Ph); (303) 447-0140 (Fax)

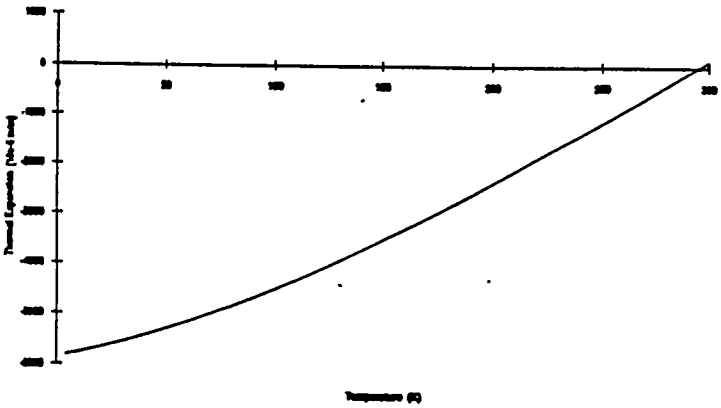
CTD-101K PROPERTIES

Temperature [K]	Compresson Strength [GPa]	Compresson Modulus [GPa]	Short Beam Shear Strength [MPa]	Short Beam Shear Modulus [MPa]	Shear/Comp Rato	Shear Strength [MPa]	Compression Strength [MPa]
76	1.3	17	108	28	75/15	111	30
					45/45	176	176
					15/75	248	933
4	1.4	20	120	34	75/15	104	28
					45/45	178	178
					15/75	277	1034

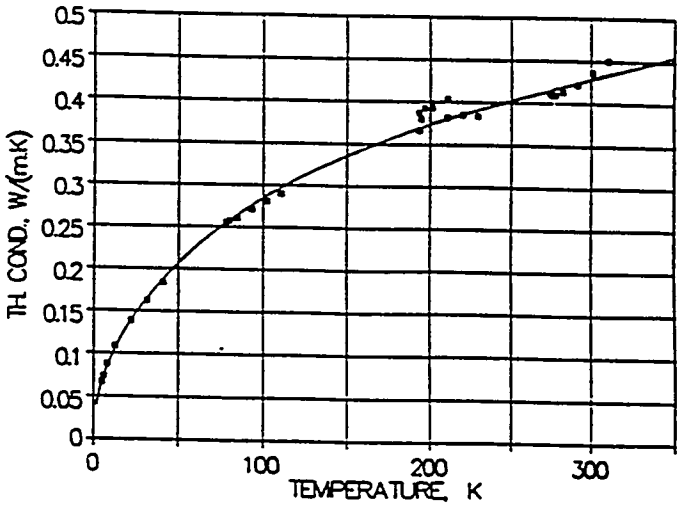


Fatigue Performance at 76 K
101K/50% S-2 Glass - Shear/Compression 45/45

Dielectric Strength of CTD-101K
79.7 (kV/mm) at 76 K



Thermal Expansion 4 K to 300 K
101K/50% S-2 Glass - thru thickness



Thermal Conductivity 4 K to 300 K
101K/50% S-2 Glass - thru thickness

COMPOSITE TECHNOLOGY DEVELOPMENT, INC
2400 Central Avenue, Suite H, Boulder, CO 80301. (303) 447-2226 (Ph); (303) 447-0140 (Fax)

CTD

CTD-112P Pre-preg Epoxy System

Radiation Resistant Electrical Insulation for Superconducting Magnets

Developed for the

International Thermonuclear Experimental Reactor (ITER)

- A modified amine cured tetrafunctional epoxy system that was developed and tested for cryogenic and ambient applications down to liquid helium temperatures (-269°C/-452°F).
- Non-carcinogenic resin system with very low toxicity. It is a non-solvent based system, and will not give off volatiles on cure.
- Excellent cryogenic fatigue performance to strss levels as high as 80% of ultimate.
- Use of a pre-preg system in fabrication of superconducting magnets:

  - ensures complete impregnation of glass through out the magnet
  - eliminates the need to vacuum seal the entire magnet
  - works well with a variety of dielectric barriers

Chemical Description Tetrafunctional (TGDM) epoxy with modified amine curing agent.

Cure: 2 Hour at 177°C, Optional post cure: 7 hours at 200°C

Out Life: 1 1/2 hours at 120°C

Process Compatabilities

* Filament winding (FW)
* Hand Lay-up
* Pultrusion

Advantages

* Non-Carcinogenic
* Low Toxicity
* Excellent adhesion to fibers and fillers
* Specific Gravity < 1.2 g/cc

Applications

* Electrical Insulation for Superconducting Magnets
* Pre-preg matrix for fiber reinforced composite materials for cryogenic structures or vessels

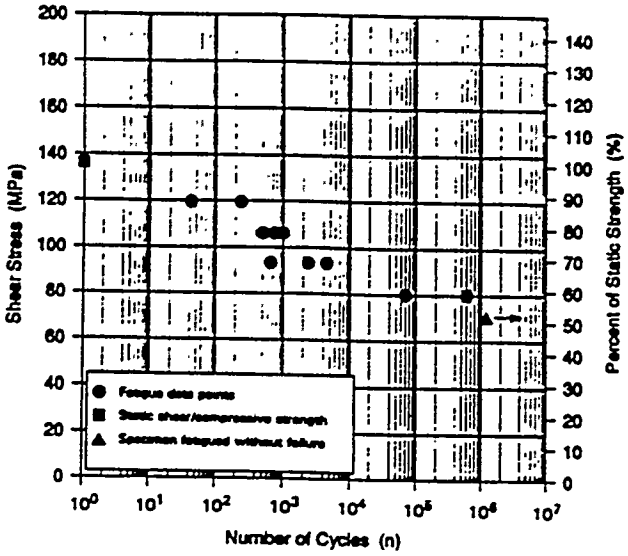
Disclaimer: The information and recommendations contained herein are based upon data believed to be accurate. However, no guarantee or warranty of any kind expressed or implied is made with respect to the information contained herein.

COMPOSITE TECHNOLOGY DEVELOPMENT, INC

2400 Central Avenue, Suite H, Boulder, CO 80301. (303) 447-2226 (Ph); (303) 447-0140 (Fax)

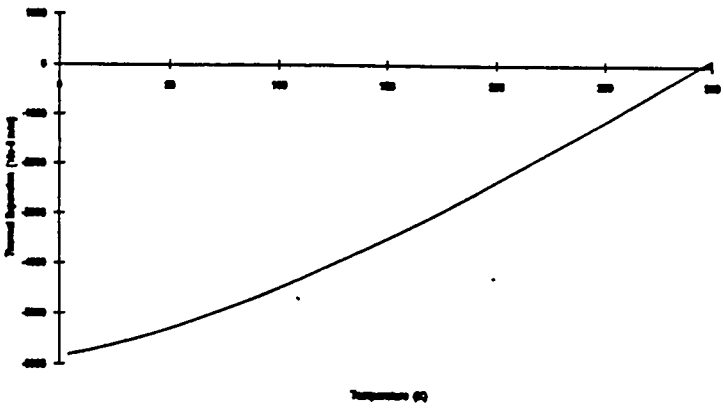
CTD-112P PROPERTIES

Temperature [K]	Compresson Strength [GPa]	Compresson Modulus [GPa]	Short Beam Shear Strength [MPa]	Short Beam Shear Modulus [GPa]	Shear/Comp Rato	Shear Strength [MPa]	Compression Strength [MPa]
76	1.2	19	67	30	75/15	53	14
					45/45	141	141
					15/75	188	701
4	1.3	24	69	28	75/15	11	3
					45/45	150	150
					15/75	220	820

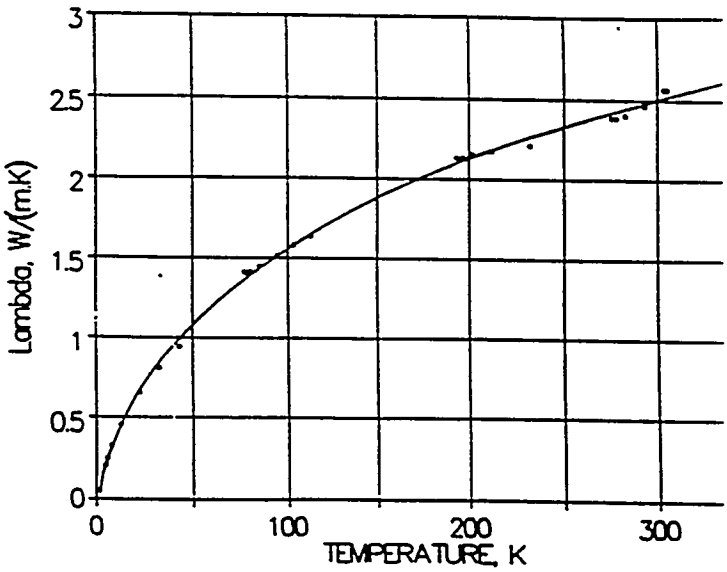


Fatigue Performance at 76 K
112P/50% S-2 Glass - Shear/Compression 45/45

Dielectric Strength
79.7 (kV/mm) at 76 K



Thermal Expansion 4 K to 300 K
112P/50% S-2 Glass - thru thickness



Thermal Conductivity 4 K to 300 K
112P/50% S-2 Glass - thru thickness

COMPOSITE TECHNOLOGY DEVELOPMENT, INC
2400 Central Avenue, Suite H, Boulder, CO 80301. (303) 447-2226 (Ph); (303) 447-0140 (Fax)

APPENDIX 8.2

QA Measurements of TTI S-2 Glass Plain Weave Tape

NEW S-2 GLASS TAPE MEASUREMENTS FROM INCOMING INSPECTION

NO. OF MEASUREMENTS	TAPE THICKNESS (in) EDGE	MIDDLE	EDGE	WIDTH
ROLL NO. 1				
1	0.0087	0.0071	0.0092	0.7066
2	0.0096	0.0070	0.0101	0.7095
3	0.0088	0.0077	0.0091	0.7059
4	0.0091	0.0075	0.0091	0.6756
5	0.0092	0.0072	0.0088	0.6715
6	0.0083	0.0074	0.0098	
7	0.0092	0.0076	0.0093	
8	0.0097	0.0074	0.0094	
Averages	**0.0091**	**0.0074**	**0.0094**	**0.69382**
ROLL NO. 2				
1	0.0091	0.0081	0.0085	0.7270
2	0.0088	0.0080	0.0087	0.7070
3	0.0081	0.0075	0.0083	0.7499
4	0.0087	0.0074	0.0084	0.7140
5	0.0089	0.0082	0.0088	0.7120
6	0.0089	0.0079	0.0086	
7	0.0083	0.0080	0.0078	
8	0.0082	0.0077	0.0089	
Averages	**0.0086**	**0.0079**	**0.0085**	**0.72198**
ROLL NO. 3				
1	0.0084	0.0071	0.0078	0.7400
2	0.0078	0.0072	0.0078	0.7430
3	0.0077	0.0071	0.0083	0.7360
4	0.0081	0.0072	0.0086	0.7390
5	0.0086	0.0074	0.0081	0.7287
6	0.0088	0.0070	0.0075	
7	0.0083	0.0071	0.0082	
8	0.0082	0.0073	0.0081	
Averages	**0.0082**	**0.0072**	**0.0081**	**0.73694**
ROLL NO. 4				
1	0.0075	0.0069	0.0084	0.7400
2	0.0078	0.0068	0.0079	0.7450
3	0.0079	0.0067	0.0074	0.7300
4	0.0084	0.0068	0.0078	0.7450
5	0.0081	0.0070	0.0075	0.7480
6	0.0077	0.0071	0.0076	
7	0.0080	0.0070	0.0070	
8	0.0077	0.0070	0.0075	
Averages	**0.0079**	**0.0069**	**0.0076**	**0.7416**
Overall Averages	**0.0085**	**0.0073**	**0.0084**	**0.7236**

APPENDIX 8.3

Fabrication and Impregnation Procedures

MANUFACTURING PROCESS OUTLINE

DATE: 11/15/94 ENGINEER: Doug Hartman

DUE DATE: 11/18/94

WORK ORDER: 112000 OPERATION NO.: 102

JOB DESCRIPTION: TPX 1x2 Conduit Samples

APPLICABLE DRAWINGS: 52379-001S; 52379-002S

APPLICABLE DOCUMENTS: 1x2 Conduit Sample Dimensions Record

RQUIRED MATERIALS:
1) Customer Supplied Inonel 908 Conduit
2) .030" to .040" x 10" x 10" Copper Sheet

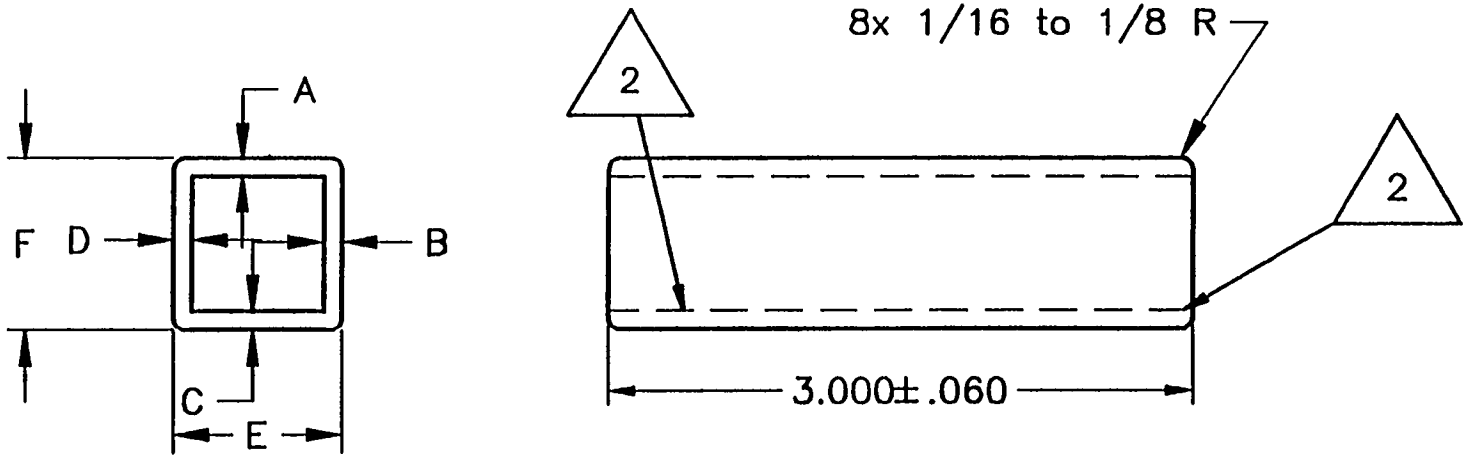
1x2 Sample Conduit Pieces:

1) Straighten the long piece of conduit material as best you can
2) Grit blast the long piece of conduit
3) Notify engineer to inspect grit blasting
4) Cut 30 pieces of conduit to length
5) Dress and deburr both ends of each piece
6) Grind a radius on all 4 sides of both ends of each piece
7) Number each end of each piece. Identify one end with an "A" and one end with a "B"...(Ex. 1A, 1B)
8) Thoroughly clean each piece inside and out in a bath of acetone or permathane.
9) Measure the length of each piece and the dimensions identified by letters on drawing 52379-001S.and record them on the 1x2 Conduit Sample Dimensions Record sheet. Make sure you measure and record both end "A" and end "B" for each piece.
10) Place finished parts in a box

1x2 End Cap Pieces:

1) Cut 60 pieces and clean with acetone or permathane
2) Deburr as required
3) Place finished parts in the box with the conduit samples
4) Notify engineer that parts are complete

REVISIONS			
REV	DESCRIPTION	DATE	APPROVED



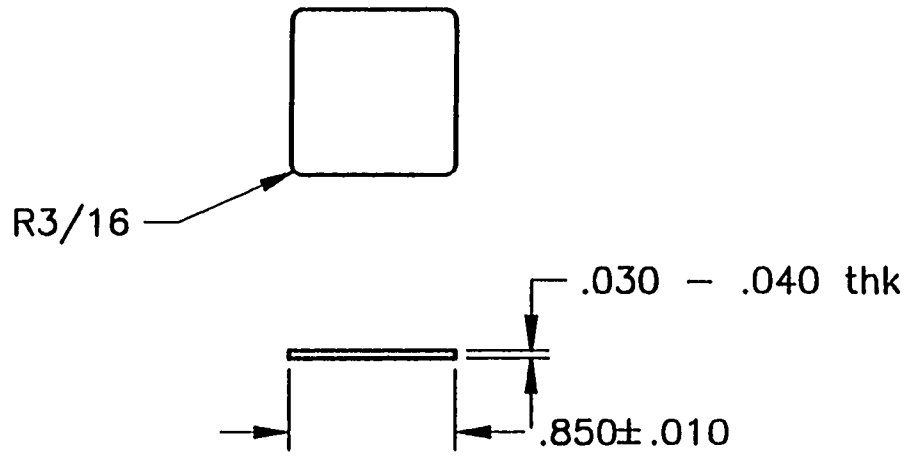
Note:
1. Mat'l: Customer supplied – Inconel 908 conduit

2 Place number on inside of conduit at these locations

everson electric co.
2000 City Line Rd • Bethlehem, PA

DO NOT SCALE	UNLESS OTHERWISE SPECIFIED	APPROVALS	DATE	TITLE
FINISH 63	DIMENSIONS ARE IN INCHES. FRACTIONS: ± 1/64 DECIMALS: .X ± .030 .XX ± .015 .XXX ± .005 ANGLES: ± 5°	DRAWN M. Kerstetter	11nov94	Conduit 1x2 Sample Pieces
		DESIGN D. Hartman	11nov94	A DWG NO 52379-001S REV –
	BREAK SHARP EDGES MAX. n/a MIN. n/a	APPROVED		SCALE 1/1 SHEET

REVISIONS			
REV	DESCRIPTION	DATE	APPROVED



Note: This item used to seal conduit for VPI.
May not protrude beyond OD of conduit piece.

Matl: .030 – .040 thk sht copper

everson electric co.
2000 City Line Rd • Bethlehem, PA

DO NOT SCALE	UNLESS OTHERWISE SPECIFIED	APPROVALS	DATE	TITLE
FINISH 63	DIMENSIONS ARE IN INCHES. FRACTIONS: ± 1/64 ANGLES: ± 5° DECIMALS: .X ± .030 .XX ± .015 .XXX± .005	DRAWN M. Kerstetter	11nov94	End Cap 1x2 Sample Pieces
		DESIGN D. Hartman	11nov94	A DWG NO 52379-002S REV –
	BREAK SHARP EDGES MAX. n/a MIN n/a	APPROVED		SCALE 1/1 SHEET

1X2 CONDUIT SAMPLE DIMENSIONS RECORD

SAM NO.	LENGTH	END -A DIMEN SIONS (INCHES)						END-B DIMEN SIONS (INCHES)					
		A	B	C	D	E	F	A	B	C	D	E	F
1	3.0635	.100	.0980	.1005	.0980	.875	.8745	.1035	.0975	.100	.0975	.873	.874
2	3.0745	.1020	.0980	.1005	.0985	.8735	.8735	.1020	.0980	.0995	.0980	.8745	.876
3	3.0765	.1020	.0975	.1000	.0975	.8765	.8760	.1000	.0980	.1010	.0990	.875	.875
4	3.0745	.1015	.0975	.1010	.0985	.8755	.8740	.1030	.0990	.1010	.0990	.878	.875
5	3.0595	.1005	.0975	.1005	.0985	.875	.8745	.1015	.0985	.1010	.0985	.877	.876
6	3.0076	.1020	.0980	.1000	.0985	.875	.8740	.1020	.0980	.1010	.0990	.8775	.8775
7	3.0510	.1025	.0985	.1010	.0975	.876	.875	.1030	.0960	.1000	.0975	.874	.8735
8	3.0790	.1025	.0970	.0995	.0980	.8725	.8725	.1005	.0990	.1000	.0990	.875	.874
9	3.0765	.1030	.0985	.0995	.0990	.8755	.8735	.1000	.0990	.1000	.0985	.877	.8745
10	3.0715	.1000	.0995	.1000	.0995	.8765	.875	.1020	.0985	.0990	.0990	.874	.8745
11	3.0750	.0995	.0980	.0995	.0985	.8765	.8745	.1025	.0980	.0995	.0985	.8745	.8735
12	3.0680	.1005	.0990	.1000	.0985	.8755	.8755	.1035	.0980	.1000	.0990	.8740	.8735
13	3.0675	.1000	.0975	.1005	.0980	.8755	.8755	.1030	.0980	.1000	.0980	.8745	.8740
14	3.0755	.1010	.0985	.1010	.0975	.8765	.8750	.1000	.0975	.1005	.0985	.8755	.8735
15	3.0810	.1015	.0980	.0995	.0970	.875	.873	.0995	.0980	.1000	.0985	.8770	.8750
16	3.0705	.1015	.0990	.1000	.0990	.8745	.8735	.1000	.0990	.0995	.0990	.8770	.8750
17	3.0675	.1015	.0980	.1000	.0980	.8745	.8740	.1000	.0985	.0995	.0990	.8765	.8745
18	3.0570	.1010	.0980	.1005	.0980	.8765	.8775	.1030	.0975	.1005	.0985	.8740	.8740
19	3.0710	.1000	.0975	.1005	.0980	.875	.8735	.1015	.0985	.1010	.0980	.8755	.8760
20	3.0795	.1020	.0975	.0995	.0990	.8745	.8730	.1005	.0990	.0990	.0980	.8770	.8745
21	3.0595	.1035	.0970	.1005	.0985	.875	.8745	.1025	.0980	.1015	.0980	.8770	.8755
22	3.0750	.1030	.0990	.1005	.0990	.875	.8735	.0995	.0995	.0995	.0980	.8765	.8770
23	3.0840	.1015	.0980	.1000	.0985	.875	.874	.1005	.0980	.0995	.0990	.8775	.8770
24	3.0720	.1010	.0990	.1000	.0985	.876	.875	.1010	.0980	.0995	.0990	.8750	.8735
25	3.0755	.1010	.0975	.1005	.0995	.8745	.8735	.1015	.0975	.1000	.0970	.8760	.8760
26	3.0755	.1010	.0975	.1000	.0980	.8745	.8745	.1020	.0970	.1000	.0990	.8745	.8745
27	3.0725	.1010	.0980	.0995	.0985	.8770	.8745	.1030	.0990	.0990	.0985	.8755	.8745
28	3.0790	.1000	.0990	.1000	.0990	.8770	.8740	.1005	.0980	.0990	.0980	.8755	.8750
29	3.0715	.1010	.0985	.1005	.0990	.8750	.8745	.1025	.0985	.1010	.0985	.8775	.8770
30	3.9825	.1025	.0970	.1010	.0975	.8750	.8745	.1020	.0975	.1000	.0980	.8775	.8740

11/15/94

tpxvpi.doc MANUFACTURING PROCESS OUTLINE

PROJECT: TPX 1x2 Insulation Samples
WORK ORDER NO.: 60028
OPERATION NO.: 102

MOLD NUMBER 1:

Prebake:

1) Prebake mold at 220°F for 1 hour.

VPI:

1) Put mold in the VPI tank and dry vacuum at or below 700 microns for 30 minutes or more.
2) While the mold is under dry vacuum, mix the CTD 101K resin and degas.
3) Use the following mixing ratio: (Requires 2 kits; 1 gallon each)

Resin	Part A	10.44lbs	M7227
Hardner	Part B	9.40lbs	M7227
Accelerator	Part C	.157lbs	M7227

4) Set mixing pot temperature between 100°F and 120°F. Mix the resin and hardner together and degas for 1 hour at or below 700 microns while mixing.
5) After the resin and hardner mix is degased, add the accelerator and degas at or below 700 microns for 20 minutes while mixing.
6) After the resin mix is fully degased, check the vacuum on the VPI tank to confirm that it is greater then the degasing vacuum but less than or equal to 700 microns.
7) Begin filling the mold.
8) Fill the mold slowly to avoid trapping air.
9) After the mold is full, vacuum for 2 hours. Keep checking the resin level to confirm that it is filled to the top of the mold.
10) Remove the mold from the VPI tank and let it at atmospheric pressure for 30 minutes.

Curing:

1) Put filled mold in oven to cure.
2) Cure for 5 hours at 230°F and then 16 hours at 260°F
3) Use chart recorder to record cure cycle.
4) Check resin level in mold every 10 minutes for the first 2 hours to make sure it has not dropped below the top of the coil sample. Top off with resin as needed.

MOLD NUMBER 2:

Prebake:

1) Prebake mold at 220°F for 1 hour.

VPI:

1) Put mold in the VPI tank and dry vacuum at or below 700 microns for 30 minutes or more.
2) While the mold is under dry vacuum, mix the Shell 826 resin and degas.
3) Use the following mixing ratio:

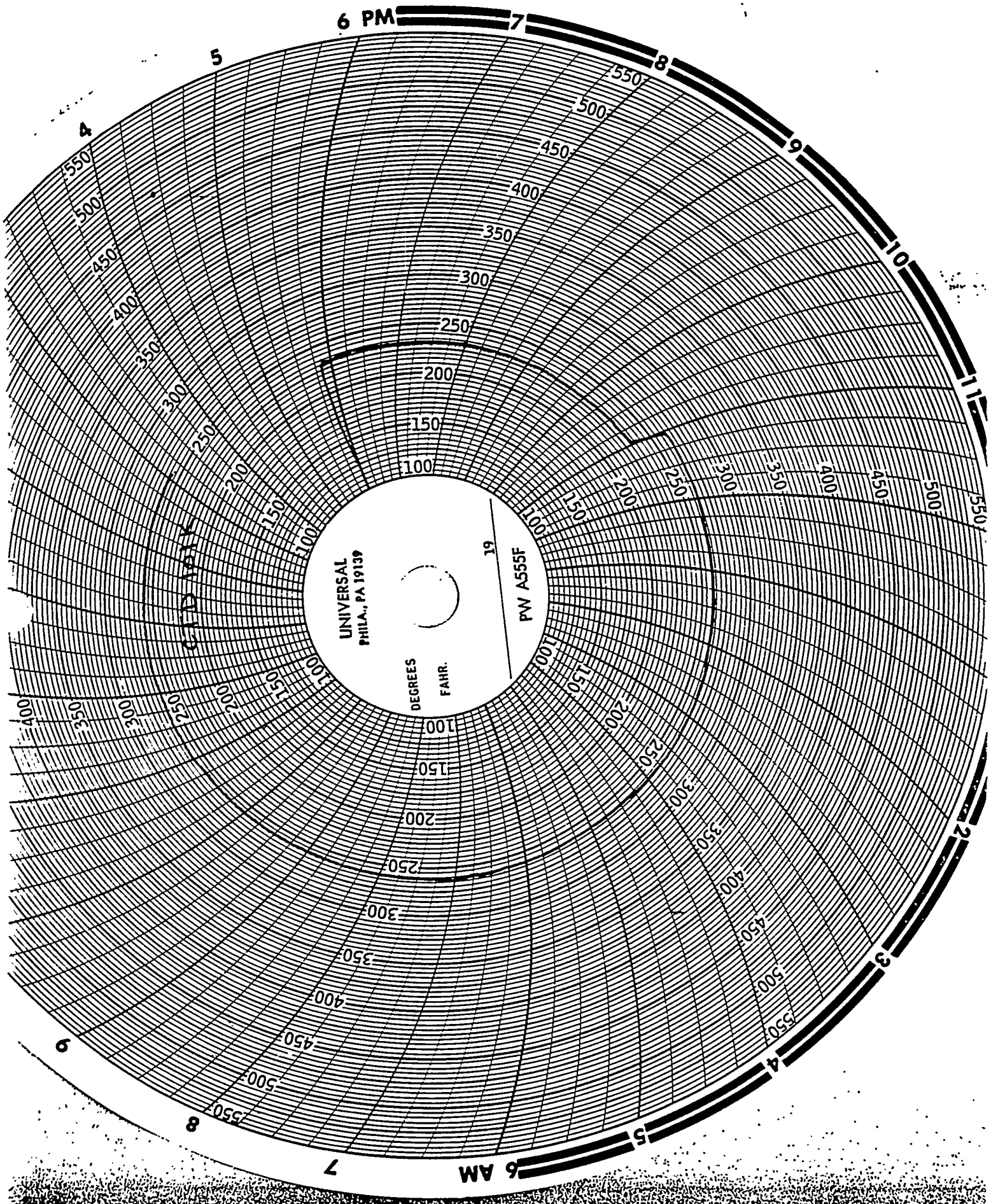
Resin	Shell 826	10.47lbs	M1204
Hardner	Cieba-Giegy (HY 906)	9.420lbs	M7231
Accelerator	Cieba-Giegy (DY 062)	.105lbs	M7232

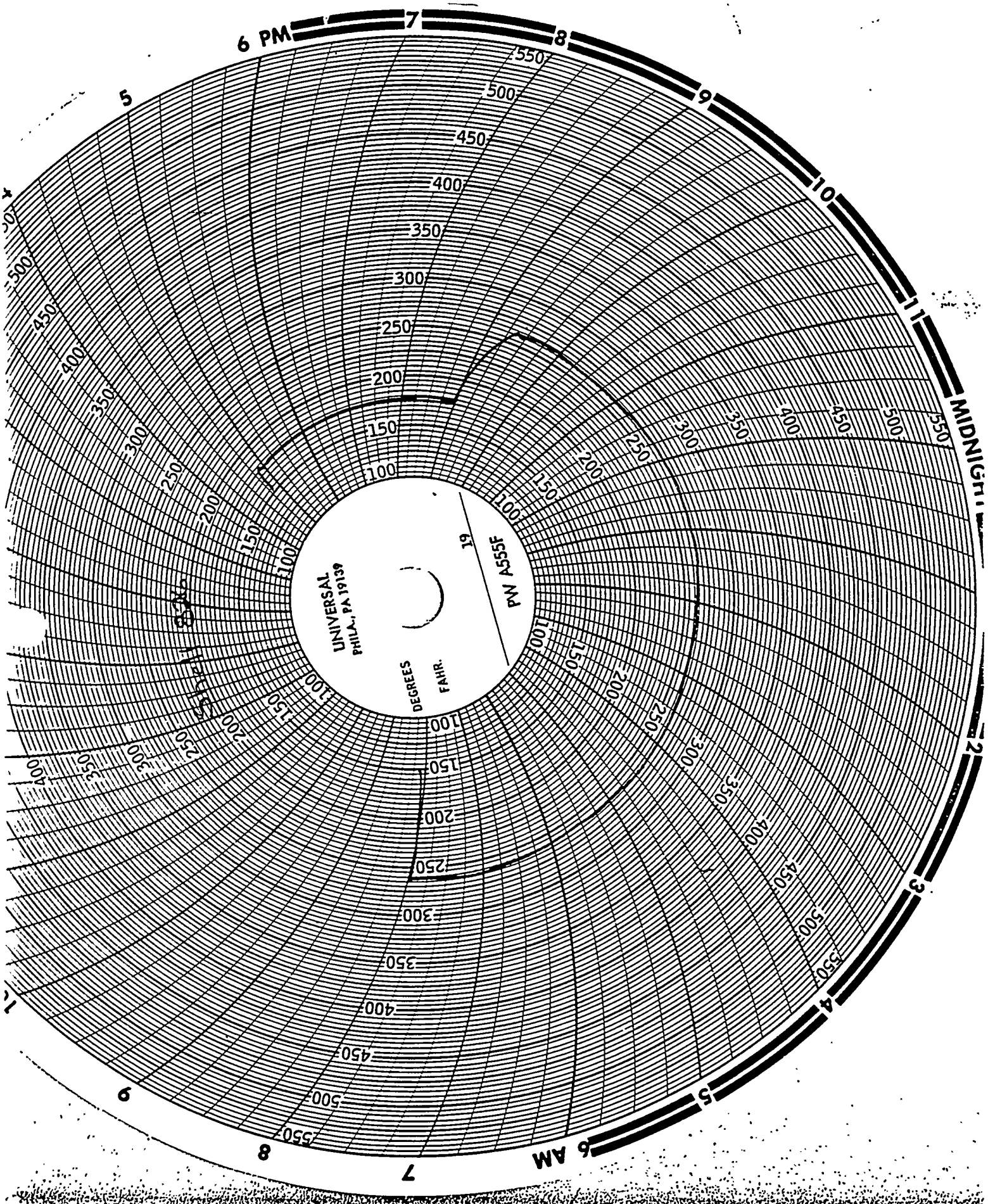
4) Set mixing pot temperature between 100°F and 120°F. Mix the resin and hardner together and degas for 1 hour at or below 700 microns while mixing.
5) After the resin and hardner mix is degased, add the accelerator and degas at or below 700 microns for 20 minutes while mixing.
6) After the resin mix is fully degased, check the vacuum on the VPI tank to confirm that it is greater then the degasing vacuum but less than or equal to 700 microns.

7) Begin filling the mold.
8) Fill the mold slowly to avoid trapping air.
9) After the mold is full, vacuum for 2 hours. Keep checking the resin level to confirm that it is filled to the top of the mold.
10) Remove the mold from the VPI tank and let it at atmospheric pressure for 30 minutes.

Curing:

1) Put filled mold in oven to cure.
2) Cure for 4 hours at 175°F and then 10 hours at 260°F
3) Use chart recorder to record cure cycle.
4) Check resin level in mold every 10 minutes for the first 2 hours to make sure it has not dropped below the top of the coil sample. Top off with resin as needed.


6 PM
7
8
9
10
11
2
3
4
5
6 AM
7
8
9
4
5
UNIVERSAL
PHILA., PA 19139
DEGREES
FAHR.
19
PW A555F
CTD 101K


UNIVERSAL
PHILA., PA 19139
DEGREES
FAHR.
19
PW A555F
6 PM
7
8
9
10
11
MIDNIGHT
2
3
4
5
6 AM
7
8
9

COMPOSITE TECHNOLOGY DEVELOPMENT, INC.
2400 Central Avenue, Suite H • Boulder, Colorado 80301
Phone: (303) 447-2226 • Fax: (303) 447-0140

CTD-101K

CTD-101K is an anhydride cured epoxy system with excellent performance at cryogenic temperatures, and excellent radiation resistance. It is formulated to have enhanced wetting properties over CTD-101A, which aid in the vacuum impregnation of highly tortuous paths. It is suitable for filament winding, vacuum impregnation, and RTM processes. Quoted performance properties are obtained by using the following procedure for mixing and curing the system.

MATERIALS	DESIGNATION	PARTS BY WEIGHT
RESIN:	PART A[1]	100.0
HARDENER:	PART B	90.0
ACCELERATOR:	PART C	1.5

MIXING TEMPERATURE: 40-60 °C

MIXING PROCEDURE: Combine the weighed components in a container equipped with heating and mechanical stirring. Heat and stir the mixture until a clear solution at 40-60 °C is obtained. Degass the mix at 27+ in Hg for approximately 20 minutes. The system is now ready for application.

POT LIFE:

Temp (°C)	Pot Life (Hr)	Viscosity (Cp)
25	145	1300
40	60	400
60	20	100

	Standard	Accelerated
CURE SCHEDULE:	5 Hr. at 110°C	1.5 Hr. at 135°C
POST CURE:	16 Hr at 125°C	No Post Cure

1 Due to the purity of this resin it can partially solidify when exposed to cold temperatures. Heating to 60 °C for about 30 minutes will restore it to the liquid state.

APPENDIX 8.4

Post Cure Dimensions of Samples CA and D

1x2 INSULATION SAMPLE MEASUREMENTS (POST CURE)								
PREPREG SAMPLES			A (in)	B (in)				
1 layer 1" Prepreg with 3/4" Kapto			1.874	0.951				
centered in middle of prepreg.			1.883	0.956				
1 layer wrapped 50% overlap,			1.881	0.951				
registering on the prepreg.								
1-Butt layer overwrap with 3/4"			1.877	0.943				
(old) S-2			1.881	0.950				
			1.876	0.943				
			1.880	0.947				
			1.883	0.954				
			1.878	0.952				
Averages			1.879	0.950				
COUNTER WRAPPED KAPTON								
2 layers of 3/4" Kapton counter			1.874	0.944				
wrapped.			1.880	0.952				
1 -Butt layer S-2 (old)			1.872	0.943				
1- 50% overlap layer S-2 (old)								
			1.878	0.948				
			1.883	0.957				
			1.880	0.948				
			1.881	0.949				
			1.881	0.952				
			1.875	0.945				
Averages			1.878	0.949				

Westinghouse
Electric Corporation

Science & Technology Center
Advanced Electromechanical Dept.

1310 Beulah Road
Pittsburgh, Pennsylvania 15235-5098
Phone: (412) 256-2200
FAX: (412) 256-1948

Memorandum

14-950718-WEC-PSanger-01

To: Distribution

From: Phillip A. Sanger

Date: July 24, 1995

Subject: Final Report on Shear Strength under Compressive Load and Through Thickness Tension of TPX Insulating Materials

---

Introduction

It is well known that many glass/epoxy composites are weakest in interlaminar shear and tension. The TPX CDR magnet baseline designs relied on a glass/epoxy structure for its mechanical and electrical integrity. The TPX insulation development program addressed this issue by implementing a series of the shear strength tests under compressive loads to examine alternate insulation designs and provide a better foundation for assessing the material capabilities of the insulating matrix. Subsequent FEA analysis of the TF structure performed by Myatt indicated that the shear stresses exceeded the projected shear allowables. Furthermore this analysis clear showed that through thickness (or interlaminar) tension was present at unacceptable levels. A review of the literature revealed that data on interlaminar tension for the insulating systems being considered was unavailable. The testing program was thus expanded to include shear strength measurments of more materials and to develop an interlaminar tension test and measure the two insulating systems of most interest to the TPX design effort. In both programs, it was recognized at the outset that the number of samples would not be sufficient to fully characterize the materials. Instead the data would serve to guide decisions. Full characterization would occur in phase II once a final selection of an insulating system had been made.

Approach

Composite Technology Development, Inc located in Boulder, CO was selected as the vendor for these measurements. CTD, in conjunction with NIST, were the original developers of a technique for the ITER project for measuring the shear strength of composites under compressive load. This technique is well documented (see reference 1, 2) and has been used extensively to characterize insulating materials.

The test reports for both programs are attached to this memo. The variables included in the shear/compression measurements are described fully in these two reports but are summarized as follows:

a) Epoxies (two versions of DGEBA, Shell 826 and CTD101K and one candidate suitable for a pre-empregnated tape CTD112P)
b) Glass tapes (a 8 harness "satin" weave, a plain weave and a specially developed "3D" tape with more glass in the interlaminar direction)
c) Sandwiches of glass/epoxy and Kapton
d) Putties for filling the corners between conductors (CTD101G and Araldite 1580)

In addition the effect of metal substrate was investigated for the low thermal contraction Incoloy 908 and type 316 stainless steel.

The scope of the interlaminar tension measurements was more limited investigating only materials options that remained in the program in January 1995. These included satin weave tape (used in the ground wall), 3D weave tape (used for the conduit wrap) and a prepreg/Kapton sandwich.

Discussion of Results

These measurement were also directed at mapping the behavior of the interlaminar shear strength under compressive and tensile loads. This parameter space is shown schematically in figure 1. The tensile region was not clearly defined since interlaminar tensile loading of insulation is undesirable. Since tensile stresses are considered likely in the TPX design, then the behavior of shear in tension must be explored. The output data of this program, besides providing

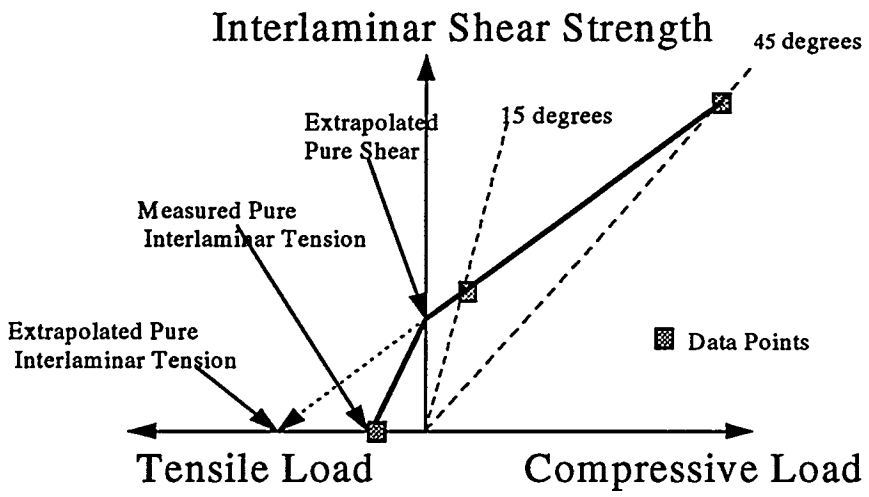


Figure 1 Schematic of the expected behavior of interlaminar shear strength under both compressive and tensile loads.

another discriminator of alternative insulation systems, was to provide measurements to support determination of the pure shear and pure tension interlaminar strengths and the slope of the shear/compression line. The behavior of the shear in both the tension and compression regions was assumed to be linear. However the mechanics of the composite were expected to be different for both and thus the slope would be different. Table 1 presents the parameters that characterize the interlaminary shear strength for the two primary composite systems in the TPX magnet designs: 3D tape and satin weave 2D tape both with Shell 826 epoxy.

Composite Type	Pure Interlaminar Tension (MPa)	Pure Interlaminar Shear (MPa)	Compressive Slope
3D S2 glass tape	46	52	0.7
8 harness satin weave S2 glass tape	60	95	0.5

The significantly lower strengths for the 3D tape is consistent with the reduced amount of float fibers in this tape. It is widely accepted that parallel fibers on the surface of the tape enhances the tape to tape bond strength by allowing the adjacent parallel fibers to nestle together. The 8 harness satin weave allows fibers to float on the surface for 8 stitches while the 3D weave allows for only two stitches of float. Reducing the float in the 3D weave is a deliberate compromise between the goal of increasing the amount of through thickness glass and retains sufficient bond strength provided by the floating fibers.

The limited number of samples in this program does not permit firm conclusions to be defined. However the following observations can be made:

1. Measured shear strength are independant of the substrate used. Both Type 316 stainless steel and Incoloy 908 were tested.

2. Sandwiches containing Kapton exhibited consistantly higher shear strengths at all angles if impregnated with Shell 826 epoxy over the CTD101K epoxy.

3. For composites without Kapton, the two epoxies performed equivalently except for the 15 degree angle. The difference between CTD 101K and Shell 826 for the 3D tape at the lowest angle is surprising since their shear strengths are equal at 45 degrees and essentially the same for the satin weave tape and the G11. While these values will be used in the analysis, it is clear that further characterization will be needed in Phase II to obtain better consistancy and explore these variations.

4. The data is not clear on the impact of the different tape configurations on the shear strength. Plain weave exhibited a large deterioration for both epoxies. While plain weave was expected to show lower values, the dramatic loss of properties for the CTD101K was not expected and is not consistant with early data explored on the ITER program

References

1. N.J.Simon, E.S.Drexler, and R.P.Reed, "Shear/Compressive Tests for ITER Magnets Insulation", Adv. Cryo. Eng., 40:977 (1994)

2. N.J.Simon, R.P.Reed, and R.P. Walsh, Compression and Shear Tests of Vacuum-Impregnated Composites at Cryogneic Temperatures", Adv.Cryo.Eng., 38:363 (1992)

COMPOSITE TECHNOLOGY DEVELOPMENT, INC.
2400 Central Avenue, Suite H • Boulder, Colorado 80301

Phone: (303) 447-2226 • Fax: (303) 447-0140

TPX Through Thickness Tension Testing

Prepared for
Westinghouse Science and Technology Center
1310 Beulah Rd.
Pittsburgh PA 15235

June 23, 1995

James B. Schutz
Engineer

Paul E. Fabian
Engineer

Summary

Through-thickness tension specimens were fabricated using the insulation systems described in the attached data summary. Reinforcements included TTI 3-dimensional weave, 6781 8-harness satin, and 6580 8-harness satin. The 6580 weave is approximately 7 mils in thickness, relative to the 9 mil thick 6781 fabric. The resin systems included Shell 826 RTM epoxy, CTD-112P prepreg epoxy, and alumina filled CTD-112PF prepreg epoxy. Kapton 200 HA barrier was included with CTD-112P and CTD-112PF systems.

Specimen preparation, layup, and cure information are contained in the attached tables. A data summary as well as test data sheets for each test series are also included.

Through Thickness Tension Specimen Preparation

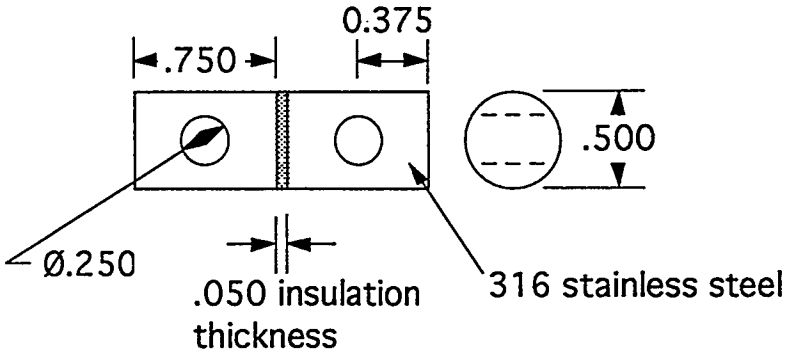
Metal Cleaning and Preparation

The following procedure was used for the preparation of the 316 stainless steel chips.

1. Ultrasonic clean in 1,1,1, Trichloroethane (TCE) for 30 minutes.
2. Sandblast such that a uniform matte finish appears on all chips using 100 grit alumina at 80 psi air pressure.
3. Blast sandblasted surfaces with dry filtered nitrogen gas at 80 psi for 30 seconds to remove debris.
4. Ultrasonic clean in 1,1,1, Trichloroethane (TCE) for 30 minutes.
5. Vapor degrease with TCE. Chips are held over simmering TCE until liquid condenses on chips and is flowing freely off of the surface (1-2 minutes).
6. Load the mold within a few hours of vapor degreasing.

Specimen Configuration and Fabrication

Fabrication of through thickness tension specimens is nearly identical to fabrication of the shear/compression specimens described previously. The major difference is that the metal specimen parts are longer, and have a hole drilled in them to accommodate the tension clevises. The mold used for specimen fabrication is also thicker to accommodate the greater specimen length. Both prepreg and resin transfer molding fabrication techniques may be used with this specimen configuration. All insulation systems were fabricated to a nominal glass volume fraction of 0.50. The through thickness tension specimen is illustrated in the following sketch.



Test Method

In order to minimize bending and ensure alignment of the specimens, the load train included a universal joint above the specimen, and a spherical nut below the specimen to couple to the cryostat. The specimens were attached to the clevises using hardened steel pins. The entire assembly was immersed in liquid nitrogen and allowed to equilibrate before testing. Tension loading was applied to the specimen at a constant displacement rate of 0.004 in/min to failure. Upon completion of each test, the specimen failure surfaces were examined to determine the primary failure mode.

Through Thickness Tension Specimen Layup and Cure Schedules

Run #	Resin System	Fabric style	Barrier	Layup	Cure schedule
TT1A	Shell 826	3d	None	3d/3d/3d/3d	4 h at 150°C
TT1B	Shell 826	6781	None	g/g/g/g/g/g	4 h at 150°C
TT2A	CTD-112P	6781	Kapton (4)	pp/k/pp/k/pp/k/pp/k/pp/pp	2 h at 177°C + 7 h at 200°C
TT2B	CTD-112PF	6580	Kapton (4)	pp/k/pp/k/pp/k/pp/k/pp/pp/pp/pp	2 h at 177°C + 7 h at 200°C
TT2C	CTD-112P	6781	Kapton (4)	pp/pp/pp/pp/pp/pp	2 h at 177°C + 7 h at 200°C
TT3A	CTD-112P	6781	Kapton (4)	pp/k/pp/k/pp/k/pp/k/pp/pp	2 h at 177°C + 7 h at 200°C
TT3B	CTD-112PF	6580	Kapton (4)	pp/k/pp/k/pp/k/pp/k/pp/pp/pp/pp	2 h at 177°C + 7 h at 200°C
TT3C	CTD-112P	6781	Kapton (4)	pp/pp/pp/pp/pp/pp	2 h at 177°C + 7 h at 200°C
TT4A	Shell 826	3d	None	3d/3d/3d/3d	4 h at 150°C
TT4B	Shell 826	6781	None	g/g/g/g/g/g	4 h at 150°C

Notes:
g - 8-harness satin glass fabric of specified style
k - Kapton 100HA
pp - prepreg of specified resin and fabric style
3d - TTI 3-dimensional weave fabric
CTD-112PF is a filled version of CTD-112PF, which contains 5% by volume of alumina

Data summary 6/23/95

TPX THROUGH THICKNESS TENSION DATA SUMMARY						
Run				Strength	Standard	Coefficient of
No.	Reinforcement	Resin System	Barrier	Average	Deviation	Variation
				(MPa)		
TT1A	TTI 3-d weave	Shell 826	None	52.5	6.7	0.13
TT1B	6781 8-h	Shell 826	None	57.3	2.5	0.04
TT2A	6781 8-h	CTD-112P	Kapton 200HA	29.5	10.2	0.35
TT2B	6580 8-h	CTD-112PF	Kapton 200HA	37.7	9.6	0.25
TT2C	6781 8-h	CTD-112P	None	28.2	1.0	0.04
TT3A	6781 8-h	CTD-112P	Kapton 200HA	20.1	7.9	0.39
TT3B	6580 8-h	CTD-112PF	Kapton 200HA	27.5	9.1	0.33
TT3C	6781 8-h	CTD-112P	None	24.4	3.7	0.15
TT4A	TTI 3-d weave	Shell 826	None	46.4	6.7	0.14
TT4B	6781 8-h	Shell 826	None	63.1	8.1	0.13

TPX THROUGH THICKNESS TENSION

Resin System: **Shell 826/HY906/DY062**
Reinforcement: **TTI 3-d weave**

Material Reference: TT1A

Test Date: 6/7/95 Test temperature: 76K

Specimen Number	Diameter (in)	Area (in^2)	Ultimate Load (lbs)	Tensile Strength (psi)	Tensile Strength (MPa)	Failure Mode
A1	0.498	0.1948	1430	7342	50.62	C
A2	0.498	0.1948	1693	8692	59.93	C
A3	0.498	0.1948	1326	6808	46.94	C
A4	0.498	0.1948	980	5031	34.69	C
A5	0.498	0.1948	1085	5570	38.41	CM

Average:	6689	46.12
Std. Dev.:	1453	10.02
Cv:	0.22	0.22

Statistics without A4 and A5:

Average:	7614	52.50
Std. Dev.:	971	6.70
Cv:	0.13	0.13

Failure Modes
C - Cohesive within composite
CM - Cohesive near metal interface. Resin adhered to metal.

Tested By: Date: 6/7/95
Analyzed By: Date: 6/12/95
Checked By: Date: 6/13/95

TPX THROUGH THICKNESS TENSION

Resin System: **Shell 826/HY906/DY062**
Reinforcement: **6781 8-harness satin**

Material Reference: TT1B

Test Date: 6/7/95 Test temperature: 76K

Specimen Number	Diameter (in)	Area (in^2)	Ultimate Load (lbs)	Tensile Strength (psi)	Tensile Strength (MPa)	Failure Mode
B1	0.498	0.1948	1659	8517	58.73	C
B2	0.498	0.1948	1558	7999	55.15	C
B3	0.498	0.1948	1599	8209	56.60	C
B4	0.498	0.1948	1723	8846	60.99	C
B5	0.498	0.1948	1560	8009	55.22	C

Average:	8316	57.34
Std. Dev.:	363	2.50
Cv:	0.04	0.04

Failure Modes
C - Cohesive within composite
CM - Cohesive near metal interface. Resin adhered to metal.

Tested By: Date: 6/7/95
Analyzed By: Date: 6/12/95
Checked By: Date: 6/13/95

TPX THROUGH THICKNESS TENSION

Resin System: **CTD-112P**
Reinforcement: **6781 8-harness satin**
Barrier: **Kapton 200 HA (4 plies)**

Material Reference: TT2A

Test Date: 6/12/95 Test temperature: 76K

Specimen Number	Diameter (in)	Area (in^2)	Ultimate Load (lbs)	Tensile Strength (psi)	Tensile Strength (MPa)	Failure Mode
A1	0.498	0.1948	1099	5642	38.90	AK
A2	0.498	0.1948	784	4025	27.75	AK
A3	0.498	0.1948	703	3609	24.89	AK
A4	0.498	0.1948	442	2269	15.65	AK
A5	0.498	0.1948	1135	5827	40.18	AK

Average:	4275	29.47
Std. Dev.:	1484	10.23
Cv:	0.35	0.35

Failure Modes
C - Cohesive within composite
CM - Cohesive near metal interface. Resin adhered to metal.
AK - Adhesive failure at Kapton interface

Tested By: JBS **Date:** 6/12/95
Analyzed By: JBS **Date:** 6/12/95
Checked By: PEZ **Date:** 6/13/95

TPX THROUGH THICKNESS TENSION

Resin System: **CTD-112PF (with alumina filler)**
Reinforcement: **6580 8-harness satin (7 mil)**
Barrier: **Kapton 200 HA (4 plies)**

Material Reference: TT2B

Test Date: 6/12/95 Test temperature: 76K

Specimen Number	Diameter (in)	Area (in^2)	Ultimate Load (lbs)	Tensile Strength (psi)	Tensile Strength (MPa)	Failure Mode
B1	0.498	0.1948	842	4323	29.81	AK
B2	0.498	0.1948	988	5072	34.97	AK
B3	0.498	0.1948	830	4261	29.38	AK
B4	0.498	0.1948	1189	6104	42.09	AK
B5	0.498	0.1948	1471	7552	52.07	C

Average:	5463	37.66
Std. Dev.:	1385	9.55
Cv:	0.25	0.25

Failure Modes
C - Cohesive within composite
CM - Cohesive near metal interface. Resin adhered to metal.
AK - Adhesive failure at Kapton interface

Tested By: JBS Date: 6/12/95
Analyzed By: JBS Date: 6/12/95
Checked By: PEF Date: 6/13/95

TPX THROUGH THICKNESS TENSION

Resin System: CTD-112P
Reinforcement: 6781 8-harness satin
Barrier: None

Material Reference: TT2C

Test Date: 6/12/95 Test temperature: 76K

Specimen Number	Diameter (in)	Area (in^2)	Ultimate Load (lbs)	Tensile Strength (psi)	Tensile Strength (MPa)	Failure Mode
B6	0.498	0.1948	804	4128	28.46	C
B7	0.498	0.1948	821	4215	29.06	C
B8	0.498	0.1948	765	3927	27.08	C

Average:	4090	28.20
Std. Dev.:	147	1.02
Cv:	0.04	0.04

Failure Modes
C - Cohesive within composite
CM - Cohesive near metal interface. Resin adhered to metal.
AK - Adhesive failure at Kapton interface

Tested By: JES Date: 6/12/95
Analyzed By: JES Date: 6/12/95
Checked By: PEZ Date: 6/13/95

TPX THROUGH THICKNESS TENSION

Resin System: **CTD-112P**
Reinforcement: **6781 8-harness satin**
Barrier: **Kapton 200 HA (4 plies)**

Material Reference: TT3A

Test Date: 6/22/95 Test temperature: 76K

Specimen Number	Diameter (in)	Area (in^2)	Ultimate Load (lbs)	Tensile Strength (psi)	Tensile Strength (MPa)	Failure Mode
A1	0.498	0.1948	510	2618	18.05	AK
A2	0.498	0.1948	368	1889	13.03	AK
A3	0.498	0.1948	520	2670	18.41	AK
A4	0.498	0.1948	952	4888	33.70	AK
A5	0.498	0.1948	412	2115	14.58	AK
A6	0.498	0.1948	502	2577	17.77	AK
A7	0.498	0.1948	402	2064	14.23	AK
A8	0.498	0.1948	886	4549	31.36	AK

Average:	2921	20.14
Std. Dev.:	1149	7.92
Cv:	0.39	0.39

Failure Modes
C - Cohesive within composite
CM - Cohesive near metal interface. Resin adhered to metal.
AK - Adhesive failure at Kapton interface

Tested By: **Date:** 6/22/95
Analyzed By: **Date:** 6/23/95
Checked By: **Date:** 6/23/95

TPX THROUGH THICKNESS TENSION

Resin System: **CTD-112PF (with alumina filler)**
Reinforcement: **6580 8-harness satin (7 mil)**
Barrier: **Kapton 200 HA (4 plies)**

Material Reference: TT3B

Test Date: 6/22/95 Test temperature: 76K

Specimen Number	Diameter (in)	Area (in^2)	Ultimate Load (lbs)	Tensile Strength (psi)	Tensile Strength (MPa)	Failure Mode
B1	0.498	0.1948	784	4025	27.75	AK
B2	0.498	0.1948	526	2700	18.62	AK
B3	0.498	0.1948	564	2896	19.96	AK
B4	0.498	0.1948	1162	5966	41.13	AK
B5	0.498	0.1948	846	4343	29.95	AK

Average:	3986	27.48
Std. Dev.:	1312	9.05
Cv:	0.33	0.33

Failure Modes
C - Cohesive within composite
CM - Cohesive near metal interface. Resin adhered to metal.
AK - Adhesive failure at Kapton interface

Tested By: [signature] **Date:** 6/22/95

Analyzed By: [signature] **Date:** 6/23/95

Checked By: [signature] **Date:** 6/27/95

TPX THROUGH THICKNESS TENSION

Resin System: **CTD-112P**
Reinforcement: **6781 8-harness satin**
Barrier: **None**

Material Reference: TT3C

Test Date: 6/22/95 Test temperature: 76K

Specimen Number	Diameter (in)	Area (in^2)	Ultimate Load (lbs)	Tensile Strength (psi)	Tensile Strength (MPa)	Failure Mode
B6	0.498	0.1948	586	3008	20.74	C
B7	0.498	0.1948	796	4087	28.18	C
B8	0.498	0.1948	682	3501	24.14	C

Average:	3532	24.35
Std. Dev.:	540	3.72
Cv:	0.15	0.15

Failure Modes
C - Cohesive within composite
CM - Cohesive near metal interface. Resin adhered to metal.
AK - Adhesive failure at Kapton interface

Tested By: [signature] **Date:** 6/22/95
Analyzed By: [signature] **Date:** 6/23/95
Checked By: [signature] **Date:** 6/23/95

TPX THROUGH THICKNESS TENSION

Resin System: **Shell 826/HY906/DY062**
Reinforcement: **TTI 3-d weave**

Material Reference: TT4A

Test Date: 6/22/95 Test temperature: 76K

Specimen Number	Diameter (in)	Area (in^2)	Ultimate Load (lbs)	Tensile Strength (psi)	Tensile Strength (MPa)	Failure Mode
A1	0.498	0.1948	1192	6120	42.20	C
A3	0.498	0.1948	1278	6561	45.24	C
A4	0.498	0.1948	1278	6561	45.24	C
A5	0.498	0.1948	1166	5986	41.27	C
A6	0.498	0.1948	1634	8389	57.84	C

Average:	6723	46.36
Std. Dev.:	966	6.66
Cv:	0.14	0.14

Failure Modes
C - Cohesive within composite
CM - Cohesive near metal interface. Resin adhered to metal.

Tested By: **Date:** 6/22/95
Analyzed By: **Date:** 6/23/95
Checked By: **Date:** 6/29/95

Composite Technology Development, Inc.

TPX THROUGH THICKNESS TENSION

Resin System: **Shell 826/HY906/DY062**
Reinforcement: **6781 8-harness satin**

Material Reference: TT4B

Test Date: 6/22/95 Test temperature: 76K

Specimen Number	Diameter (in)	Area (in^2)	Ultimate Load (lbs)	Tensile Strength (psi)	Tensile Strength (MPa)	Failure Mode
B1	0.498	0.1948	1396	7167	49.42	C
B2	0.498	0.1948	1848	9488	65.42	C
B3	0.498	0.1948	1796	9221	63.58	C
B4	0.498	0.1948	1988	10206	70.37	C
B5	0.498	0.1948	1890	9703	66.90	C

Average:	9157	63.14
Std. Dev.:	1170	8.07
Cv:	0.13	0.13

Failure Modes
C - Cohesive within composite
CM - Cohesive near metal interface. Resin adhered to metal.

Tested By: [signature] **Date:** 6/22/9

Analyzed By: [signature] **Date:** 6/23/95

Checked By: [signature] **Date:** 6/23/95

COMPOSITE TECHNOLOGY DEVELOPMENT, INC.
2400 Central Avenue, Suite H • Boulder, Colorado 80301
Phone: (303) 447-2226 • Fax: (303) 447-0140

TPX Shear/Compression Testing
Final Report

Prepared for
Westinghouse Science and Technology Center
1310 Beulah Rd.
Pittsburgh PA 15235

July 7, 1995

James B. Schutz
Engineer

Paul E. Fabian
Engineer

Summary

Shear/compression specimens were fabricated using the insulation systems described in the attached specimen matrix. Shear/compression tests at 15°, 45°, and 75° were performed on specimens from each system. Materials included Shell 826 and CTD-101K vacuum impregnation resins, and a hybrid prepreg/vacuum impregnation CTD-112P/CTD-101K combination. Reinforcements included 6781 8-harness satin, plain and 3-dimensional weave fabric provided by the customer; all reinforcements were woven from S-2 glass. Electrical barriers included Kapton HA, G-11CR, AV 1580, and CTD-101G.

Specimen preparation, layup, and cure information are also discussed. A summary and brief synopsis of the test data for each phase of the program are also included. Test data sheets for each insulation system are attached.

TPX Shear/Compression Specimen Matrix, Layups, and Cure Cycles

	Chip Run	Resin System	Fabric Style	Metal	Barrier	Layup	Cure Cycle	Test Angle (°)	Number of Tests
1A	143A	CTD-101K	Satin	316	Kapton (1)	g/g/g/k/g/g/g/	1.5 h at 135°C	15	2
								45	2
								75	1
1B	143B	CTD-101K	Satin	908	Kapton (1)	g/g/g/k/g/g/g/	1.5 h at 135°C	15	2
								45	2
								75	1
1C	143C	CTD-101K	Satin	908	G10CR	g/g/g/G10/g/g	1.5 h at 135°C	15	1
								45	1
								75	1
2A	145A	CTD-1PFS/ Shell 826	Satin	316	Kapton (4)	pf/k/pf/k/g/g/k/pf/k/pf	4 h at 150°C + 2 h at 177°C	15	2
								45	2
								75	1
2B	145B	Shell 826	Satin	908	Kapton (1)	g/g/g/k/g/g/g/	4 h at 150°C	15	2
								45	2
								75	1
2C	145C	Shell 826	Satin	908	G10CR	g/g/g/G10/g/g	4 h at 150°C	15	1
								45	1
								75	1
3A	142A	CTD-112P	Satin	316	Kapton (4)	pp/k/pp/k/pp/k/pp/k/pp/pp	2 h at 177°C + 7 h at 200°C	15	2
								45	2
								75	1
3B	142B	CTD-112P	Satin	908	Kapton (4)	pp/k/pp/k/pp/k/pp/k/pp/pp	2 h at 177°C + 7 h at 200°C	15	2
								45	2
								75	1
4A	141A	CTD-101K	Satin	316	Kapton (4)	g/k/g/k/g/k/g/k/g/g	1.5 h at 135°C	15	2
								45	2
								75	1
4B	141B	CTD-101K	Satin	908	Kapton (4)	g/k/g/k/g/k/g/k/g/g	1.5 h at 135°C	15	2
								45	2
								75	1
5A	144A	CTD-112P/ CTD-101K	Satin	316	Kapton (4)	pp/k/pp/k/g/g/k/pp/k/pp	2 h at 177°C + 7 h at 200°C	15	2
								45	2
								75	1
5B	144B	CTD-112P/ CTD-101K	Satin	908	Kapton (4)	pp/k/pp/k/g/g/k/pp/k/pp	2 h at 177°C + 7 h at 200°C	15	2
								45	2
								75	1

g - 6781 8-harness satin glass fabric
k - Kapton 100HA
G11 - G-11CR
pp - CTD-112P/6781 prepreg
pf - CTD-1PFS/6781 prepreg
3d - TTI 3-dimensional weave fabric
p - TTI plain weave fabric

TPX Shear/Compression Specimen Matrix, Layups, and Cure Cycles

	Chip Run	Resin System	Fabric Style	Metal	Barrier	Layup	Cure Cycle	Test Angle (°)	Number of Tests
6A	160A	CTD-101K	Satin	316	Kapton (4)	g/k/g/k/g/k/g/k/g/g	1.5 h at 135°C	15 45 75	3 3 1
6B	161A	CTD-112P/ CTD-101K	Satin	316	Kapton (4)	pp/k/pp/k/g/g/k/pp/k/pp	2 h at 177°C + 7 h at 200°C	15 45 75	3 3 1
7A	159A	Shell 826	Satin	316	Kapton (4)	g/k/g/k/g/k/g/k/g/g	4 h at 150°C	15 45 75	3 3 1
7B	162A	CTD-112P/ Shell 826	Satin	316	Kapton (4)	pp/k/pp/k/g/g/k/pp/k/pp	2 h at 177°C + 7 h at 200°C	15 45 75	3 3 1
8A	160B	CTD-101K	Satin	316	G11CR(1)	g/g/G11/g/g	1.5 h at 135°C	15 45 75	3 3 1
8B	164A	CTD-101K	3-D weave	316	None	3d/3d/3d/3d	1.5 h at 135°C	15 45 75	3 3 1
8C	164B	CTD-101K	Plain	316	Kapton (4)	p/p/k/p/k/p/k/p/k/p/p/p	1.5 h at 135°C	15 45 75	3 3 1
9A	159B	Shell 826	Satin	316	G11CR(1)	g/g/G11/g/g	4 h at 150°C	15 45 75	3 3 1
9B	163A	Shell 826	3-D weave	316	None	3d/3d/3d/3d	4 h at 150°C	15 45 75	3 3 1
9C	163B	Shell 826	Plain	316	Kapton (4)	p/p/k/p/k/p/k/p/k/p/p/p	4 h at 150°C	15 45 75	3 3 1
10A	165A	Shell 826	Satin	316	CTD-101G	g/101G/g	4 h at 150°C	15 45 75	3 3 1
10B	165B	Shell 826	Satin	316	AV 1580	g/AV1580/g	4 h at 150°C	15 45 75	3 3 1

NOTE: 8B, 8C, 9B, AND 9C were originally to be tested at two angles only. Two additional fabrication runs were performed, and full characterization at all three angles was done. Testing against dummy specimens was not require as had been originally proposed.

g - 6781 8-harness satin glass fabric
k - Kapton 100HA
G11 - G-11CR
pp - CTD-112P/6781 prepreg
pf - CTD-1PFS/6781 prepreg
3d - TTI 3-dimensional weave fabric
p - TTI plain weave fabric

Shear/Compression Specimen Preparation

Metal Cleaning and Preparation

The following procedure was used for the preparation of the 316 stainless steel chips.

1. Ultrasonic clean in 1,1,1, Trichloroethane (TCE) for 30 minutes.
2. Sandblast such that a uniform matte finish appears on all chips using 100 grit alumina.
3. Blast sandblasted surfaces with dry nitrogen gas at 80 psi for 30 seconds to remove debris.
4. Ultrasonic clean in 1,1,1, Trichloroethane (TCE) for 30 minutes.
5. Vapor degrease with TCE. Chips are held over simmering TCE until liquid condenses on chips and is flowing freely off of the surface.
6. Load the mold within a few hours of vapor degreasing.

G-11CR Cleaning and Preparation

1. Ultrasonic clean in 1,1,1, Trichloroethane (TCE) for 3-5 minutes.
2. Sandblast very lightly such that a uniform matte finish appears on all chips using 100 grit alumina.
3. Blast sandblasted surfaces with dry filtered nitrogen gas at 80 psi for 30 seconds to remove debris.
4. Ultrasonic clean in 1,1,1, Trichloroethane (TCE) for 3-5 minutes.
5. Vapor degrease with TCE. Chips are held over simmering TCE until liquid condenses on chips and is flowing freely off of the surface.
6. Load the mold within a few hours of vapor degreasing.

CTD-101G and AV-1580 Cleaning and Preparation

1A. CTD-101G was molded in 0.125 in thick plates, and cured for 1.5 hours at 135°C.

1B. AV-1580 was molded in plates, approximately 0.125 in thick, and cured at room temperature for 24 hours. A post-cure of 4 hours at 80°C was applied to assure complete cure.

2. Disks were machined from cured plates, 0.498 in diameter, 0.030 in thick.
3. Ultrasonic clean in 1,1,1, Trichloroethane (TCE) for 3-5 minutes.
4. Sandblast very lightly such that a uniform matte finish appears on all chips using 100 grit alumina.
5. Blast sandblasted surfaces with dry nitrogen gas at 80 psi for 30 seconds to remove debris.
6. Ultrasonic clean in 1,1,1, Trichloroethane (TCE) for 3-5 minutes.
7. Vapor degrease with TCE. Chips are held over simmering TCE until liquid condenses on chips and is flowing freely off of the surface.
8. Load the mold within a few hours of vapor degreasing.

Synopsis of TPX shear/compression test data

The TPX shear compression test program was performed in two phases, with a reevaluation of some specimens from the Phase I specimens which had been held in reserve. This was because of a possible misalignment of test fixturing during the initial phase of the program. A retest of the reserve specimens was intended to show if gross differences in the test data occurred, which could be attributed to the aforementioned misalignment.

The Phase I program was intended to highlight systematic differences in shear/compression strengths attributable to metal substrates, resins, and several barriers. Therefore, discussion of the data is presented in a more systematic fashion. The specific comparisons are discussed for the retest data. Phase II was intended to provide more direct comparisons between specific insulation systems, and these data are discussed on an individual basis.

Discussion of Phase I data (1A through 5B)

Most of the tests with G-10CR barrier layers resulted in adhesive failure at the metal interface. This is very unusual in our experience with this test specimen. One possible explanation is the presence residual mold release on the G-10CR from the lamination process, which may have migrated during the processing of the specimen. The G-10CR was thoroughly cleaned and sandblasted prior to use, but mold release agents are notorious for being difficult to remove, and for migrating where they are not wanted. The limited viable data which was obtained with the G-10CR suggest that this system is stronger than hybrids with the Kapton, as long as good adhesion to the barrier laminate is obtained.

One specimen from Run 4A failed at about half the strength of the other replicates. If this data point is neglected, the strength of the multiple Kapton/CTD-101K/316 system is 117 MPa, which is comparable to data for the corresponding system on Incoloy 908.

The strengths for the CTD-112P/Kapton systems are lower than the CTD-112P/CTD-101K/Kapton hybrid and the CTD-101K/Kapton systems. These strengths are lower than previous data on similar systems.

Metal

There is no difference in strengths when the 316 stainless and the Incoloy 908 are used. This is as expected, since the failures are almost exclusively in the composite or in the barrier, for all insulation systems.

Resin

We have had only a very limited amount of experience with VPI systems combined with Kapton. The strengths for the Shell 826 appear to be higher than comparable CTD-101K data. Previous tests with these two systems, but without the Kapton, showed no strength differences. It is possible that this difference with the Kapton could be attributable to improved adhesion of the 826 over the CTD-101K to the polyimide film.

The strengths of the hybrid prepreg/VPI systems are approximately equivalent. These strengths are intermediate between the previous CTD-101K and CTD-112P data. Apparently, the more severe cure cycle of the CTD-112P system, 200°C as opposed to 135°C, did not significantly degrade the properties of the CTD-101K.

TPX Shear/Compression Data Summary

	Chip Run	Resin System	Fabric Style	Metal	Barrier	Test Angle (°)	Shear Strength (MPa)	Std. Dev. (MPa)	Compr. Strength (MPa)	Std. Dev. (MPa)	Failure Mode	
1A	143A	CTD-101K	Satin	316	Kapton (1)	15	90.6	0.1	24.3	0.0	C/K	
						45	108.9	25.7	108.8	25.7	C/K	
						75	158.5		591.4		C/K	
1B	143B	CTD-101K	Satin	908	Kapton (1)	15	75.1	6.4	20.1	1.7	C/K,A/K	
						45	99.3	10.4	99.3	10.4	C/K	
						75	150.5		561.4		C/K	
1C	143C	CTD-101K	Satin	908	G10CR	15	28.6		7.7		A/M	1
						45	28.6		28.6		A/M	1
						75	255.4		952.8		C	
2A	145A	CTD-1PFS/ Shell 826	Satin	316	Kapton (4)	15	87.8	7.7	23.5	2.1	C/K	
						45	128.3	10.4	128.3	10.4	C/K	
						75	146.5		546.6		C/K	
2B	145B	Shell 826	Satin	908	Kapton (1)	15	99.0	3.5	26.5	0.9	C/K	
						45	158.0	3.8	158.0	3.8	C/K	
						75	183.8		685.7		C/K	
2C	145C	Shell 826	Satin	908	G10CR	15	0.0		0.0		A/M	1
						45	173.0		173.0		C	
						75	263.3		982.1		C	
3A	142A	CTD-112P	Satin	316	Kapton (4)	15	52.3	0.6	14.0	0.1	C/K	
						45	68.8	8.0	68.8	8.0	A/K,C/K	
						75	76.7		286.1		C/K	
3B	142B	CTD-112P	Satin	908	Kapton (4)	15	53.8	3.4	14.4	0.9	A/K	
						45	58.8	5.1	58.8	5.1	A/K	
						75	81.2		302.8		C/K	
		RETEST reserve specimens				**45**	**82.6**	**4.0**	**82.6**	**4.0**	C/K	
4A	141A	CTD-101K	Satin	316	Kapton (4)	15	50.7	7.2	13.6	1.9	C/K	
						45	88.2	41.6	88.1	41.6	A/K	2
						75	137.3		512.1		C/K	
4B	141B	CTD-101K	Satin	908	Kapton (4)	15	55.4	8.1	14.9	2.2	A/K	
						45	105.9	2.4	105.9	2.4	C/K	
						75	135.2		504.5		C/K	
		RETEST reserve specimens				**45**	**120.5**	**11.7**	**120.5**	**11.7**	C/K	
5A	144A	CTD-112P/ CTD-101K	Satin	316	Kapton (4)	15	70.9	0.8	19.0	0.2	A/K	
						45	139.9	1.3	139.8	1.3	A/K	
						75	137.6		513.2		C/K	
5B	144B	CTD-112P/ CTD-101K	Satin	908	Kapton (4)	15	80.7	6.9	21.6	1.8	C,C/K	
						45	133.0	4.5	133.0	4.5	C/K,A/K	
						75	133.7		498.7		A/K	
		RETEST reserve specimens				**45**	**133.1**	**9.2**	**133.1**	**9.2**	C/K,A/K	

Notes:

1. Adhesive failures at metal are highly unusual, and render data suspect.
2. One specimen failed low. Ignoring that data point, strength is 117 MPa.

TPX Shear/Compression Data Summary

	Chip Run	Resin System	Fabric Style	Metal	Barrier	Test Angle (°)	Shear Strength (MPa)	Std. Dev. (MPa)	Compr. Strength (MPa)	Std. Dev. (MPa)	Failure Mode
6A	160A	CTD-101K	Satin	316	Kapton (4)	15	59.2	10.4	15.9	2.8	A/K
						45	122.5	4.3	122.5	4.3	A/K, C/K
						75	131.4		490.0		C/K
6B	161A	CTD-112P/ CTD-101K	Satin	316	Kapton (4)	15	31.4	3.8	8.4	1.0	A/K
						45	102.5	4.7	102.5	4.7	C/K
						75	120.5		449.6		A/K
7A	159A	Shell 826	Satin	316	Kapton (4)	15	84.4	11.8	22.6	3.2	C/K, A/K
						45	144.0	6.3	144.0	6.3	C/K, A/K
						75	147.2		549.1		A/K
7B	162A	CTD-112P/ Shell 826	Satin	316	Kapton (4)	15	44.7	7.3	12.0	2.0	A/K
						45	106.2	11.2	106.2	11.2	C/K
						75	123.3		460.0		C/K
8A	160B	CTD-101K	Satin	316	G11CR(1)	15	104.1	16.5	27.9	4.4	C,G,AM
						45	180.9	3.3	180.9	3.3	C,C,G
						75	271.1		1011.3		C,G
8B	164A	CTD-101K	3-D weave	316	None	15	82.1	15.2	22.0	4.1	C, AM
						45	172.5	1.3	172.4	1.3	C, AM
						75	253.0		943.7		C
8C	164B	CTD-101K	Plain	316	Kapton (4)	15	8.5	2.1	2.3	0.6	A/K
						45	28.0	5.1	28.0	5.1	A/K
						75	132.5		494.2		A/K
9A	159B	Shell 826	Satin	316	G11CR(1)	15	110.2	20.1	29.5	5.4	C, C,G
						45	184.6	1.2	184.5	1.2	C
						75	252.8		943.1		C,G
9B	163A	Shell 826	3-D weave	316	None	15	63.7	9.1	17.1	2.4	C,AM
						45	173.4	3.2	173.4	3.2	C
						75	244.9		913.6		C
9C	163B	Shell 826	Plain	316	Kapton (4)	15	47.1	10.2	12.6	2.7	A/K
						45	111.4	7.8	111.4	7.8	A/K
						75	145.5		542.9		C/K
10A	165A	Shell 826	Satin	316	CTD-101G	15	87.8	22.3	23.5	6.0	B,AB,C,AM
						45	154.6	8.2	154.6	8.2	B
						75	226.6		845.2		B,C
10B	165B	Shell 826	Satin	316	AV 1580	15	64.7	4.6	17.3	1.2	B
						45	109.5	4.7	109.5	4.7	B
						75	196.3		732.2		B,C

Failure Modes:

A/M-Adhesive failure at the metal

A/K-Adhesive failure at the Kapton

C-Cohesive failure in the composite

C/K-Cohesive failure in the Kapton, tearing of the Kapton

C,AM-Failure located at metal interface; epoxy adhering to surface; some composite damage

A/B - Adhesive failure at the Barrier

B - Breakage/cohesive failure in the barrier

Synopsis of TPX shear/compression test data

The TPX shear compression test program was performed in two phases, with a reevaluation of some specimens from the Phase I specimens which had been held in reserve. This was because of a possible misalignment of test fixturing during the initial phase of the program. A retest of the reserve specimens was intended to show if gross differences in the test data occurred, which could be attributed to the aforementioned misalignment.

The Phase I program was intended to highlight systematic differences in shear/compression strengths attributable to metal substrates, resins, and several barriers. Therefore, discussion of the data is presented in a more systematic fashion. The specific comparisons are discussed for the retest data. Phase II was intended to provide more direct comparisons between specific insulation systems, and these data are discussed on an individual basis.

Discussion of Phase I data (1A through 5B)

Most of the tests with G-10CR barrier layers resulted in adhesive failure at the metal interface. This is very unusual in our experience with this test specimen. One possible explanation is the presence residual mold release on the G-10CR from the lamination process, which may have migrated during the processing of the specimen. The G-10CR was thoroughly cleaned and sandblasted prior to use, but mold release agents are notorious for being difficult to remove, and for migrating where they are not wanted. The limited viable data which was obtained with the G-10CR suggest that this system is stronger than hybrids with the Kapton, as long as good adhesion to the barrier laminate is obtained.

One specimen from Run 4A failed at about half the strength of the other replicates. If this data point is neglected, the strength of the multiple Kapton/CTD-101K/316 system is 117 MPa, which is comparable to data for the corresponding system on Incoloy 908.

The strengths for the CTD-112P/Kapton systems are lower than the CTD-112P/CTD-101K/Kapton hybrid and the CTD-101K/Kapton systems. These strengths are lower than previous data on similar systems.

Metal

There is no difference in strengths when the 316 stainless and the Incoloy 908 are used. This is as expected, since the failures are almost exclusively in the composite or in the barrier, for all insulation systems.

Resin

We have had only a very limited amount of experience with VPI systems combined with Kapton. The strengths for the Shell 826 appear to be higher than comparable CTD-101K data. Previous tests with these two systems, but without the Kapton, showed no strength differences. It is possible that this difference with the Kapton could be attributable to improved adhesion of the 826 over the CTD-101K to the polyimide film.

The strengths of the hybrid prepreg/VPI systems are approximately equivalent. These strengths are intermediate between the previous CTD-101K and CTD-112P data. Apparently, the more severe cure cycle of the CTD-112P system, 200°C as opposed to 135°C, did not significantly degrade the properties of the CTD-101K.

Single versus Multiple Kapton layers

The strength for systems with multiple plies of Kapton are slightly lower than specimens with a single ply. This is attributable to the statistical effect of multiple interfaces, each with an associated strength distribution. More interfaces would have a slightly higher probability of failure at a lower stress level.

Discussion of Phase I Reserve Retest Data (3B, 4B, and 5B)

The 3B retest specimens (CTD-112P/Kapton) tested higher than the original test series, but do not match the ITER Characterization report CTD-112P data, which has a strength of 140 MPa in the 45° test. It is recommended that the ITER characterization program data be used, rather than performing a new set of tests on this material. The ITER specimens were identical to current specimens, except that there were three plies of Kapton 100 HA, rather than four. This data has been confirmed by multiple test series.

Retests on the 4B reserve specimens (CTD-101K/Kapton) were slightly higher than the original test series. Since this is one of the impregnation systems of particular interest, it was recommended that this system be evaluated in a later phase of the program. As there was no independent confirmation of the Shell 826 data, and the comparison between this system and the CTD-101K is of special interest, it was also recommended that the Shell 826 be evaluated in a later phase of the program.

The data from retests of 5B reserve specimens (hybrid CTD-112P/CTD-101K) are identical to the previous tested data.

Discussion of Phase II Data (6A through 10B)

6A (160A) - CTD-101K/Kapton
Almost identical to previous data (4B), including 4B retests. Slightly higher than CTD-112P/Kapton 100HA

6B (161A) - CTD-101K/CTD-112P/Kapton
Lower than previous CTD-101K/CTD-112P/Kapton results. Identical results from another run (number 157, not reported here).
Approximately equivalent to current Shell 826/CTD-112P results.

7A (159A) - Shell 826/Kapton
Slightly lower than previous data series.

7B (162A) - Shell 826/CTD-112P/Kapton
Lower than previous CTD-101K/CTD-112P/Kapton data. Much lower than Shell 826/Kapton 100HA data. Approximately equivalent to current CTD-101K/CTD-112P results.

8A (160B) - CTD-101K/G-11CR
Much better than previous results with G-10; no significant adhesive metal failures. Equivalent to CTD-101K data with no barriers.

8B (164A) - CTD-101K/3-d weave
Equivalent to CTD-101K/6781, except at 15° where CTD-101K/6781 is higher.

Equivalent to Shell 826/3-d weave.

8C (164B) - CTD-101K/plain weave/Kapton
Lower than Shell 826/plain weave/Kapton. Lower than CTD-101K/6781/Kapton except at 75°. Lowest strength in this test series. Low values at 15° and 45° not consistent with previous and expected values.

9A (159B) - Shell 826/G-11CR
Better than previous results with G-10; no significant adhesive metal failures. Equivalent to CTD-101K data with no barriers.

9B (163A) - Shell 826/3-d weave
Equivalent to previous Shell 826/6781 data (from characterization report) except lower at 15°. Failures for 15° tests occurred at metal interface, however the presence of epoxy on the metal surface indicates that the failure was not completely adhesive. There was also some damage in the composite.

9C (163B) - Shell 826/plain weave/Kapton
Lower than Shell 826/6781/Kapton 100HA except approximately equivalent at 75°. Higher than CTD-101K/Plain weave/Kapton except at 75°.

10A (165A) - Shell 826/CTD-101G
Equivalent to or better than Shell 826 with Kapton barrier. Lower than Shell 826 with no barrier, or with G-11CR barrier. Higher than equivalent system with AV-1580 barrier.

10B (165B) - Shell 826/AV-1580
Lower than Shell 826 with no barrier, Kapton barrier, or with G-11CR barrier.
Lower than equivalent system with CTD-101G barrier.

TPX Shear/Compression Test Results

Resin System: CTD-101K
Reinforcement: S-2 Glass - 6781 Condition: AR
Barrier: Kapton HA (1 ply of 1 mil)
Specimen Type: S/C - Stainless Steel Chips 316LN
Material Reference #: Batch #1 - Run #143

Load Rate: 0.0018 mm/s

Test Fixture: 15° Test Temperature: 76K
Test Date: 12/20/94

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
1A2-1	15	B1	A2	T	8.20	11.8	12.65	90.6	24.3	C/K
1A2-2	15	A1	A2	B	8.18	11.7	12.62	90.5	24.3	C/K

SHEAR STRENGTH

AVERAGE (MPa): 90.6
STD.DEV. (MPa): 0.1
CV: 0.00

COMPRESSIVE STRENGTH

AVERAGE (MPa): 24.3
STD.DEV. (MPa): 0.0
CV: 0.00

Test Fixture: 45° Test Temperatue: 76K
Test Date: 12/19/94

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
1A1-1	45	A2	B3	B	8.18	22.6	12.65	127.0	127.0	C/K
1A1-2	45	B2	A2	T	8.18	16.1	12.65	90.7	90.7	C/K

SHEAR STRENGTH

AVERAGE (MPa): 108.9
STD.DEV. (MPa): 25.7
CV: 0.24

COMPRESSIVE STRENGTH

AVERAGE (MPa): 108.8
STD.DEV. (MPa): 25.7
CV: 0.24

Tested By: JSM Date: 1/3/95
Analyzed By: JSM Date: 1/3/95
Checked By: JSS Date: 1/4/95

Failure Mode:

A/M - Adhesive failure at the metal chip
A/K - Adhesive failure between the glass ply and the Kapton.
C - Cohesive failure in the composite.
C/K - Cohesive failure in the Kapton, tearing of the Kapton.

Resin System: CTD-101K
Reinforcement: S-2 Glass - 6781 Condition: AR
Barrier: Kapton HA (1ply of 1 mil)
Specimen Type: S/C - Stainless Steel Chips 316LN
Material Reference #: Batch #1 - Run #143

Load Rate: 0.0018 mm/s

Test Fixture: 75° Test Temperatue: 76K
Test Date: 12/19/94

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
1A3-1	75	A3	A1	Both	8.18	76.9	12.65	158.5	591.4	C/K

SHEAR STRENGTH

AVERAGE (MPa): 158.5
STD.DEV. (MPa): N/A
CV: N/A

COMPRESSIVE STRENGTH

AVERAGE (MPa): 591.4
STD.DEV. (MPa): N/A
CV: N/A

Failure Mode:

A/M - Adhesive failure at the metal chip
A/K - Adhesive failure between the glass ply and the Kapton.
C - Cohesive failure in the composite.
C/K - Cohesive failure in the Kapton, tearing of the Kapton.

Tested By: JSM Date: 1/3/95
Analyzed By: JSM Date: 1/3/95
Checked By: [illegible] Date: 1/4/9[illegible]

Composite Technology Development, Inc.

TPX Shear/Compression Test Results

Resin System: CTD-101K
Reinforcement: S-2 Glass - 6781 Condition: AR
Barrier: Kapton HA (1 ply of 1 mil)
Specimen Type: S/C - Incoloy 908 Chips
Material Reference #: Batch #1 - Run #143

Load Rate: 0.0018 mm/s

Test Fixture: 15° Test Temperature: 76K
Test Date: 12/20/94

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
1B2-1	15	B4	A6	B	8.18	10.4	12.65	79.6	21.3	C/K
1B2-2	15	A5	B4	B	8.18	9.2	12.65	70.6	18.9	A/K

SHEAR STRENGTH

AVERAGE (MPa): 75.1
STD.DEV. (MPa): 6.4
CV: 0.08

COMPRESSIVE STRENGTH

AVERAGE (MPa): 20.1
STD.DEV. (MPa): 1.7
CV: 0.08

Test Fixture: 45° Test Temperatue: 76K
Test Date: 12/19/94

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
1B1-1	45	A4	B5	T	8.18	18.9	12.62	106.6	106.6	C/K
1B1-2	45	B6	B5	B	8.18	16.1	12.57	92.0	92.0	C/K

SHEAR STRENGTH

AVERAGE (MPa): 99.3
STD.DEV. (MPa): 10.4
CV: 0.10

COMPRESSIVE STRENGTH

AVERAGE (MPa): 99.3
STD.DEV. (MPa): 10.4
CV: 0.10

Tested By: JSM Date: 1/3/95
Reviewed: JSM Date: 1/3/95
Approved By: JBB Date: 1/4/95

Failure Mode:

A/M - Adhesive failure at the metal chip
A/K - Adhesive failure between the glass ply and the Kapton.
C - Cohesive failure in the composite.
C/K - Cohesive failure in the Kapton, tearing of the Kapton.

Resin System: CTD-101K
Reinforcement: S-2 Glass - 6781 Condition: AR
Barrier: Kapton HA (1ply of 1 mil)
Specimen Type: S/C - Incoloy 908
Material Reference #: Batch #1 - Run #143

Load Rate: 0.0018 mm/s

Test Fixture: 75° Test Temperatue: 76K
Test Date: 12/19/94

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
1B3-1	75	B6	A5	Both	8.18	72.7	12.62	150.5	561.4	C/K

SHEAR STRENGTH

AVERAGE (MPa): 150.5
STD.DEV. (MPa): N/A
CV: N/A

COMPRESSIVE STRENGTH

AVERAGE (MPa): 561.4
STD.DEV. (MPa): N/A
CV: N/A

Failure Mode:

A/M - Adhesive failure at the metal chip
A/K - Adhesive failure between the glass ply and the Kapton.
C - Cohesive failure in the composite.
C/K - Cohesive failure in the Kapton, tearing of the Kapton.

Tested By: OSM Date: 1/3/95
Analyzed By: OSM Date: 1/3/95
Checked By: [illegible] Date: 1/4/95

Composite Technology Development, Inc.

TPX Shear/Compression Test Results

Resin System: CTD-101K
Reinforcement: S-2 Glass - 6781 Condition: AR
Barrier: G10 (1 ply of 20 mil)
Specimen Type: S/C - Incoloy 908 Chips
Material Reference #: Batch #1 - Run #143

Load Rate: 0.0018 mm/s

Test Fixture: 15° Test Temperature: 76K
Test Date: 12/20/94

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
1C2-1	15	A8	B8	B	8.23	3.7	12.65	28.6	7.7	A/M

SHEAR STRENGTH

AVERAGE (MPa): 28.6
STD.DEV. (MPa): N/A
CV: N/A

COMPRESSIVE STRENGTH

AVERAGE (MPa): 7.7
STD.DEV. (MPa): N/A
CV: N/A

Test Fixture: 45° Test Temperatue: 76K
Test Date: 12/19/94

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
1C1-1	45	A8	B7	B	8.23	5.1	12.62	28.6	28.6	A/M

SHEAR STRENGTH

AVERAGE (MPa): 28.6
STD.DEV. (MPa): N/A
CV: N/A

COMPRESSIVE STRENGTH

AVERAGE (MPa): 28.6
STD.DEV. (MPa): N/A
CV: N/A

Failure Mode:

A/M - Adhesive failure at the metal chip
A/K - Adhesive failure between the glass ply and the Kapton.
C - Cohesive failure in the composite.
C/K - Cohesive failure in the Kapton, tearing of the Kapton.

Tested By: JSM Date: 1/3/95
Analyzed By: JSM Date: 1/3/95
Checked By: JB Date: 1/4/95

Composite Technology Development, Inc.

Resin System: CTD-101K
Reinforcement: S-2 Glass - 6781 Condition: AR
Barrier: G10 (1 ply of 20 mil)
Specimen Type: S/C - Incoloy 908
Material Reference #: Batch #1 - Run #143

Load Rate: 0.0018 mm/s

Test Fixture: 75° Test Temperatue: 76K
Test Date: 12/21/94

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
1C3-1	75	A7	A8	Both	8.23	123.9	12.65	255.4	952.8	C

SHEAR STRENGTH

AVERAGE (MPa): 255.4
STD.DEV. (MPa): N/A
CV: N/A

COMPRESSIVE STRENGTH

AVERAGE (MPa): 952.8
STD.DEV. (MPa): N/A
CV: N/A

Failure Mode:

A/M - Adhesive failure at the metal chip
A/K - Adhesive failure between the glass ply and the Kapton.
C - Cohesive failure in the composite.
C/K - Cohesive failure in the Kapton, tearing of the Kapton.

Tested By: DSM Date: 1/3/95
Analyzed By: DSM Date: 1/3/95
Checked By: [signature] Date: 1/4/95

Composite Technology Development, Inc.

TPX Shear/Compression Test Results

Resin System: Shell 826/CTD-1PFS
Reinforcement: S-2 Glass - 6781 Condition: AR
Barrier: Kapton HA (4 ply of 1 mil)
Specimen Type: S/C - Stainless Steel Chips 316LN
Material Reference #: Batch #2 - Run #145

Load Rate: 0.0018 mm/s

Test Fixture: 15° Test Temperature: 76K
Test Date: 12/20/94

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
2A2-1	15	B8	A6	T	8.18	12.1	12.62	93.2	25.0	C/K
2A2-2	15	B7	A6	T	8.15	10.7	12.65	82.3	22.1	C/K

SHEAR STRENGTH

AVERAGE (MPa): 87.8
STD.DEV. (MPa): 7.7
CV: 0.09

COMPRESSIVE STRENGTH

AVERAGE (MPa): 23.5
STD.DEV. (MPa): 2.1
CV: 0.09

Test Fixture: 45° Test Temperatue: 76K
Test Date: 12/19/94

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
2A1-1	45	B6	A7	T	8.15	21.5	12.65	121.0	120.9	C/K
2A1-2	45	A8	A7	B	8.18	24.0	12.62	135.7	135.7	C/K

SHEAR STRENGTH

AVERAGE (MPa): 128.3
STD.DEV. (MPa): 10.4
CV: 0.08

COMPRESSIVE STRENGTH

AVERAGE (MPa): 128.3
STD.DEV. (MPa): 10.4
CV: 0.08

Tested By: JSM Date: 1/3/5
Analyzed By: JSM Date: 1/3/5
Checked By: [illegible] Date: 1/4/9

Failure Mode:

A/M - Adhesive failure at the metal chip
A/K - Adhesive failure between the glass ply and the Kapton.
C - Cohesive failure in the composite.
C/K - Cohesive failure in the Kapton, tearing of the Kapton.

Resin System: Shell 826/CTD-1PFS
Reinforcement: S-2 Glass - 6781 Condition: AR
Barrier: Kapton HA (4ply of 1 mil)
Specimen Type: S/C - Stainless Steel Chips 316LN
Material Reference #: Batch #2 - Run #145

Load Rate: 0.0018 mm/s

Test Fixture: 75° Test Temperatue: 76K
Test Date: 12/19/94

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
2A3-1	75	A8	A6	Both	8.18	71.1	12.65	146.5	546.6	C/K

SHEAR STRENGTH

AVERAGE (MPa): 146.5
STD.DEV. (MPa): N/A
CV: N/A

COMPRESSIVE STRENGTH

AVERAGE (MPa): 546.6
STD.DEV. (MPa): N/A
CV: N/A

Failure Mode:

A/M - Adhesive failure at the metal chip
A/K - Adhesive failure between the glass ply and the Kapton.
C - Cohesive failure in the composite.
C/K - Cohesive failure in the Kapton, tearing of the Kapton.

Tested By: DSM Date: 1/3/95
[illegible]ed By: DSM Date: 1/3/95
[illegible]d By: [illegible] [illegible] 1/4/95

Composite Technology Development, Inc.

TPX Shear/Compression Test Results

Resin System: Shell 826
Reinforcement: S-2 Glass - 6781 Condition: AR
Barrier: Kapton HA (1 ply of 1 mil)
Specimen Type: S/C - Incoloy 908 Chips
Material Reference #: Batch #2 - Run #145

Load Rate: 0.0018 mm/s

Test Fixture: 15° Test Temperature: 76K
Test Date: 12/20/94

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
2B2-1	15	A4	B3	B	8.18	12.5	12.62	96.5	25.9	C/K
2B2-2	15	A3	A4	T	8.18	13.2	12.65	101.5	27.2	C/K

SHEAR STRENGTH

AVERAGE (MPa): 99.0
STD.DEV. (MPa): 3.5
CV: 0.04

COMPRESSIVE STRENGTH

AVERAGE (MPa): 26.5
STD.DEV. (MPa): 0.9
CV: 0.04

Test Fixture: 45° Test Temperatue: 76K
Test Date: 12/19/94

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
2B1-1	45	B4	A5	B	8.18	28.5	12.65	160.7	160.6	C/K
2B1-2	45	B3	B4	B	8.15	27.6	12.65	155.3	155.3	C/K

SHEAR STRENGTH

AVERAGE (MPa): 158.0
STD.DEV. (MPa): 3.8
CV: 0.02

COMPRESSIVE STRENGTH

AVERAGE (MPa): 158.0
STD.DEV. (MPa): 3.8
CV: 0.02

Failure Mode:

A/M - Adhesive failure at the metal chip
A/K - Adhesive failure between the glass ply and the Kapton.
C - Cohesive failure in the composite.
C/K - Cohesive failure in the Kapton, tearing of the Kapton.

By: JSM Date: 1/3/95
Analyzed By: JSM Date: 1/3/95
Checked By: [illegible] Date: 1/4/95

Composite Technology Development, Inc.

Resin System: Shell 826
Reinforcement: S-2 Glass - 6781 Condition: AR
Barrier: Kapton HA (1 ply of 1 mil)
Specimen Type: S/C - Incoloy 908 Chips
Material Reference #: Batch #2 - Run #145

Load Rate: 0.0018 mm/s

Test Fixture: 75° Test Temperatue: 76K
Test Date: 12/21/94

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
2B3-1	75	A4	B5	Both	8.18	88.8	12.62	183.8	685.7	C/K

SHEAR STRENGTH

AVERAGE (MPa): 183.8
STD.DEV. (MPa): N/A
CV: N/A

COMPRESSIVE STRENGTH

AVERAGE (MPa): 685.7
STD.DEV. (MPa): N/A
CV: N/A

Failure Mode:

A/M - Adhesive failure at the metal chip
A/K - Adhesive failure between the glass ply and the Kapton.
C - Cohesive failure in the composite.
C/K - Cohesive failure in the Kapton, tearing of the Kapton.

Tested By: CSM Date: 1/3/9
Anlyzed By: CSM Date: 1/3/9
Checked By: [signature] Date: 1/9/9

Composite Technology Development, Inc.

TPX Shear/Compression Test Results

Resin System: Shell 826
Reinforcement: S-2 Glass - 6781 Condition: AR
Barrier: G10 (1 ply of 20 mil)
Specimen Type: S/C - Incoloy 908 Chips
Material Reference #: Batch #2 - Run #145

Load Rate: 0.0018 mm/s

Test Fixture: 15° Test Temperature: 76K
Test Date: 12/20/94

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
2C2-1	15	A2	B2	B2	8.23	0.0	12.62	0.0	0.0	**

SHEAR STRENGTH

AVERAGE (MPa): 0.0
STD.DEV. (MPa): N/A
CV: N/A

COMPRESSIVE STRENGTH

AVERAGE (MPa): 0.0
STD.DEV. (MPa): N/A
CV: N/A

** Specimen B2 failed adhesively while loading into the fixture. No load was applied.

Test Fixture: 45° Test Temperatue: 76K
Test Date: 12/19/94

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
2C1-1	45	B1	A2	T	8.26	30.6	12.62	173.0	173.0	C

SHEAR STRENGTH

AVERAGE (MPa): 173.0
STD.DEV. (MPa): N/A
CV: N/A

COMPRESSIVE STRENGTH

AVERAGE (MPa): 173.0
STD.DEV. (MPa): N/A
CV: N/A

Failure Mode:

A/M - Adhesive failure at the metal chip
A/K - Adhesive failure between the glass ply and the Kapton.
C - Cohesive failure in the composite.
C/K - Cohesive failure in the Kapton, tearing of the Kapton.

Tested By: JSM Date: 1/3/95
Analyzed By: JSM Date: 1/3/95
Checked By: [illegible] Date: 1/4/95

Composite Technology Development, Inc.

Resin System: Shell 826
Reinforcement: S-2 Glass - 6781 Condition: AR
Barrier: G10 (1 ply of 20 mil)
Specimen Type: S/C - Incoloy 908
Material Reference #: Batch #2 - Run #145

Load Rate: 0.0018 mm/s

Test Fixture: 75° Test Temperatue: 76K
Test Date: 12/21/94

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
2C3-1	75	A2	A1	Both	8.26	127.2	12.62	263.3	982.1	C

SHEAR STRENGTH

AVERAGE (MPa): 263.3
STD.DEV. (MPa): N/A
CV: N/A

COMPRESSIVE STRENGTH

AVERAGE (MPa): 982.1
STD.DEV. (MPa): N/A
CV: N/A

Failure Mode:

A/M - Adhesive failure at the metal chip
A/K - Adhesive failure between the glass ply and the Kapton.
C - Cohesive failure in the composite.
C/K - Cohesive failure in the Kapton, tearing of the Kapton.

Tested By: JM Date: 1/3/95
Analyzed By: JM Date: 1/3/95
Checked By: [illegible] Date: 1/4/95

Composite Technology Development, Inc.

TPX Shear/Compression Test Results

Resin System: CTD-112P
Reinforcement: S-2 Glass - 6781 Condition: AR
Barrier: Kapton HA (4 ply of 1 mil)
Specimen Type: S/C - Stainless Steel Chips 316LN
Material Reference #: Batch #3 - Run #142

Load Rate: 0.0018 mm/s

Test Fixture: 15° Test Temperature: 76K
Test Date: 12/20/94

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
3A2-1	15	B3	A3	B	8.18	6.7	12.65	51.9	13.9	C/K
3A2-2	15	A2	B3	B	8.20	6.8	12.62	52.6	14.1	C/K

SHEAR STRENGTH

AVERAGE (MPa): 52.3
STD.DEV. (MPa): 0.6
CV: 0.01

COMPRESSIVE STRENGTH

AVERAGE (MPa): 14.0
STD.DEV. (MPa): 0.1
CV: 0.01

Test Fixture: 45° Test Temperatue: 76K
Test Date: 12/19/94

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
3A1-1	45	A1	B4	T	8.20	13.2	12.62	74.5	74.5	A/K
3A1-2	45	A3	B4	B	8.18	11.2	12.65	63.2	63.2	C/K

SHEAR STRENGTH

AVERAGE (MPa): 68.8
STD.DEV. (MPa): 8.0
CV: 0.12

COMPRESSIVE STRENGTH

AVERAGE (MPa): 68.8
STD.DEV. (MPa): 8.0
CV: 0.12

Failure Mode:

A/M - Adhesive failure at the metal chip
A/K - Adhesive failure between the glass ply and the Kapton.
C - Cohesive failure in the composite.
C/K - Cohesive failure in the Kapton, tearing of the Kapton.

Tested By: JSM Date: 1/3/9
[illegible] By: JSM Date: 1/3/9
[illegible] By: [illegible] Date: 1/4/9

Composite Technology Development, Inc.

Resin System: CTD-112P

Reinforcement: S-2 Glass - 6781 Condition: AR

Barrier: Kapton HA (4 ply of 1 mil)

Specimen Type: S/C - Stainless Steel Chips 316LN

Material Reference #: Batch #3 - Run #142

Load Rate: 0.0018 mm/s

Test Fixture: 75° Test Temperatue: 76K

Test Date: 12/21/94

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
3A3-1	75	A2	B2	Both	8.18	37.2	12.65	76.7	286.1	C/K

SHEAR STRENGTH

AVERAGE (MPa): 76.7

STD.DEV. (MPa): N/A

CV: N/A

COMPRESSIVE STRENGTH

AVERAGE (MPa): 286.1

STD.DEV. (MPa): N/A

CV: N/A

Failure Mode:

A/M - Adhesive failure at the metal chip

A/K - Adhesive failure between the glass ply and the Kapton.

C - Cohesive failure in the composite.

C/K - Cohesive failure in the Kapton, tearing of the Kapton.

Tested By: JSM Date: 1/3/95

Analyzed By: JSM Date: 1/3/95

Checked By: [illegible] Date: 1/4/95

Composite Technology Development, Inc.

TPX Shear/Compression Test Results

Resin System: CTD-112P
Reinforcement: S-2 Glass - 6781 Condition: AR
Barrier: Kapton HA (4 ply of 1 mil)
Specimen Type: S/C - Incoloy 908 Chips
Material Reference #: Batch #3 - Run #142

Load Rate: 0.0018 mm/s

Test Fixture: 15° Test Temperature: 76K
Test Date: 12/20/94

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
3B2-1	15	A5	B5	T	8.20	6.6	12.60	51.4	13.8	A/K
3B2-2	15	A7	B5	T	8.18	7.3	12.65	56.2	15.1	A/K

SHEAR STRENGTH

AVERAGE (MPa): 53.8
STD.DEV. (MPa): 3.4
CV: 0.06

COMPRESSIVE STRENGTH

AVERAGE (MPa): 14.4
STD.DEV. (MPa): 0.9
CV: 0.06

Test Fixture: 45° Test Temperatue: 76K
Test Date: 12/19/94

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
3B1-1	45	A6	B8	T	8.18	11.0	12.62	62.4	62.4	A/K
3B1-2	45	A7	B8	B	8.18	9.8	12.62	55.2	55.1	A/K

SHEAR STRENGTH

AVERAGE (MPa): 58.8
STD.DEV. (MPa): 5.1
CV: 0.09

COMPRESSIVE STRENGTH

AVERAGE (MPa): 58.8
STD.DEV. (MPa): 5.1
CV: 0.09

Failure Mode:

A/M - Adhesive failure at the metal chip
A/K - Adhesive failure between the glass ply and the Kapton.
C - Cohesive failure in the composite.
C/K - Cohesive failure in the Kapton, tearing of the Kapton.

By: DSM Date: 1/3/95
yzed By: DSM Date: 1/3/95
cked By: Date: 1/4/95

Composite Technology Development, Inc.

Resin System: CTD-112P

Reinforcement: S-2 Glass - 6781 Condition: AR

Barrier: Kapton HA (4 ply of 1 mil)

Specimen Type: S/C - Incoloy 908 Chips

Material Reference #: Batch #3 - Run #142

Load Rate: 0.0018 mm/s

Test Fixture: 75° Test Temperatue: 76K

Test Date: 12/21/94

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
3B3-1	75	B5	B7	Both	8.18	39.4	12.65	81.2	302.8	C/K

SHEAR STRENGTH

AVERAGE (MPa): 81.2

STD.DEV. (MPa): N/A

CV: N/A

COMPRESSIVE STRENGTH

AVERAGE (MPa): 302.8

STD.DEV. (MPa): N/A

CV: N/A

Failure Mode:

A/M - Adhesive failure at the metal chip

A/K - Adhesive failure between the glass ply and the Kapton.

C - Cohesive failure in the composite.

C/K - Cohesive failure in the Kapton, tearing of the Kapton.

Checked By: DSM Date: 1/3/95

Checked By: DSM Date: 1/3/95

Date: 1/4/95

Composite Technology Development, Inc.

TPX Shear/Compression Test Results

Resin System: CTD-101K
Reinforcement: S-2 Glass - 6781 Condition: AR
Barrier: Kapton HA (4 ply of 1 mil)
Specimen Type: S/C -Stainless Steel Chips 316LN
Material Reference #: Batch #4 - Run #141

Load Rate: 0.0018 mm/s

Test Fixture: 15° Test Temperature: 76K
Test Date: 12/20/94

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
4A2-1	15	A4	B2	T	8.18	7.2	12.62	55.8	15.0	C/K
4A2-2	15	A2	B2	T	8.13	5.9	12.65	45.6	12.2	C/K

SHEAR STRENGTH

AVERAGE (MPa): 50.7
STD.DEV. (MPa): 7.2
CV: 0.14

COMPRESSIVE STRENGTH

AVERAGE (MPa): 13.6
STD.DEV. (MPa): 1.9
CV: 0.14

Test Fixture: 45° Test Temperatue: 76K
Test Date: 12/19/94

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
4A1-1	45	A3	B4	T	8.15	10.4	12.65	58.7	58.7	A/K
4A1-2	45	A4	B4	B	8.18	20.9	12.65	117.6	117.6	A/K

SHEAR STRENGTH

AVERAGE (MPa): 88.2
STD.DEV. (MPa): 41.6
CV: 0.47

COMPRESSIVE STRENGTH

AVERAGE (MPa): 88.1
STD.DEV. (MPa): 41.6
CV: 0.47

Failure Mode:

A/M - Adhesive failure at the metal chip
A/K - Adhesive failure between the glass ply and the Kapton.
C - Cohesive failure in the composite.
C/K - Cohesive failure in the Kapton, tearing of the Kapton.

Tested By: JSM Date: 1/3/95
Analyzed By: JSM Date: 1/3/95
Checked By: [illegible] Date: 1/4/95

Composite Technology Development, Inc.

Resin System: CTD-101K
Reinforcement: S-2 Glass - 6781 Condition: AR
Barrier: Kapton HA (4 ply of 1 mil)
Specimen Type: S/C -Stainless Steel Chips 316LN
Material Reference #: Batch #4 - Run #141

Load Rate: 0.0018 mm/s

Test Fixture: 75° Test Temperatue: 76K
Test Date: 12/21/94

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
4A3-1	75	B1	B2	Both	8.18	66.6	12.65	137.3	512.1	C/K

SHEAR STRENGTH

AVERAGE (MPa): 137.3
STD.DEV. (MPa): N/A
CV: N/A

COMPRESSIVE STRENGTH

AVERAGE (MPa): 512.1
STD.DEV. (MPa): N/A
CV: N/A

Failure Mode:

A/M - Adhesive failure at the metal chip
A/K - Adhesive failure between the glass ply and the Kapton.
C - Cohesive failure in the composite.
C/K - Cohesive failure in the Kapton, tearing of the Kapton.

Tested By: JSM Date: 1/3/95
Analyzed By: JSM Date: 1/3/95
Checked By: JBS Date: 1/4/95

Composite Technology Development, Inc.

TPX Shear/Compression Test Results

Resin System: CTD-101K
Reinforcement: S-2 Glass - 6781 Condition: AR
Barrier: Kapton HA (4 ply of 1 mil)
Specimen Type: S/C - Incoloy 908 Chips
Material Reference #: Batch #4 - Run #141

Load Rate: 0.0018 mm/s

Test Fixture: 15° Test Temperature: 76K
Test Date: 12/20/94

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
4B2-1	15	A7	B8	B	8.18	6.4	12.62	49.7	13.3	A/K
4B2-2	15	A8	A7	B	8.18	7.9	12.60	61.2	16.4	A/K

SHEAR STRENGTH

AVERAGE (MPa): 55.4
STD.DEV. (MPa): 8.1
CV: 0.15

COMPRESSIVE STRENGTH

AVERAGE (MPa): 14.9
STD.DEV. (MPa): 2.2
CV: 0.15

Test Fixture: 45° Test Temperatue: 76K
Test Date: 12/19/94

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
4B1-1	45	A6	B7	B	8.18	18.4	12.60	104.2	104.1	C/K
4B1-2	45	B8	A6	B	8.18	19.0	12.62	107.6	107.6	C/K

SHEAR STRENGTH

AVERAGE (MPa): 105.9
STD.DEV. (MPa): 2.4
CV: 0.02

COMPRESSIVE STRENGTH

AVERAGE (MPa): 105.9
STD.DEV. (MPa): 2.4
CV: 0.02

Failure Mode:

A/M - Adhesive failure at the metal chip
A/K - Adhesive failure between the glass ply and the Kapton.
C - Cohesive failure in the composite.
C/K - Cohesive failure in the Kapton, tearing of the Kapton.

Tested By: DSM Date: 1/3
Analyzed By: DSM Date: 1/3
Checked By: [illegible] Date: 1/4

Composite Technology Development, Inc.

Resin System: CTD-101K
Reinforcement: S-2 Glass - 6781 Condition: AR
Barrier: Kapton HA (4 ply of 1 mil)
Specimen Type: S/C - Incoloy 908 Chips
Material Reference #: Batch #4 - Run #141

Load Rate: 0.0018 mm/s

Test Fixture: 75° Test Temperatue: 76K
Test Date: 12/21/94

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
4B3-1	75	B6	A8	Both	8.18	65.4	12.62	135.2	504.5	C/K

SHEAR STRENGTH

AVERAGE (MPa): 135.2
STD.DEV. (MPa): N/A
CV: N/A

COMPRESSIVE STRENGTH

AVERAGE (MPa): 504.5
STD.DEV. (MPa): N/A
CV: N/A

Failure Mode:

A/M - Adhesive failure at the metal chip
A/K - Adhesive failure between the glass ply and the Kapton.
C - Cohesive failure in the composite.
C/K - Cohesive failure in the Kapton, tearing of the Kapton.

Tested By: JSM Date: 1/3/95
Analyzed By: JSM Date: 1/3/95
Reviewed By: [illegible] Date: 1/4/95

Composite Technology Development, Inc.

TPX Shear/Compression Test Results

Resin System: CTD-101K/CTD-112P
Reinforcement: S-2 Glass - 6781 Condition: AR
Barrier: Kapton HA (4 ply of 1 mil)
Specimen Type: S/C - Stainless Steel Chips 316LN
Material Reference #: Batch #5 - Run #144

Load Rate: 0.0018 mm/s

Test Fixture: 15° Test Temperature: 76K
Test Date: 12/20/94

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
5A2-1	15	B4	A4	B	8.20	9.3	12.62	71.5	19.2	A/K
5A2-2	15	B2	B4	T	8.18	9.1	12.65	70.3	18.8	A/K

SHEAR STRENGTH

AVERAGE (MPa): 70.9
STD.DEV. (MPa): 0.8
CV: 0.01

COMPRESSIVE STRENGTH

AVERAGE (MPa): 19.0
STD.DEV. (MPa): 0.2
CV: 0.01

Test Fixture: 45° Test Temperatue: 76K
Test Date: 12/19/94

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
5A1-1	45	B3	A2	B	8.18	25.0	12.65	140.8	140.7	A/K
5A1-2	45	B4	B3	B	8.20	24.7	12.65	139.0	139.0	A/K

SHEAR STRENGTH

AVERAGE (MPa): 139.9
STD.DEV. (MPa): 1.3
CV: 0.01

COMPRESSIVE STRENGTH

AVERAGE (MPa): 139.8
STD.DEV. (MPa): 1.3
CV: 0.01

Tested By: JSM Date: 1/3/95
Anlyzed By: JSM Date: 1/3/95
Rev'd By: [illegible] Date: 1/4/95

Failure Mode:

A/M - Adhesive failure at the metal chip
A/K - Adhesive failure between the glass ply and the Kapton.
C - Cohesive failure in the composite.
C/K - Cohesive failure in the Kapton, tearing of the Kapton.

TPX Shear/Compression Test Results

Resin System: CTD-101K/CTD-112P
Reinforcement: S-2 Glass - 6781 Condition: AR
Barrier: Kapton HA (4 ply of 1 mil)
Specimen Type: S/C - Incoloy 908 Chips
Material Reference #: Batch #5 - Run #144

Load Rate: 0.0018 mm/s

Test Fixture: 15° Test Temperature: 76K
Test Date: 12/20/94

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
5B2-1	15	A5	B6	T	8.20	9.9	12.65	75.8	20.3	C,C/K
5B2-2	15	A7	B6	T	8.20	11.1	12.62	85.6	22.9	C,C/K

SHEAR STRENGTH

AVERAGE (MPa): 80.7
STD.DEV. (MPa): 6.9
CV: 0.09

COMPRESSIVE STRENGTH

AVERAGE (MPa): 21.6
STD.DEV. (MPa): 1.8
CV: 0.09

Test Fixture: 45° Test Temperatue: 76K
Test Date: 12/19/94

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
5B1-1	45	B7	A5	T	8.18	24.1	12.62	136.2	136.1	C/K
5B1-2	45	B5	A5	T	8.20	23.0	12.62	129.8	129.8	A/K

SHEAR STRENGTH

AVERAGE (MPa): 133.0
STD.DEV. (MPa): 4.5
CV: 0.03

COMPRESSIVE STRENGTH

AVERAGE (MPa): 133.0
STD.DEV. (MPa): 4.5
CV: 0.03

Failure Mode:

A/M - Adhesive failure at the metal chip
A/K - Adhesive failure between the glass ply and the Kapton.
C - Cohesive failure in the composite.
C/K - Cohesive failure in the Kapton, tearing of the Kapton.

DSM 1/3/95
DSM 1/3/95
1/4/95

Composite Technology Development, Inc.

Resin System: CTD-101K/CTD-112P
Reinforcement: S-2 Glass - 6781 Condition: AR
Barrier: Kapton HA (4 ply of 1 mil)
Specimen Type: S/C - Incoloy 908 Chips
Material Reference #: Batch #5 - Run #144

Load Rate: 0.0018 mm/s

Test Fixture: 75° Test Temperatue: 76K
Test Date: 12/21/94

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
5B3-1	75	A8	B6	Both	8.20	64.9	12.65	133.7	498.7	A/K

SHEAR STRENGTH

AVERAGE (MPa): 133.7
STD.DEV. (MPa): N/A
CV: N/A

COMPRESSIVE STRENGTH

AVERAGE (MPa): 498.7
STD.DEV. (MPa): N/A
CV: N/A

Failure Mode:

A/M - Adhesive failure at the metal chip
A/K - Adhesive failure between the glass ply and the Kapton.
C - Cohesive failure in the composite.
C/K - Cohesive failure in the Kapton, tearing of the Kapton.

Tested By: DSM Date: 1/3/95
Typed By: DSM Date: 1/3/95
[illegible] Date: 1/4/95

Composite Technology Development, Inc.

TPX Shear/Compression Test Results

Resin System: CTD-112P/CTD-101K
Reinforcement: S-2 Glass - 6781 Condition: AR
Barrier: Kapton HA (4 ply of 1 mil)
Specimen Type: S/C - Stainless Steel Chips
Material Reference #: Batch #5 - Run 144 test of reserved specimens

Load Rate: 0.0018 mm/s

Test Fixture: 45° Test Temperature: 76K
Test Date: 1/26/95

Test #	Fixture Angle (Deg)	Top Specimen Number	Bottom Specimen Number	Specimen Failed (T or B)	Specimen Thickness (mm)	Ultimate Load (kN)	Spec. Dia. (mm)	Spec. Dia. (in)	Shear Strength (MPa)	Comp. Strength (MPa)	Failure Type
144-5A-1	45	B1	A3	B	8.20	25.3	12.65	0.498	142.4	142.4	C/K
144-5B-1	45	A6	B8	T	8.20	22.0	12.62	0.497	124.1	124.1	C/K
144-5AB-3	45	B8	B1	T	8.20	23.5	12.62	0.497	132.7	132.7	A/K

SHEAR STRENGTH

AVERAGE (MPa): 133.1
STD.DEV. (MPa): 9.2
CV: 0.07

COMPRESSION STRENGTH

AVERAGE (MPa): 133.0
STD.DEV. (MPa): 9.2
CV: 0.07

Failure Mode:

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

Tested By: Date: 1/26/95
Analyzed By: Date: 1/27/95
Checked By: Date: 1/30/95

Composite Technology Development, Inc.

TPX Shear/Compression Test Results

Resin System: CTD-101K
Reinforcement: S-2 Glass - 6781 Condition: AR
Barrier: Kapton HA (4 ply of 1 mil)
Specimen Type: S/C - Stainless Steel Chips
Material Reference #: Run # Batch #4 - Run 141 test of reserved specimens

Load Rate: 0.0018 mm/s

Test Fixture: 45° Test Temperature: 76K
Test Date:

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
141-4a-1	45	A1	B3	T	8.18	18.2	12.60	103.0	103.0	
141-4b-1	45	B5	A5	T	8.20	22.4	12.62	126.6	126.6	
141-4ab-3	45	A5	B3	B	8.18	22.5	12.65	126.8	126.8	
141-ab-4	45	A4-94	A5	B	8.18	22.1	12.60	125.7	125.6	

SHEAR STRENGTH

AVERAGE (MPa): 120.5
STD.DEV. (MPa): 11.7
CV: 0.10

COMPRESSION STRENGTH

AVERAGE (MPa): 120.5
STD.DEV. (MPa): 11.7
CV: 0.10

Failure Mode:

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

Tested By: Date: 1/26/95
Analyzed By: Date: 1/27/95
Checked By: Date: 1/30/95

Composite Technology Development, Inc.

TPX Shear/Compression Test Results

Resin System: CTD-112P
Reinforcement: S-2 Glass - 6781 Condition: AR
Barrier: Kapton HA (4 ply of 1 mil)
Specimen Type: S/C - Stainless Steel Chips
Material Reference #: Batch #3 - Run 142 test of reserved specimens

Load Rate: 0.0018 mm/s

Test Fixture: 45° Test Temperature: 76K
Test Date: 1/26/95

Test #	Fixture Angle (Deg)	Top Specimen Number	Bottom Specimen Number	Specimen Failed (T or B)	Specimen Thickness (mm)	Ultimate Load (kN)	Spec. Dia. (mm)	Spec. Dia. (in)	Shear Strength (MPa)	Comp. Strength (MPa)	Failure Type
142-3A-1	45	A4	B1	B	8.18	15.5	12.62	0.497	87.8	87.7	C/K
142-3B-1	45	A8	B6	B	8.18	14.7	12.65	0.498	82.9	82.9	C/K
142-3AB-3	45	A4	A8	B	8.20	14.5	12.65	0.498	81.8	81.8	C/K
142-3AB-4	45	A1-153	A4	B	8.20	13.8	12.62	0.497	78.0	77.9	C/K

SHEAR STRENGTH

AVERAGE (MPa): 82.6
STD.DEV. (MPa): 4.0
CV: 0.05

COMPRESSION STRENGTH

AVERAGE (MPa): 82.6
STD.DEV. (MPa): 4.0
CV: 0.05

* Specimen is CTD-112P, with no Kapton. Stiffness similar to A4 to enable test.

Failure Mode:

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

Tested By: Date: 1/26/95
Analyzed By: Date: 1/27/95
Checked By: Date: 1/30/95

Composite Technology Development, Inc.

TPX Shear/Compression Test Results

Resin System: CTD-101K
Reinforcement: S-2 Glass - 6781 Condition: AR
Barrier: Kapton 100HA (4 plies)
Specimen Type: S/C - Stainless Steel Chips
Material Reference #: Run # 160A 6A

Load Rate: 0.0018 mm/s

Test Fixture: 15° Test Temperature: 76K
Test Date: 3/30/95

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
160A-4	15	A1	B1	B	8.15	7.3	12.60	56.4	15.1	A/K
160A-5	15	A1	A3	T	8.20	9.1	12.60	70.7	18.9	A/K
160A-6	15	A3	B4	B	8.15	6.5	12.60	50.5	13.5	A/K

SHEAR STRENGTH

AVERAGE (MPa): 59.2
STD.DEV. (MPa): 10.4
CV: 0.18

COMPRESSION STRENGTH

AVERAGE (MPa): 15.9
STD.DEV. (MPa): 2.8
CV: 0.18

Test Fixture: 45° Test Temperature: 76K

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
160A-1	45	A4	B2	B	8.15	20.8	12.60	118.3	118.3	C/K
160A-2	45	A4	B1	T	8.20	21.6	12.60	122.5	122.5	C/K
160A-3	45	B1	B3	B	8.15	22.4	12.60	126.8	126.8	A/K

SHEAR STRENGTH

AVERAGE (MPa): 122.5
STD.DEV. (MPa): 4.3
CV: 0.03

COMPRESSION STRENGTH

AVERAGE (MPa): 122.5
STD.DEV. (MPa): 4.3
CV: 0.03

Test Fixture: 75° Test Temperature: 76K

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
160A-7	75	A2	A3	BOTH	8.19	63.2	12.60	131.4	490.0	C/K

SHEAR STRENGTH

AVERAGE (MPa): 131.4
STD.DEV. (MPa): #DIV/0!
CV: #DIV/0!

COMPRESSION STRENGTH

AVERAGE (MPa): 490.0
STD.DEV. (MPa): #DIV/0!
CV: #DIV/0!

Failure Mode:
A/M - Adhesive failure at the metal.
A/K - Adhesive failure at the Kapton.
C/K - Cohesive failure at the Kapton; tearing of the Kapton.
C - Cohesive failure in the composite.

Tested By: Date: 3/30/95
Reviewed By: Date: 4/18/95
Approved By: Date: 4/21/95

Composite Technology Development, Inc.

TPX Shear/Compression Test Results

Resin System: CTD-101K (RTM)/CTD-1112P (PREPREG)
Reinforcement: S-2 Glass - 6781 **Condition:** AR
Barrier: KAPTON 100HA (4 ply)
Specimen Type: S/C - Stainless Steel Chips
Material Reference #: Run # 161A 6B

Load Rate: 0.0018 mm/s

Test Fixture: 15° **Test Temperature:** 76K
Test Date: 4/7/95

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
161A-4	15	A8	A6	B	8.18	4.4	12.60	33.9	9.1	A/K
161A-5	15	A8	B7	T	8.20	3.5	12.60	27.1	7.3	A/K
161A-6	15	B7	A4	T	8.18	4.3	12.60	33.4	8.9	A/K

SHEAR STRENGTH

AVERAGE (MPa): 31.4
STD.DEV. (MPa): 3.8
CV: 0.12

COMPRESSION STRENGTH

AVERAGE (MPa): 8.4
STD.DEV. (MPa): 1.0
CV: 0.12

Test Fixture: 45° **Test Temperature:** 76K

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
161A-1	45	A7	B4	B	8.18	18.1	12.60	102.7	102.7	C/K
161A-2	45	A7	B5	T	8.18	17.2	12.60	97.7	97.7	C/K
161A-3	45	B7	B5	B	8.20	18.9	12.60	107.1	107.1	C/K

SHEAR STRENGTH

AVERAGE (MPa): 102.5
STD.DEV. (MPa): 4.7
CV: 0.05

COMPRESSION STRENGTH

AVERAGE (MPa): 102.5
STD.DEV. (MPa): 4.7
CV: 0.05

Test Fixture: 75° **Test Temperature:** 76K

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
161A-7	75	A4	A5	BOTH	8.19	58.0	12.60	120.5	449.6	A/K

SHEAR STRENGTH

AVERAGE (MPa): 120.5
STD.DEV. (MPa): #DIV/0!
CV: #DIV/0!

COMPRESSION STRENGTH

AVERAGE (MPa): 449.6
STD.DEV. (MPa): #DIV/0!
CV: #DIV/0!

Tested By: Date: 4/7/95
Analyzed By: Date: 4/18/95
Checked By: Date: 4/21/95

Failure Mode:
A/M - Adhesive failure at the metal.
A/K - Adhesive failure at the Kapton.
C/K - Cohesive failure at the Kapton; tearing of the Kapton.
C - Cohesive failure in the composite.

TPX Shear/Compression Test Results

Resin System: SHELL 826
Reinforcement: S-2 Glass - 6781 **Condition:** AR
Barrier: Kapton 100HA (4 plies)
Specimen Type: S/C - Stainless Steel Chips
Material Reference #: Run # 159A 7 A

Load Rate: 0.0018 mm/s

Test Fixture: 15° **Test Temperature:** 76K
Test Date: 3/30/95

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
159A-4	15	A3	B4	B	8.20	9.6	12.60	74.6	20.0	C/K
159A-5	15	A3	A1	B	8.18	10.5	12.60	81.1	21.7	C/K
159A-6	15	A3	A2	T	8.20	12.6	12.60	97.6	26.1	A/K

SHEAR STRENGTH

AVERAGE (MPa): 84.4
STD.DEV. (MPa): 11.8
CV: 0.14

COMPRESSION STRENGTH

AVERAGE (MPa): 22.6
STD.DEV. (MPa): 3.2
CV: 0.14

Test Fixture: 45° **Test Temperature:** 76K

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
159A-1	45	B2	B1	T	8.18	24.2	12.60	137.3	137.3	C/K
159A-2	45	B1	A1	T	8.23	26.4	12.60	149.8	149.8	C/K
159A-3	45	A1	B3	B	8.18	25.4	12.57	144.8	144.8	A/K

SHEAR STRENGTH

AVERAGE (MPa): 144.0
STD.DEV. (MPa): 6.3
CV: 0.04

COMPRESSION STRENGTH

AVERAGE (MPa): 144.0
STD.DEV. (MPa): 6.3
CV: 0.04

Test Fixture: 75° **Test Temperature:** 76K

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
159A-7	75	A2	A4	BOTH	8.18	70.6	12.57	147.2	549.1	A/K

SHEAR STRENGTH

AVERAGE (MPa): 147.2
STD.DEV. (MPa): #DIV/0!
CV: #DIV/0!

COMPRESSION STRENGTH

AVERAGE (MPa): 549.1
STD.DEV. (MPa): #DIV/0!
CV: #DIV/0!

Failure Mode:
A/M - Adhesive failure at the metal.
A/K - Adhesive failure at the Kapton.
C/K - Cohesive failure at the Kapton; tearing of the Kapton.
C - Cohesive failure in the composite.

Tested By: JBZ Date: 3/30/95
Reviewed By: JBZ Date: 4/18/95
Approved By: RSF Date: 4/21/95

Composite Technology Development, Inc.

TPX Shear/Compression Test Results

Resin System: SHELL 826 (RTM)/CTD-1112P (PREPREG)
Reinforcement: S-2 Glass - 6781 **Condition:** AR
Barrier: KAPTON 100HA (4 ply)
Specimen Type: S/C - Stainless Steel Chips
Material Reference #: Run # 162A 7B

Load Rate: 0.0018 mm/s

Test Fixture: 15° **Test Temperature:** 76K
Test Date: 4/15/95

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
162A-4	15	A8	A4	B	8.20	5.5	12.60	42.4	11.4	A/K
162A-5	15	A8	B5	B	8.18	6.8	12.60	52.9	14.2	A/K
162A-6	15	A5	A8	T	8.18	5.0	12.60	38.8	10.4	A/K

SHEAR STRENGTH

AVERAGE (MPa): 44.7
STD.DEV. (MPa): 7.3
CV: 0.16

COMPRESSION STRENGTH

AVERAGE (MPa): 12.0
STD.DEV. (MPa): 2.0
CV: 0.16

Test Fixture: 45° **Test Temperature:** 76K

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
162A-1	45	A4	B4	B	8.20	20.6	12.60	117.1	117.1	C/K
162A-2	45	A4	A6	B	8.18	18.8	12.60	106.8	106.7	C/K
162A-3	45	A4	B8	B	8.18	16.7	12.60	94.8	94.8	C/K

SHEAR STRENGTH

AVERAGE (MPa): 106.2
STD.DEV. (MPa): 11.2
CV: 0.11

COMPRESSION STRENGTH

AVERAGE (MPa): 106.2
STD.DEV. (MPa): 11.2
CV: 0.11

Test Fixture: 75° **Test Temperature:** 76K

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
162A-7	75	B6	A7	BOTH	8.19	59.3	12.60	123.3	460.0	C/K

SHEAR STRENGTH

AVERAGE (MPa): 123.3
STD.DEV. (MPa): #DIV/0!
CV: #DIV/0!

COMPRESSION STRENGTH

AVERAGE (MPa): 460.0
STD.DEV. (MPa): #DIV/0!
CV: #DIV/0!

Failure Mode:
A/M - Adhesive failure at the metal.
A/K - Adhesive failure at the Kapton.
C/K - Cohesive failure at the Kapton; tearing of the Kapton.
C - Cohesive failure in the composite.

Tested By: [illegible] Date: 4/15/95
Reviewed By: [illegible] Date: 4/18/95
Checked By: [illegible] Date: 4/21/95

Composite Technology Development, Inc.

TPX Shear/Compression Test Results

Resin System: CTD-101K
Reinforcement: S-2 Glass - 6781 **Condition:** AR
Barrier: G-11CR (0.020 1 ply)
Specimen Type: S/C - Stainless Steel Chips
Material Reference #: Run # 160B 8A

Load Rate: 0.0018 mm/s

Test Fixture: 15° **Test Temperature:** 76K
Test Date: 3/30/95

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
160B-4	15	A7	A5	T	8.18	11.0	12.60	85.6	22.9	C,AM
160B-5	15	A5	B7	T	8.18	14.1	12.60	109.1	29.2	C,G
160B-6	15	B7	B8	T	8.18	15.1	12.60	117.4	31.5	C,G

SHEAR STRENGTH

AVERAGE (MPa): 104.1
STD.DEV. (MPa): 16.5
CV: 0.16

COMPRESSION STRENGTH

AVERAGE (MPa): 27.9
STD.DEV. (MPa): 4.4
CV: 0.16

Test Fixture: 45° **Test Temperature:** 76K

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
160B-1	45	A7	A8	B	8.15	32.5	12.60	184.3	184.3	C
160B-2	45	A7	B5	B	8.20	31.2	12.57	177.7	177.6	C,G
160B-3	45	A7	B6	B	8.18	31.8	12.60	180.7	180.7	C

SHEAR STRENGTH

AVERAGE (MPa): 180.9
STD.DEV. (MPa): 3.3
CV: 0.02

COMPRESSION STRENGTH

AVERAGE (MPa): 180.9
STD.DEV. (MPa): 3.3
CV: 0.02

Test Fixture: 75° **Test Temperature:** 76K

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
160B-7	75	A6	B8	BOTH	8.18	130.2	12.59	271.1	1011.3	C,G

SHEAR STRENGTH

AVERAGE (MPa): 271.1
STD.DEV. (MPa): #DIV/0!
CV: #DIV/0!

COMPRESSION STRENGTH

AVERAGE (MPa): 1011.3
STD.DEV. (MPa): #DIV/0!
CV: #DIV/0!

Tested By: [illegible] Date: 3/30/95
Reviewed By: [illegible] Date: 4/18/95
Checked By: [illegible] Date: 4/21/95

Failure Mode:
A/M - Adhesive failure at the metal.
A/K - Adhesive failure at the Kapton.
C,G - Cohesive failure of composite and G-11CR
C - Cohesive failure in the composite.

Composite Technology Development, Inc.

TPX Shear/Compression Test Results

Resin System: CTD-101K
Reinforcement: 3-d Weave (4 plies) **Condition:** AR
Barrier: None
Specimen Type: S/C - Stainless Steel Chips
Material Reference #: Run # 164A 8B

Load Rate: 0.0018 mm/s

Test Fixture: 15° **Test Temperature:** 76K
Test Date: 4/15/95

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
164A-4	15	A3	B1	T	8.15	11.8	12.57	91.5	24.5	C,AM
164A-5	15	B4	B1	B	8.15	11.6	12.57	90.3	24.2	C,AM
164A-6	15	B4	A1	B	8.15	8.3	12.57	64.6	17.3	C,AM

SHEAR STRENGTH

AVERAGE (MPa): 82.1
STD.DEV. (MPa): 15.2
CV: 0.19

COMPRESSION STRENGTH

AVERAGE (MPa): 22.0
STD.DEV. (MPa): 4.1
CV: 0.19

Test Fixture: 45° **Test Temperature:** 76K

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
164A-1	45	A2	A4	T	8.15	30.5	12.57	173.7	173.7	C, A/M
164A-2	45	A1	A4	B	8.15	30.0	12.57	171.1	171.1	C, A/M
164A-3	45	A1	B3	B	8.15	30.3	12.57	172.6	172.6	C, A/M

SHEAR STRENGTH

AVERAGE (MPa): 172.5
STD.DEV. (MPa): 1.3
CV: 0.01

COMPRESSION STRENGTH

AVERAGE (MPa): 172.4
STD.DEV. (MPa): 1.3
CV: 0.01

Test Fixture: 75° **Test Temperature:** 76K

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
164A-7	75	B4	B2	BOTH	8.15	121.3	12.57	253.0	943.7	C

SHEAR STRENGTH

AVERAGE (MPa): 253.0
STD.DEV. (MPa): #DIV/0!
CV: #DIV/0!

COMPRESSION STRENGTH

AVERAGE (MPa): 943.7
STD.DEV. (MPa): #DIV/0!
CV: #DIV/0!

Tested By: Date: 4/15/95
Approved By: Date: 4/18/95
Checked By: Date: 4/21/95

Failure Mode:
A/M - Adhesive failure at the metal.
A/K - Adhesive failure at the Kapton.
C,A/M - Failure located at metal interface; epoxy adhering to metal surface; some composite damage present.
C - Cohesive failure in the composite.

TPX Shear/Compression Test Results

Resin System: CTD-101K
Reinforcement: TTI Plain weave (8 plies) Condition: AR
Barrier: Kapton 100HA (4 Plies)
Specimen Type: S/C - Stainless Steel Chips
Material Reference #: Run # 164B 8C

Load Rate: 0.0018 mm/s

Test Fixture: 15° Test Temperature: 76K
Test Date: 4/15/95

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
164B-4	15	A7	B7	T	8.15	1.0	12.57	7.7	2.1	A/K
164B-5	15	A5	B7	B	8.15	0.9	12.55	6.8	1.8	A/K
164B-6	15	A5	A6	B	8.18	1.4	12.55	10.9	2.9	A/K

SHEAR STRENGTH

AVERAGE (MPa): 8.5
STD.DEV. (MPa): 2.1
CV: 0.25

COMPRESSION STRENGTH

AVERAGE (MPa): 2.3
STD.DEV. (MPa): 0.6
CV: 0.25

Test Fixture: 45° Test Temperature: 76K

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
164B-1	45	B5	B6	B	8.18	4.6	12.57	26.2	26.2	A/K
164B-2	45	B5	A5	T	8.15	4.2	12.57	23.9	23.9	A/K
164B-3	45	A8	A5	T	8.18	5.9	12.55	33.8	33.8	A/K

SHEAR STRENGTH

AVERAGE (MPa): 28.0
STD.DEV. (MPa): 5.1
CV: 0.18

COMPRESSION STRENGTH

AVERAGE (MPa): 28.0
STD.DEV. (MPa): 5.1
CV: 0.18

Test Fixture: 75° Test Temperature: 76K

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
164B-7	75	A5	B8	BOTH	8.15	63.5	12.57	132.5	494.2	A/K

SHEAR STRENGTH

AVERAGE (MPa): 132.5
STD.DEV. (MPa): #DIV/0!
CV: #DIV/0!

COMPRESSION STRENGTH

AVERAGE (MPa): 494.2
STD.DEV. (MPa): #DIV/0!
CV: #DIV/0!

Tested By: JS Date: 4/15/95
Analyzed By: JS Date: 4/18/95
Checked By: [illegible] Date: 4/21/95

Failure Mode:
A/M - Adhesive failure at the metal.
A/K - Adhesive failure at the Kapton.
C/K - Cohesive failure at the Kapton; tearing of the Kapton.
C - Cohesive failure in the composite.

Composite Technology Development, Inc.

TPX Shear/Compression Test Results

Resin System: SHELL 826
Reinforcement: S-2 Glass - 6781 Condition: AR
Barrier: G-11CR (1 ply 0.020 in)
Specimen Type: S/C - Stainless Steel Chips
Material Reference #: Run # 159B 9A

Load Rate: 0.0018 mm/s

Test Fixture: 15° Test Temperature: 76K
Test Date: 4/7/95

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
159B-4	15	B7	A7	T	8.18	11.3	12.60	87.2	23.4	C
159B-5	15	A7	B5	T	8.18	15.3	12.60	118.6	31.8	C
159B-6	15	A5	B5	B	8.20	16.0	12.57	124.8	33.4	C,G

SHEAR STRENGTH

AVERAGE (MPa): 110.2
STD.DEV. (MPa): 20.1
CV: 0.18

COMPRESSION STRENGTH

AVERAGE (MPa): 29.5
STD.DEV. (MPa): 5.4
CV: 0.18

Test Fixture: 45° Test Temperature: 76K

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
159B-1	45	B6	A6	B	8.20	32.3	12.60	183.5	183.5	C
159B-2	45	B6	B8	T	8.20	32.4	12.57	184.3	184.3	C
159B-3	45	B7	B8	B	8.20	32.6	12.57	185.8	185.8	C

SHEAR STRENGTH

AVERAGE (MPa): 184.6
STD.DEV. (MPa): 1.2
CV: 0.01

COMPRESSION STRENGTH

AVERAGE (MPa): 184.5
STD.DEV. (MPa): 1.2
CV: 0.01

Test Fixture: 75° Test Temperature: 76K

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
159B-7	75	A8	A5	BOTH	8.19	121.7	12.60	252.8	943.1	C,G

SHEAR STRENGTH

AVERAGE (MPa): 252.8
STD.DEV. (MPa): #DIV/0!
CV: #DIV/0!

COMPRESSION STRENGTH

AVERAGE (MPa): 943.1
STD.DEV. (MPa): #DIV/0!
CV: #DIV/0!

Tested By: Date: 4/7/95
Date: 4/18/95
4/21/95

Failure Mode:
A/M - Adhesive failure at the metal.
A/K - Adhesive failure at the Kapton.
C,G - Cohesive failure of composite and G-11CR
C - Cohesive failure in the composite.

TPX Shear/Compression Test Results

Resin System: SHELL 826
Reinforcement: 3-D Weave (4 plies) **Condition:** AR
Barrier: None
Specimen Type: S/C - Stainless Steel Chips
Material Reference #: Run # 163A 9B

Load Rate: 0.0018 mm/s

Test Fixture: 15° **Test Temperature:** 76K
Test Date: 4/15/95

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
163A-4	15	B3	A3	T	8.18	7.2	12.57	56.3	15.1	C,AM
163A-5	15	B1	A3	B	8.18	7.9	12.60	61.0	16.3	C,AM
163A-6	15	B1	B4	T	8.20	9.5	12.60	73.9	19.8	C,AM

SHEAR STRENGTH

AVERAGE (MPa): 63.7
STD.DEV. (MPa): 9.1
CV: 0.14

COMPRESSION STRENGTH

AVERAGE (MPa): 17.1
STD.DEV. (MPa): 2.4
CV: 0.14

Test Fixture: 45° **Test Temperature:** 76K

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
163A-1	45	A2	A1	B	8.18	30.0	12.60	170.5	170.4	C
163A-2	45	A2	B1	T	8.18	30.4	12.57	173.0	173.0	C
163A-3	45	A4	B1	T	8.18	31.0	12.57	176.9	176.8	C

SHEAR STRENGTH

AVERAGE (MPa): 173.4
STD.DEV. (MPa): 3.2
CV: 0.02

COMPRESSION STRENGTH

AVERAGE (MPa): 173.4
STD.DEV. (MPa): 3.2
CV: 0.02

Test Fixture: 75° **Test Temperature:** 76K

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
163A-7	75	B2	B4	BOTH	8.20	117.6	12.59	244.9	913.6	C

SHEAR STRENGTH

AVERAGE (MPa): 244.9
STD.DEV. (MPa): #DIV/0!
CV: #DIV/0!

COMPRESSION STRENGTH

AVERAGE (MPa): 913.6
STD.DEV. (MPa): #DIV/0!
CV: #DIV/0!

Tested By: JBB Date: 4/15/95
Reviewed By: JBB Date: 4/18/95
Checked By: [illegible] Date: 4/21/95

Failure Mode:
A/M - Adhesive failure at the metal.
A/K - Adhesive failure at the Kapton.
C,AM - Failure located at metal interface; epoxy adhering to metal surface; some composite damage present.
C - Cohesive failure in the composite.

TPX Shear/Compression Test Results

Resin System: SHELL 826
Reinforcement: TTI Plain weave (8 plies) Condition: AR
Barrier: Kapton 100HA (4 Plies)
Specimen Type: S/C - Stainless Steel Chips
Material Reference #: Run # 163B 9C

Load Rate: 0.0018 mm/s

Test Fixture: 15° Test Temperature: 76K
Test Date: 4/15/95

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
163B-4	15	B8	A6	B	8.18	5.5	12.60	42.3	11.3	A/K
163B-5	15	B8	B5	B	8.18	5.2	12.60	40.2	10.8	A/K
163B-6	15	B6	B8	T	8.20	7.6	12.57	58.8	15.8	A/K

SHEAR STRENGTH

AVERAGE (MPa): 47.1
STD.DEV. (MPa): 10.2
CV: 0.22

COMPRESSION STRENGTH

AVERAGE (MPa): 12.6
STD.DEV. (MPa): 2.7
CV: 0.22

Test Fixture: 45° Test Temperature: 76K

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
163B-1	45	B7	A5	B	8.20	20.5	12.57	116.9	116.9	A/K
163B-3	45	B7	A7	B	8.18	18.7	12.60	105.9	105.9	A/K

SHEAR STRENGTH

AVERAGE (MPa): 111.4
STD.DEV. (MPa): 7.8
CV: 0.07

COMPRESSION STRENGTH

AVERAGE (MPa): 111.4
STD.DEV. (MPa): 7.8
CV: 0.07

Test Fixture: 75° Test Temperature: 76K

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
163B-7	75	B8	B7	BOTH	8.18	70.1	12.60	145.5	542.9	C/K

SHEAR STRENGTH

AVERAGE (MPa): 145.5
STD.DEV. (MPa): #DIV/0!
CV: #DIV/0!

COMPRESSION STRENGTH

AVERAGE (MPa): 542.9
STD.DEV. (MPa): #DIV/0!
CV: #DIV/0!

Tested By: JS Date: 4/15/95
Analyzed By: JS Date: 4/18/95
Checked By: [illegible] Date: 4/20/95

Failure Mode:
A/M - Adhesive failure at the metal.
A/K - Adhesive failure at the Kapton.
C/K - Cohesive failure at the Kapton; tearing of the Kapton.
C - Cohesive failure in the composite.

Composite Technology Development, Inc.

TPX Shear/Compression Test Results

Resin System: SHELL 826
Reinforcement: S-2 Glass - 6781 **Condition:** AR
Barrier: CTD-101G
Specimen Type: S/C - Stainless Steel Chips
Material Reference #: Run # 165A 10 A

Load Rate: 0.0018 mm/s

Test Fixture: 15° **Test Temperature:** 76K
Test Date: 5/5/95

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
165A-4	15	B3	B2	B	8.20	8.1	12.60	62.7	16.8	B
165A-5	15	B3	B1	B	8.20	12.3	12.60	95.7	25.6	AB
165A-6	15	A3	B3	B	8.20	13.6	12.60	105.1	28.2	C,AM

SHEAR STRENGTH

AVERAGE (MPa): 87.8
STD.DEV. (MPa): 22.3
CV: 0.25

COMPRESSION STRENGTH

AVERAGE (MPa): 23.5
STD.DEV. (MPa): 6.0
CV: 0.25

Test Fixture: 45° **Test Temperature:** 76K

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
165A-1	45	B2	A2	B	8.18	28.8	12.57	164.1	164.1	B
165A-2	45	B2	B4	B	8.18	26.4	12.60	149.9	149.9	B
165A-3	45	A1	B2	T	8.20	26.4	12.60	149.8	149.8	B

SHEAR STRENGTH

AVERAGE (MPa): 154.6
STD.DEV. (MPa): 8.2
CV: 0.05

COMPRESSION STRENGTH

AVERAGE (MPa): 154.6
STD.DEV. (MPa): 8.2
CV: 0.05

Test Fixture: 75° **Test Temperature:** 76K

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
165A-7	75	A3	A4	BOTH	8.20	109.1	12.60	226.6	845.2	B,C

SHEAR STRENGTH

AVERAGE (MPa): 226.6
STD.DEV. (MPa): #DIV/0!
CV: #DIV/0!

COMPRESSION STRENGTH

AVERAGE (MPa): 845.2
STD.DEV. (MPa): #DIV/0!
CV: #DIV/0!

Tested By: [signature] Date: 5/12/95
Analyzed By: [signature] Date: 5/16/95
Checked By: [signature] Date: 5/17/95

Failure Mode:
A/M - Adhesive failure at the metal.
A/B - Adhesive failure at the Barrier
C/K - Cohesive failure at the Kapton; tearing of the Kapton.
C - Cohesive failure in the composite.
B - Breakage/cohesive failure in the barrier

E

TPX Shear/Compression Test Results

Resin System: SHELL 826
Reinforcement: S-2 Glass - 6781 **Condition:** AR
Barrier: AV-1580
Specimen Type: S/C - Stainless Steel Chips
Material Reference #: Run # 165B 10B

Load Rate: 0.0018 mm/s

Test Fixture: 15° **Test Temperature:** 76K
Test Date: 5/5/95

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
165B-4	15	B6	B5	B	8.18	7.7	12.60	59.7	16.0	B
165B-5	15	A6	B8	B	8.18	8.9	12.60	68.7	18.4	B
165B-6	15	A6	B6	B	8.20	8.5	12.60	65.7	17.6	B

SHEAR STRENGTH

AVERAGE (MPa): 64.7
STD.DEV. (MPa): 4.6
CV: 0.07

COMPRESSION STRENGTH

AVERAGE (MPa): 17.3
STD.DEV. (MPa): 1.2
CV: 0.07

Test Fixture: 45° **Test Temperature:** 76K
Test Date:

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
165B-1	45	B5	A7	B	8.18	19.7	12.57	112.0	111.9	B
165B-2	45	B5	B7	B	8.18	19.8	12.60	112.5	112.5	B
165B-3	45	A5	B5	T	8.20	18.4	12.60	104.2	104.1	B

SHEAR STRENGTH

AVERAGE (MPa): 109.5
STD.DEV. (MPa): 4.7
CV: 0.04

COMPRESSION STRENGTH

AVERAGE (MPa): 109.5
STD.DEV. (MPa): 4.7
CV: 0.04

Test Fixture: 75° **Test Temperature:** 76K
Test Date:

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
165B-7	75	A6	A8	BOTH	8.18	94.5	12.60	196.3	732.2	B,C

SHEAR STRENGTH

AVERAGE (MPa): 196.3
STD.DEV. (MPa): #DIV/0!
CV: #DIV/0!

COMPRESSION STRENGTH

AVERAGE (MPa): 732.2
STD.DEV. (MPa): #DIV/0!
CV: #DIV/0!

Tested By: [signature] **Date:** 5/12/95
Analyzed By: [signature] **Date:** 5/16/95
Checked By: [signature] **Date:** 5/17/95

Failure Mode:
A/M - Adhesive failure at the metal.
A/B - Adhesive failure at the Barrier
C/K - Cohesive failure at the Kapton; tearing of the Kapton.
C - Cohesive failure in the composite.
B - Breakage/cohesive failure in the barrier

TPX Insulation & Impregnation R&D - 1x2 Test Report

J. F. Roach and W. M. Urban
Advanced Electromechanical Systems Department

D. Hartman
Everson Electric Company

August 4, 1995

TPX 14-950630-WEC-FRoach-01

APPROVED:

P. A. Sanger
Westinghouse TPX Chief Scientist

APPROVED:

D. R. Potter
Westinghouse TPX Engineering Manager

Westinghouse Electric Corporation
Electronic Systems Group

401 East Hendy Avenue, Sunnyvale, California 94088-3499

CONTENTS

LIST OF FIGURES iv

LIST OF TABLES iv

ABSTRACT v

1. OBJECTIVE AND SCOPE 1-1

2. INSULATION SYSTEM OPTIONS 2-1

3. CONCLUSIONS 3-1

4. ELECTRICAL TEST PROGRAM 4-1

4.1 SAMPLE DESIGNS 4-1

4.2 FABRICATION AT EVERSON ELECTRIC 4-6

4.3 TEST MATRIX, EQUIPMENT, AND PROCEDURES 4-9

5. TEST RESULTS 5-1

5.1 DIELECTRIC, HIPOT, AND PARTIAL DISCHARGE PERFORMANCE. 5-1

5.2 AC LIFE TESTING 5-4

5.3 HIPOT TO FAILURE TESTS 5-5

5.4 COMPARATIVE DIELECTRIC PERFORMANCE 5-5

6. REFERENCES 6-1

7. ACKNOWLEDGMENTS 7-1

8. APPENDIX 8-1

LIST OF FIGURES

Figure 1 — Photograph of as received 3x3 Model 1, CDR Baseline design, side view 4-7

Figure 2 — Photograph of as received 3x3 Model 1, CDR Baseline design, end view. 4-8

LIST OF TABLES

Table 1 — Summary of 3x3 Insulation Model Designs 4-2

Table 2 — Electrical Testing Evolution and Matrix for 3x3 Models. 4-10

Table 3 — Summary of Dielectric Performance of TPX 3x3 Insulation Models 5-2

Table 4 — Summary of 1 Hour, 60 Hz Life Test for TPX 3x3 Models, 4B, 5A and 6A 5-6

ABSTRACT

Electrical insulation test results are reported and analyzed for the 3x3 TPX Insulation & Impregnation R&D program. The focus of the 3x3 sample electrical testing was verification of electrical insulation integrity of insulation design options after mechanical life cycle testing at liquid nitrogen temperature. The 3x3 samples were fabricated at the Everson Electric Company in Allentown, PA. The mechanical cycling and electrical verification testing was carried out at the Westinghouse Science & Technology Center, Pittsburgh, PA. The electrical performance of the TPX CDR fully bonded baseline epoxy/glass insulation system and proposed alternate insulation systems employing Kapton insulation on conduits were evaluated in as received post cure sample condition and after mechanical life cycling. The Shell 826, DGBA impregnation system was selected for all dry glass wrapped 3x3 samples. The CTD101K, Flexibilized DGBA impregnation system was used for 3x3 samples wrapped with CTD112P prepreg. Incoloy 908 dummy conductor was used for all 3x3 samples. Samples were electrically tested in as received post cure condition, after 15,000 mechanical cycles in liquid nitrogen, and after incipient mechanical failure. Capacitance, dielectric loss (tan δ), and insulation resistance (IR) dielectric characteristics were measured for all samples. Partial discharge performance in air was measured to determine onset/offset voltage and peak discharge levels (pC) up to 10 kVac at 60 Hz. Turn-to-turn Hipot testing was performed at 20 kVdc acceptance level. After completion of all screening tests a final Hipot-to-failure test was performed up to 40 kVdc with power supply trip set at 50 μA leakage current limit. Accelerated life testing was proposed late in the 3x3 program and was performed on the Kapton Slip and Hybrid Prepreg design options. Samples were cross sectioned, polished, and evaluated for impregnation quality and insulation damage due to mechanical cycling. Based upon the 3x3 results and after review with LLNL and B&W, the Kapton Slip option, incorporating 3-D weave dry glass wrap and 3-D corner filler, was downselected for acceptance testing in the 5x5 program.

1. OBJECTIVE AND SCOPE

The principle objective of the TPX 3X3 Insulation & Impregnation R&D program was to develop an insulation system for both TF and PF winding pack designs which meets the electrical, thermal, and mechanical performance requirements under all TPX operational senarios with acceptable safety margins. The focus of the electrical testing was to develop a clear understanding of the insulation performance and degradation over life cycle mechanical stress, and to assess potential failure modes between turns and layer insulation. The electrical testing procedures evolved over the course of the 3x3 program to measure and compare insulation capability for as received samples, after 15,000 mechanical life cycles under liquid nitrogen, and after incipient mechanical failure. The basic insulation was verified throughout the testing program at a 20 kVdc Hipot with a 50 μA leakage current limit for failure, and following completion of mechanical failure testing, Hipot to failure up to 40 kVdc withstand capability was measured. Partial discharge performance up to 10 kVrms with <1000 pC discharge level limit was measured. An electrical AC (60 Hz) life test was introduced late in the program to simulate the number of electrical stress cycles expected during TPX machine life. A 10 kVrms, 15 min test was proposed to test insulation life equivalent to one life cycle at average stress of >6 kVrms/mm.

The 3x3 program explored Kapton/Epoxy/Dry Glass and Kapton/Epoxy/Prepreg Glass insulation design options to the fully bonded CDR baseline design, that is Barrier/Epoxy/Dry Glass. The 3x3 samples incorporated a variety of materials, including Kapton film with or without adhesive, 2-D and 3-D dry glass wraps, 2-D prepreg wrap, and a number of corner fillers. Glass roving bundles, epoxy resin putty, and 3-D woven structures, including tackified preforms

were tried as corner filler approaches. The material selection goal was to optimize the mechanical strength, modulus, and thermal expansion properties of impregnated insulation wraps and void fillers with respect to conductor material so that the insulation will survive the through-tension, compressive, and shear force combinations induced during TPX machine operation. The selection of 3-D glass materials was principly driven by the necessity for improvement in insulation material properties to be able to survive the expected mechanical stresses within the winding pack over life cycle. In all cases the optional insulation designs eliminate the G11CR barrier sheets between layers and strips between turns proposed in the CDR baseline design. Incoloy 908 dummy conductor was use in the construction of all the 3x3 samples and was cut into 125 mm or 250 mm nominal lengths. The 3x3 samples were impregnated and cured in an aluminum mold without groundwall insulation and with extended end insulation sufficient to ensure encapsulated ends to prevent end turn electrical failure.

The 3x3 electrical insulation test objectives were to:

- Compare electrical performance of CDR baseline and optional Kapton insulation designs
- Demonstrate insulation capability after mechanical life cycle test under liquid nitrogen for 15,000 cycles
- Assess insulation margin after mechanical life via Hipot to failure and AC voltage life testing
- Correlate insulation failure with cyclic mechanical load damage to insulation structure such as gross cracks, local crazing, and lack of impregnation
- Recommend insulation system for verification and acceptance in the 5x5 R&D program follow-up

2. INSULATION SYSTEM OPTIONS

The 3x3 program investigates Kapton insulation system options to the CDR baseline which offer not only improved dielectric performance, but insulation material properties which help solve structural integrity problems with the CDR insulation design identified by MIT structural analyses, Reference 1. The 1x2 R&D screening program, Reference 2 explored several Kapton insulation options and demonstrated excellent dielectric performance of the Kapton Slip option, and this option was selected as the primary candidate for further evaluation in the 3x3 program. The interleaved Kapton/Dry Glass fully bonded approach tested in the 1x2 program was believed to be too high a risk for manufacturing, posing problems in wrapping interleaved Kapton and dry glass tapes as well as achieving through impregnation through the interleaved glass wicking paths to the conduit/glass interface with potential weak bonding between Kapton and glass interfaces. At the inception of the 3x3 program the ITER Kapton/Prepreg insulation concept as modified and tested in the 1x2 program was held in reserve pending resolution of poor 1x2 sample impregnation resulting from the hybrid prepreg/VPI curing process tried.

In the initial phase of the 3x3 program three samples were built focusing on the electrical/mechanical performance of the CDR baseline with either glass bundle corner roving, 125 mm Sample 1 or Araldite epoxy resin putty corner filler, 250 mm Sample 3, and the Kapton Slip option, 250 mm Sample 2 with XMPI adhesives used to seal the conductor surface from the VPI resin. The Shell 826 resin system was downselected from the 1x2 program for the 3x3 VPI process. Following the Insulation Workshop and MSIM #4 held at WEC, Sunnyvale, CA, 02/01-02/95, three insulation systems were recommended and agreed upon by WEC, B&W, LLNL,

MIT, and PPPL for evaluation in the balance of the 3x3 program. The three insulation systems focused on 3-D materials for conductor wrapping and/or corner filler for improved mechanical and thermal material properties. Consequently, six additional 3x3 samples were fabricated, two identical 125 mm long samples per each of three impregnation runs. The final 3x3 sample configurations were: Kapton/Dry Glass(3-D Weave) without adhesive on Kapton, Samples 4A and 4B; Hybrid Prepreg(2-D CTD112P prepreg) with interleaved Kapton and 3-D weave overwrap, Samples 5A and 5B; and 3-D Thick Weave in a "Cigar Roll" wrap directly around conductor without Kapton, Samples 6A and 6B. In all cases the samples in impregnation batches 4-6 employed 3-D shaped corner fillers either dry glass or tackified to the void fill shape.

3. CONCLUSIONS

Based upon the electrical test results for the TPX Insulation & Impregnation R&D-3x3 program discussed in this report, the following conclusions are reached:

1. The CDR Baseline design employing glass roving bundles for corner fillers performed without insulation failure at the 10 kVdc Hipot level through 3 thermal and 15,000 mechanical cycles. Partial discharge onset voltage for 100 pC discharges dropped only slightly from the as received condition at 4.8 kVrms to 4.0 kVrms after mechanical cycling, with <1000 pC peak discharges at 7 kVrms. The CDR Baseline design incorporating Araldite epoxy resin putty corner filler failed 20 kVdc Hipot for all turn pairs except one after mechanical failure following 2 thermal and 15,000 mechanical cycles due to gross cracking of the Araldite cured resin and fracture of the layer barrier.
2. The adhesive(XMPI) Kapton Slip Plane design employing glass roving for corner fillers and plane weave dry glass wrap had no turn pair failures at 20 kVdc Hipot after mechanical failure following 3 thermal and 15,000 mechanical cycles with minimum turn-to-turn withstand of 27 kVdc for all turn pairs at 50 μA current limit. The Kapton Slip Plane design without adhesive on Kapton and using 3-D weave dry glass wrap and 3-D shaped corner fillers had a withstand of at least 31 kVdc for all turns after 2 thermal and 15,000 mechanical cycles; after 3 thermal cycles following mechanical failure only one turn pair failed 20 kVdc Hipot, but all turns withstood 16 kVdc for 60 s. For Hipot >20 kVdc several turn pairs failed.
3. The Hybrid Prepreg/3-D design with 2-D prepreg glass, 3-D dry glass overwrap, and 3-D shaped corner fillers, failed 20 kVdc Hipot for one turn pair following 2 thermal and 15,000 mechanical cycles. After 3 thermal cycles and load to

failure, there was gross mechanical failure of the 3x3 structure and complete loss of insulation integrity.

4. The all 3-D Cigar Roll design with 3-D woven cloth wrap and 3-D shaped corner fillers failed all turn pairs at 20 kVdc Hipot following 2 thermal and 15,000 mechanical cycles. Microcracking of the 3-D woven cloth was suspected as the cause for the dielectric failure. Initial concerns with the quality of the impregnation were proven to be unfounded by subsequent cross sectioning without heating; overheating during original sample cross sectioning was determined to be the cause ot the insulation blackening and softness leading erroneously to impregnation concerns.
5. On the basis of the electrical test results a recommendation was made to downselect for the 5x5 program as an Interim PDR Baseline the Kapton Slip Plane design based upon 3x3 Models 4A and 4B. The Interim Baseline configuration is 2-50% laps of 0.0254 mm thick, 25.4 mm wide Kapton without adhesive overwrapped with 1-50% 3-D S-2 glass tape 0.356 mm thick, 25.4 mm wide, and 3-D shaped and tackified corner fillers. Shell 826 is chosen as the VPI resin system.

4. ELECTRICAL TEST PROGRAM

4.1 SAMPLE DESIGNS

The 3x3 sample designs are summarized in Table 1. The conductor insulation wrap, corner filler, and VPI system configurations are presented. The post cure sample dimensions and deduced insulation builds are also given in Table 1. Detailed descriptions of the insulation materials, specifications, vendor interactions, and development of 3-D glass wraps and corner fillers used in the 3x3 program are found in Reference 3. The sample or model numbers given in Table 1 are in the fabrication sequence. Incoloy 908 dummy conductors were used for all 3x3 models. The Shell 826 resin system was used to VPI all models except the Hybrid Prepreg models 5A and 5B which used the CTD101K resin system for compatibility with the CTD112P prepreg resin applied to plain weave S-2 glass tape obtained from Carolina Narrow Fabric(CNF). The CFN S-2 glass tape was prepreged by Electromat, Inc., Mars, PA.

All 3x3 models were aligned arrays of turns one on top of the other without offsets. No groundwall insulation was applied. Prior to wrapping with insulation, the dummy conductors were sealed at both ends using RTV. The RTV sealing proved to be effective seals, preventing epoxy from getting inside the conductors during impregnation. The models were impregnated in an aluminum mold, 660 mm long designed originally to accommodate two 250 mm long 3x3 models in a single impregnation. The mold cavity was designed to close based upon the design goal for the CDR Baseline configuration. Tedlar was wrapped around the models as a mold release. The Models 1 and 3 are CDR Baseline designs employing 2-D glass wraps directly over grit blasted Incoloy 908 conductors. G-10 barrier sheets, 0.036 mm

Table 1 — Summary of 3x3 Insulation Model Designs

Model	Insulation System	Corner Roving	VPI System	Conduit Insulation Build mils	Insulation Build L-L & T-T mm	Model Length L (Metal Flat) inches	Model Cross Section H x W inches
1-CDR Baseline	TTI Satin weave wrap 3/4"x.010" with G-10 L-L barriers	Glass bundle	Shell 826	45.6	2.672 L-L 2.316 T-T	5.375	2.937 x 2.914
2-Slip Plane Option	Kapton H .001" with XMPI adhesive with TTI Plain weave wrap 3/4"x.008"	Glass bundle	Shell 826	30.9	1.570 L-L & T-T	9.938	2.820 x 2.820
3-CDR Baseline with Araldite	TTI Plain weave wrap 3/4"x.008" with G-10 L-L barriers	Araldite Epoxy Resin Putty	Shell 826	25.9	1.671 L-L 1.316 T-T	9.938	2.816 x 2.791
4A-Interim Baseline with 3-D Overwrap	Kapton H .001" w/o adhesive and Techniweave 3-D 1"x.014" wrap	3-D Shape Dry (16)	Shell 826	32.5	1.651 L-L & T-T	4.812	2.824 x 2.834
4B-Interim Baseline with 3-D Overwrap	Same as 4A	3-D Shape Tackified (16)	Shell 826	36.9	1.875 L-L & T-T	4.812	2.857 x 2.854

Table 1 — Summary of 3x3 Insulation Model Designs (Cont.)

Model	Insulation System	Corner Roving	VPI System	Conduit Insulation Build mils	Insulation Build L-L & T-T mm	Model Length L (Metal Flat) inches	Model Cross Section H x W inches
5A-Hybrid Prepreg with 3-D Overwrap	CNF Plain weave 1"x.007 with CTD 112P prepreg and Kapton H 1"x.007" on top with Techniweave 3-D 1"x.014" overwrap	3-D Shape Tackified (16)	CTD 101K (No mold preheat)	30.6	1.554 L-L & T-T	4.812	2.824 x 2.826
5B-Hybrid Prepreg with 3-D Overwrap	Same as 5A	3-D Shape Tackified (12) Dry (4)	CTD 101K (No mold preheat) 101K	31.3	1.590 L-L & T-T	4.812	2.828 x 2.830
6A-3-D Cigar Roll	Techniweave 3-D cloth 3.75"x.032" with .016 seam tabs	3-D Shape Tackified (8) Dry (8)	Shell 826	30.6 L-L 27.1 T-T	1.554 L-L 1.377 T-T	4.812	2.825 x 2.804
6B-3-D Cigar Roll	Same as 6A	3-D Shape Tackified (9) Dry (7)	Shell 826	29.6 L-L 26.3 T-T	1.504 L-L 1.336T-T	4.812	2.819 x 2.799

thick were placed between the two 3-turn layers in the horizontal plane only; no barriers were placed between turns in the vertical direction. Therefore, the 3x3 CDR Baseline models represent modifications since the baseline design incorporates barrier strips beween turns within a pancake layer. Model 1 employed a 4-harness Satin finish S-2 glass tape purchased from Textiles Technology, Inc.(TTI), Hatboro, PA. The TTI glass tape was designed for a thickness of 0.178 mm but the product shipped had a nominal thickness of 0.25 mm, which led to a nominal turn-to-turn insulation build of 2.32 mm considerably larger than the design goal of 1.626 mm. Glass roving bundles were used for corner fillers in Model 1, using adhesive Kapton to hold bundles together. Model 3 was a CDR Baseline model with Araldite epoxy resin putty employed for corner fillers. In Model 3 the insulation builds were improved by using a TTI plain weave S-2 glass tape with nominal thickness of 0.20 mm. The Araldite putty was formed by mixing the Araldite AV 1580 GB Bisphenol A epoxy resin and HV 1580 GB hardener, rolling into a cylindrical shape with diameter estimated for the putty completely fill a corner void, and then gently pressed into the corner voids. The Araldite putty cured at room temperature over a period of several hours.

Model 2 was the Kapton Slip option explored in the 1x2 program. In this case an XMPI adhesive was used on the 0.0254 mm thick Kapton film to seal the two half lap Kapton wraps on the conductor in an effort to prevent VPI resin from getting to the conductor wall. Adhesive was on just the top of the inner wrap on the conductor and on both top and bottom sides of the outer Kapton wrap. After wrapping the two 50% laps of adhesive Kapton the conductors were placed in an oven and the XMPI adhesive kicked-off at 185°C. After bonding of the Kapton wraps was complete, the glass wraps were applied and the model assembled and VPI'ed. Model 2 used glass roving bundles for corner filler and did not have any G-10 barrier sheets. The TTI plain weave glass tape used in Model 3 was employed, and the turn-to-turn insulation build of 1.57 mm was very close to the design goal.

Models 4A and 4B were Kapton Slip designs using two 50% Kapton layers without adhesive, 1-50% layer of 3-D S-2 glass tape nominally 0.36 mm thick, and

3-D S-2 glass woven into the shape of the corner void. Model 4A employed the dry glass 3-D shaped void fillers while for Model 4B the 3-D void fillers were molded to shape and tackified with Shell 826 resin cut with acetone to form solid shapes The 3-D glass tape and corner void fillers were obtained from Techniweave, Inc., Rochester, NH. Development of 3-D materials for the 3x3 program is discussed in Reference 3.

Models 5A and 5B were Hybrid Prepreg with interleaved Kapton/prepreg wrap and 3-D dry glass tape overwrap using tackified corner void fillers. The Hybrid Prepreg appoach is based upon a modification of the ITER conduction insulation design. In the TPX case, the interleaved Kapton/prepreg wrap is not separately cured as in the ITER design, but a hybrid curing was attempted such that the CTD112P prepreg was cured during the VPI process using CTD101K resin system. Although it would be ideal to precure the prepreg wrap before the VPI process, it was believed that a reasonable hybrid cure could be obtained sufficient to evaluate the electrical and mechanical performance. In order to prevent premature curing of the prepreg before the injection of the VPI resin, the mold was not preheated during initial evacuation, and therefore, the VPI impregnation process was not optimal.

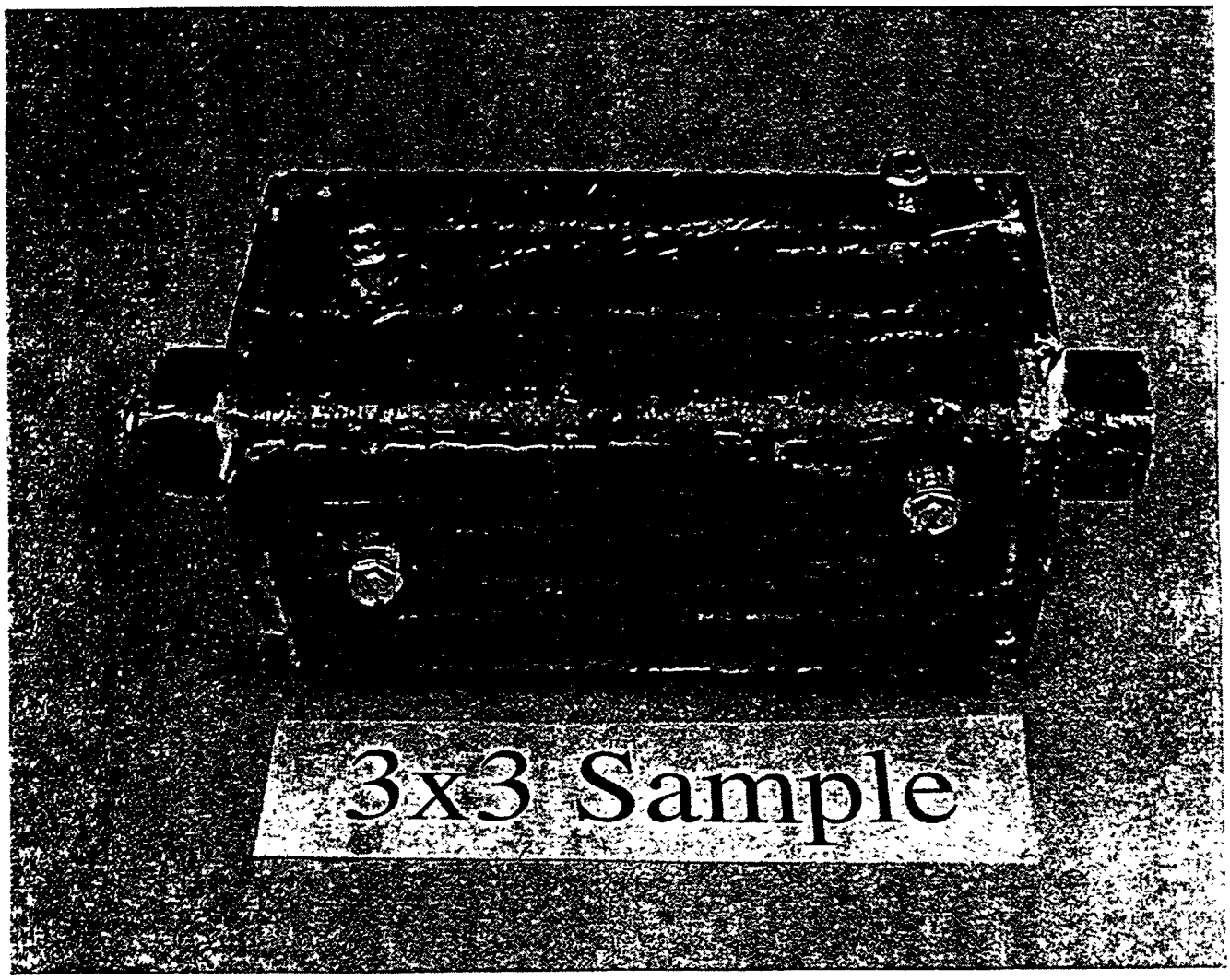
Models 6A and 6B were fully bonded 3-D weave designs which are in principle equivalent to the CDR Baseline with the exception that turn and layer barriers are not necessary. In the 3-D Cigar Roll design, a 3-D cloth nominally 95 mm wide and 0.81 mm thick is directly wrapped around the conductors in the longitudinal direction, as if wrapping a cigar or cigarette. The 3-D cloth was designed by the B&W team working with Techniweave, Inc. and provided to the WEC team for the 3x3 program. The 3-D cloth was designed so that the body of the cloth tapered on both edges so that the wrapped cloth formed an overlapping seam which had the nominal build of the body of the tape. For these full 3-D models the both tackified and dry 3-D corner fillers were used. The turn-to-turn builds for these models were nominally 1.35 mm between turns without the seam and 1.52 mm with

one seam. Therefore, the overlapping design of the 3-D cloth led to an increase build of about 0.17 mm.

4.2 FABRICATION AT EVERSON ELECTRIC

The fabrication, assembly, and impregnation of the 3x3 samples were carried out at the Everson Electric Company, Allentown, PA under the direction of Mr. Doug Hartman. The 3x3 models were constructed under factory environments by Everson Electric personnel experienced in insulation and impregnation processes. The 3x3 models were build employing the same procedures for the 1x2 program described in Reference 2, and incorporated the lessons learned in fabrication during the 1x2 program. The impregnation process used in the 1x2 program, Reference 2 was followed for the 3x3 program. Except of the Hybrid Prepreg models, the mold was preheated and evacuated hot prior to resin injection. The final cure of the VPI resin system was done with atmospheric pressure on the mold resin. The completed samples were shipped to the WEC Science & Technology Center for electrical testing.

A typical 3x3 sample as received from Everson Electric is shown in Figures 1 and 2 which are photographs of the CDR Baseline, Model 1. The 3x3 models all had extended central conductors for improved electrical creep path between the central conductor and the adjacent outside conductors as can be seen in Figure 1. The electrical leads were attached at WEC-STC. As seen in Figure 1 sheet metal screws threaded into the conductor wall through holes drilled through the insulation to the conduit wall or along the axis of the central conductor provided electrical posts. Banana plug connections were employed for subsequent models to improve external flashover between leads and partial discharge activity at lead posts. The end turns were label on each model from left to right and top to bottom from 1-9 for identification during electrical testing. The cyclic compressive load was applied across the face of upper turns 1-3 and lower turns 7-9.



RM-34138

Figure 1— Photograph of as received 3x3 Model 1, CDR Baseline design, side view.

RM-34137

Figure 2 —Photograph of as received 3x3 Model 1, CDR Baseline design, end view.

4.3 TEST MATRIX, EQUIPMENT, AND PROCEDURES

The electrical testing plan evolved during the course of the 3x3 program. The electrical test matrix showing the tests applied to each of the 3x3 models is presented in Table 2. For all models the dielectric properties to characterize the sample capacitance(pC), dielectric loss(%), and insulation resistance IR(Ω) were measured as received, after mechanical life cycling, and mechanical failure. Hipot testing evolved from a verification test at 10 kVdc for 5 s to 20 kVdc for 15 s followed by 16 kVdc for 60 s. Hipot to failure tests were conducted up to 40 kVdc withstand. Partial discharge tests were performed in air up to 10 kVrms at 60 Hz, measuring PD onset/offset, average and peak pC discharge levels. AC life testing was introduced after Model 3 was tested and applied to Models 4B Kapton Slip design and 5A Hybrid Prepreg design. The AC life test was applied to selected turn pairs and was conceived as a 10 kVrms voltage test for 1 hour to simulated 7.2 electrical life cycles at an average electrical stress level between turns of 6 kVrms/mm.

The following test equipment was employed at W-STC in the electrical evaluation of the 3x3 samples:

TEST EQUIPMENT	MEASUREMENT
4274A Multi-frequency LCR Meter	Capacitance, loss tangent to 100 kHz
1864 Megohm Meter, General Radio	Insulation resistance (IR) to 1000 V
100 kV Hipot Facility	DC withstand and leakage current
50 kV Biddle Instruments Partial Discharge Detector, Model 66/5700	Peak and average partial discharge, 60 Hz
40 kV Biddle DC/AC Hipot Tester	DC withstand and leakage current

The electrical testing procedures used in the 1x2 program described in Reference 2 were generally followed in the 3x3 program. The 3x3 Hipot testing was performed on all adjacent turn pairs of the 3x3 conductor array. The partial discharge testing was generally perfomed with the high voltage applied to the central conductor with the eight adjacent conductors grounded; in some cases where faulted turns existed due to mechanical damage, selected adjacent turns and turn groups were used for partial discharge measurements.

Table 2 — Electrical Testing Evolution and Matrix for 3x3 Models

MODEL	DIELECTRIC PROPERTIES			DC HIPOT AR/15,000/Failure				PARTIAL DISCHARGE To 10 kVrms in 0.5 kVrms steps Average & Peak pC			AC LIFE TEST Selected Turn Pairs at 10 kVrms for 1 hr 7.2 LC at 6 kVrms/mm
	C pF	Loss %	IR Ω	10 kVdc 5s	20 kVdc 15s	16 kVdc 60s	40 kVdc Withstand Maximum	All pairs	Selected pairs	Selected pairs & <2000 pC	Selected Turn Pairs
1-CDR Baseline	√	√	√	√				√			
3-CDR Baseline with Araldite	√	√	√			√	All pairs (1 Fault)		√		
2-Slip Plane Option	√	√	√		√	√	Only after cycling			√	
4B-Interim Baseline	√	√	√		√	√	All ext. pairs until two faults			√	√ After Failure
5A-Hybrid Prepreg	√	√	√		√	√	All ext. pairs until two faults			√	√ After 15,000 cycles
6A-3-D Cigar Roll	√	√	√		√	√	All ext. pairs until two faults				

5. TEST RESULTS

5.1 DIELECTRIC, HIPOT, AND PARTIAL DISCHARGE PERFORMANCE

A summary of the electrical performance for the 3x3 program is presented in Table 3. The measured values are given under selected test conditions for in as received condition and after the thermal and mechanical cycles indicated. The model capacitance and loss tangent for the central turn to the adjacent outside turns is given at 1 kHz test frequency and varied little over the 0.1 to 10 kHz range. The loss tangent at 1 Hz was in the range 0.2-0.6 %. The insulation resistance in the as received condition measured between 2 to $>100 \times 10^{12}$ Ω and generally was reduced by factors ranging from 3-10 after mechanical cycling and cracking damage. Partial discharge onset voltage for as received samples at the 100 pC level was typically in the 3.5-6.5 kVrms range with activity >1000 pC measured when the applied voltage was in the 5.5-9.5 kVrms range. The as received dielectric measurements of loss tangent, IR and partial discharge generally indicated that all 3x3 models were well impregnated. Every 3x3 sample passed the as received Hipot test level, 10 kVdc for the CDR Baseline, Model 1 and 20 kVdc for all other models. The 10 kV level was initially established for the 3x3 program based upon 4.5 kV as the nominal peak PF line voltage and employing a test voltage criteria as 2x4.5 kV + 1 kV = 10 kV test voltage turn-to-turn acceptance. After the completion of the Model 1 testing the Hipot criteria was changed to 20 kVdc for 15 s followed by 16 kVdc for 60 s. The Hipot power supply was set to trip on the most sensitive setting at about 10 μA minimum to 50 μA maximum leakage current for fault indication. Following mechanical cycling Hipot was performed on all turn pairs to probe for dielectric weakness resulting from the thermal and mechanical load cycles. And following the final mechanical loading to incipient mechanical failure, that is first indication of

Table 3. Summary of Dielectric Performance of TPX 3x3 Insulation Models

Models	Test Conditions	Capacit. (ε) 1 kHz	Loss Tangent 1 kHz	Insulation Resist. at 1000 V	Partial Discharge Performance kVrms		DC Hipot Performance Based on 50 μA, Max. Trip Sensitivity kVdc				
1, 3, 2 (order of testing)	Number of Thermal & Mech Load Cycles	pF	%	$10^{12}\Omega$	100 pC Onset Minimum	1000 pC Pk Level Minimum	20 kVdc 15 s	16 kVdc 60 s	Turn-Turn Withstand Minimum	Turn-Turn Faults	Average Stress kV/mm
1-CDR Baseline/ Roving Filler	AR	196 (5.50)	0.31	>100	4.8	9.0	10 kVdc	-	-	-	>4.3 (Withstand)
	1 Thermal	196	0.29	>100	4.5	7.0	10 kVdc	-	-	-	>4.3 (Withstand)
	2 Thermal & 7500 cycles	195	0.30	>100	4.5	7.0	10 kVdc	-	-	-	>4.3 (Withstand)
	3 Thermal & 15000 cycles	195	0.32	>100	4.0	7.0	10 kVdc	-	-	-	>4.3 (Withstand)
3-CDR Baseline/ Araldite Filler	AR	531 (5.06) 5-4 Short	0.41 5-4 Short	1.8 5-4 Short	4.0 5-4 Short	5.5 5-4 Short	P	P	>22 (for all turn pairs)	29 5-4 Short	17.3 (Fault)
	2 Thermal & 15000 cycles plus Failure	425	0.58 (29.9 from turns 5-4)	<0.2	2.5	>5.0	P(1-2) F(other turn pairs)	P(1-2, & 6-9) F(other turn pairs)	<21 (for all turn pairs)	5 to 12 (T-T pairs) 8-21 (L-L pairs)	3.8-9.1 (T-T pairs) 4.8-12.6 (L-L pairs) (Faults)
2-Slip Plane Option/ Roving Filler	AR	517 (5.21)	0.21	20	5.0	7.0	P	P	-	-	12.7 (Withstand)-
	2 Thermal & 15000 cycles	516	0.28	1.5	3.5	5.5	P	P	27.5 to 38.5 (for all turn pairs)	-	17.5 to 24.5 (Withstand)
	3 Thermal & 15000 cycles plus Failure	439	0.25	3.0	2.5	3.0	P	P	29.5 to 38.1 (for all turn pairs)	21.8 5-2 pair (with 5000 μA trip)	13.9 (Fault)

Table 3. Summary of Dielectric Performance of TPX 3x3 Insulation Models (Cont.)

Models	Test Conditions	Capacit. (ε) at 1 kHz	Loss Tangent at 1 kHz	Insulation Resist. at 1000 V	Partial Discharge Performance kVrms		DC Hipot Performance Based on 50 μA, Max. Trip Sensitivity kVdc				
4B, 5A, 6A (order of testing)	Number of Thermal & Mech Load Cycles	pF	%	$10^{12}\Omega$	100 pC Onset Minimum	1000 pC Pk Level Minimum	20 kVdc 15 s	16 kVdc 60 s	Turn-Turn Withstand Minimum	Turn-Turn Faults	Average Stress kV/mm
4-Interim Baseline/3-D	AR	192 (4.7)	0.23	100	6.5	9.5	P	P	28 to 38 (for all turn pairs)	-	>14.9 (Withstand)
	2 Thermal & 15000 cycles	192	0.58	30	4.5	5.0	P	P	31-40 (for all turn pairs)	-	>16.5 (Withstand)
	3 Thermal & 15000 cycles plus Failure	164	0.34	50	2.5	3.0	P (all pairs except 1-2)	P	31-35 (for pairs 2-3, 7-8, 3-6)	20(1-2) 26(1-4) 22-34(for 7 pairs at ends)	10.7 (Fault)
5-Hybrid Prepreg/3-D	AR	240 (4.95)	0.45	30	5.0	6.0	P	P	26-40 (for all turn pairs)	-	>16.7 (Withstand)
	2 Thermal & 15000 cycles	240	0.42	30	3.5	6.0	P (all pairs except 5-2 short)	P (all pairs except 5-2 short)	28-40 (for 5 pairs 2-1, 4-1, 6-9, 5-4, 5-8)	28-36 (for 6 pairs at ends) (5-2 shorted)	18.0 (Fault)
Note: Gross failure.	3 Thermal & 15000 cycles plus Failure	-	-	-	-	-	F	-	-	7-16 (all pairs fail) (5-2 shorted)	4.5 (Fault)
6-3-D Cigar Roll	AR	283 (5.51)	0.26	120	3.5	5.5	P	P	<23 (for 4 pairs only 2-1, 2-3, 8-7, 8-9)	23-32 (for same 4 pairs, lead to adjacent turn, ext. puncture)	<1 Creep (Failure for >25 mm path)
	2 Thermal & 15000 cycles	282	0.27	>100	Fault s at 4.5-5.5 kVrms	<800 pC at failure	Fault all pairs; 6 shorted	Not tested	No withstand	6 Shorted 6 pairs 4.4-9.2	<3

loss load carrying capability in the stress vs. strain record, samples (except Model 1) were subjected to Hipot voltage up to 40 kVdc withstand to assess residual dielectric capability.

The CDR Baseline, Model 1 survived 3 thermal cycles and 15000 mechanical cycles with essentially no change in electrical performance with the Hipot test limit of 10 kVdc. The CDR Baseline with Araldite epoxy resin corner filler, Model 2 failed the 20 kVdc Hipot for all turn pairs except one after 2 thermal cycles and 15000 mechanical cycles following mechanical failure; electrical testing was not performed after mechanical cycles and before mechanical failure load. Both Kapton Slip plane insulation options Models 2 and 4B had excellent Hipot performance through 3 thermal cycles, 15000 mechanical cycles through mechanical failure due to the presence of the Kapton barrier wraps directly on the conductors. Model 2 which had adhesive Kapton had no turn-to-turn faults after mechanical failure while Model 4B without adhesive on Kapton had only one turn-to-turn fault after mechanical failure. The Hybrid Prepreg/3-D wrap and void fill, Model 5A survived the 20 kVdc Hipot for all turn pairs except on following 2 thermal cycles and 15000 mechanical cycles. Model 5A had gross mechanical failure with debonding and separated turns during the mechanical loading test to failure, and no turn pairs survived the 20 kVdc Hipot. The 3-D Cigar Roll all 3-D materials, Model 6A failed for all turn pairs at 20 kVdc Hipot following 2 thermal cycles and 15000 mechanical cycles. After 2 thermal cycles and 15000 mechanical cycles, but prior to failure load, all Kapton insulated samples had a minimum turn-to-turn withstand of 26 kVdc with some turn pairs surviving the 40 kVdc test voltage limit. The CDR Baseline design with the Araldite corner filler had a withstand <21 kVdc for all turn pairs after mechanical cycling.

5.2 AC LIFE TESTING

AC life testing was introduced late in the test program. The test procedure is to apply 60 Hz voltage for a time equivalent to a set number of life cycles(LC) for the expected peak voltages experienced by the TPX winding packs. The required test

duration at 60 Hz is defined as (30,000 cycles/LC)x(Number of test LC)/60 Hz, where 30,000 cycles of peak electrical stress is assumed to represent the actual worst case scenario for the TPX coils. It was planned to Models 4B, 5A, and 6A employing the AC life cycle test to evaluate the long term electrical stress capability of the 3x3 insulation models in air. Because of the dielectric failure of the all 3-D design, Model 6A could not AC life tested as planned. The AC life test results are presented in Table 4. The Kapton Slip design, Model 4A passed 7.2 LC at 7 kVrms and 1.4 LC at 10 kVrms for selected turns after mechanical failure. The Hybrid Prepreg, Model 5A survived 3.6 LC at 10 kVrms after 15000 mechanical cycles but before mechanical failure. Life testing was not performed on Model 5A after mechanical failure because of the catastrophic nature of the failure and total lack of voltage withstand.

5.3 HIPOT TO FAILURE TESTS

Hipot to failure tests were correlated with observed mechanical damage in the form of cracks and fractures from 3x3 polished cross sections and dye penetrant tests. In general a good correlation was found between faulted turn pairs and mechanical cracking in the vicinity of the electrical fault. Since the leakage current limit was <50 μA for Hipot fault detection, electrical tracking was not observed in the 3x3 cross sections. The correlations between mechanical damage and turn pair faults is found in the Appendix , Tables 5, 6A, and 6 for Models 3,2, and 4B, VuGraphs 14, 15, 16, respectively.

5.4 COMPARATIVE DIELECTRIC PERFORMANCE

The Appendix includes a series of bar graph representations of the dielectric performance of Models 1-6 for easy comparison, VuGraphs 17-25. These bar graphs are helpful in understanding and comparing the trends of the electrical insulation measurements as the testing progressed from as received through mechanical cycling and ultimate mechanical failure. Also, Table 4, VuGraph 13 presents a summary of capacitance measurements and estimated effective relative dielectric

Table 4. Summary of 1 Hour, 60 Hz Life Test for TPX 3x3 Models 4B, 5A and 6A

MODEL	TEST SEQUENCE	CONFIGURATION OF TEST LEADS		TEST VOLTAGE	PARTIAL DISCHARGE LEVELS		TEST DURATION		FAILED TURN PAIRS
		HV Turn	GD Turns	kVrms	pCav	pCpk	hrs	LC	
4B-Interim Baseline	After mech. failure	7	4 & 8	7.0	5.5	300 to 1500	1.0 Pass	7.2	Withstand
	After mech. failure	3	2 & 6	10.0	18.0	3000 to 6000	0.2 Fail	1.4	3-6 Short
5A-Hybrid Prepreg	After 15,000 cycles	5	All outside turns	10.0	35.0	1200 to 2400	0.5 Fail	3.6	5-2 Short
	After mech. failure (Model too damaged for life testing)	-	-	-	-	-	-	-	-
6A-3-D Cigar Roll	After 15,000 cycles								
	After mech. failure								

constants for the insulation systems which averaged 5.1 +/-8%. Loss of sample capacitance was measured for Models 2, 3, and 4B following mechanical failure, indicating loss of turn insulation capability and turn shorts.

VuGraph 26 in the Appendix presents a brief summary of dielectric loss measurements, i.e., loss tangent (tanδ) with an interpretation of the meaning of the results for the TPX coils. For the expected 30,000 electrical life cycles of the TPX system, dielectric losses should not be an issue. Loss tangents of <0.8% should be acceptable. The 3x3 test samples had loss tangents <0.6% in for all samples tested.

6. REFERENCES

1. Effects of Variations in the TF Coil Design on Reducing Stresses in the Insulation, R.L. Myatt, MIT Plasma Fusion Center, TPX Document No. 13-940407-MIT/LMyatt-01.

2. TPX Insulation & Impregnation R&D-*1x2 Test Report,* J. F. Roach and W. M. Urban, WEC-STC, and D. Hartman, Everson Electric Company, TPX Document No. 14-950630-WEC-FRoach-01, 07-31-95. (STC Doc. No. 95-1TM4-TPXAC-R1).

3. Development of Three-Dimensional Woven Fiberglass Components for the TPX PF and TF Magnet Electrical Insulation Systems, J. F. Lowry, P. A. Sanger, and J. F. Roach, STCDoc.No. 95-8TM4-TPXAC-R5, 07-28-95.

7. ACKNOWLEDGMENTS

The Everson Electric participation was guided by Mr. Greg Naumovich, TPX Project Manager at EE. The authors wish to thank Mr. Naumovich for his cooperation in using EE factory facilities. The EE factory personnel who performed the manufacturing of the 3X3 samples were very dedicated and cooperative, and the authors wish to personally thank them. Much of the dielectric testing was conducted in the Dielectrics Laboratory at W-STC with the cooperation of Dr. Lyon Mandelcorn, Manager, Ceramics & Coatings Department. Mr. R. W. Lancaster of the Ceramic & Coatings Department who performed many of the measurements is thanked for his hard work and advice during the program. Finally, the authors wish to thank Dr. P. A. Sanger, TPX Project Manager at W-STC for his many suggestions and technical direction during the performance of the 3X3 program.

8.0 APPENDIX

3X3 Insulation Test Program

J. F. Roach, WEC

VuGraph Presentation
MSIM #5

Lynchburg, VA
May 02-03, 1995

(Attach Power Point File: 3X3RPTAP.PPT)

TPX

MARINE DIVISION

3x3 Insulation Test Program

J. F. Roach

Westinghouse STC

May 02, 1995

CONCLUSIONS

Interim Baseline Design is Selected for 5x5 Qualification

- Highest electrical breakdown margins
  - Up to 40 kVdc withstand turn to turn
- Maintains electrical strength after mechanical failure
  - >20 kVdc capability turn to turn
- Demonstrated life cycle (LC) under AC stress
  - 7.4 LC at 7 kVrms ; 1.4 LC at 10 kVrms after mechanical failure
- 3-D tape and 3-D tackified filler perform well mechanically
  - Large cracks not found in tackified fillers
  - Only two of four inner corner showed delamination after failure stress
  - No fracture of the 3-D tape wrap

3x3 INSULATION TESTING APPROACH

Evolution and Rationale

- Model 1,CDR Baseline
  - Probe insulation degradation via partial discharge(PD) measurements for all turn pairs to 10 kVrms in 0.5 kVrms steps
    - 10 kVdc Hipot before PD testing
- Model 3,CDR Baseline/Araldite
  - Initiate 16 kVdc, 60 s Hipot and 50 microamplimit before PD testing
    - Testing peak lead to ground of 7.5 kV at 2 times + 1000V
  - Test all turn pairs to 40 kVdc max. withstand to determine ultimate margin
- Model 2,Kapton Slip Option
  - Add 20 kVdc 15 s Hipot performed before PD testing
  - Test all turn pairs to 40 kVdc max. withstand only after 15,000 cycles
  - Partial discharge testing only toAC voltage level for <2000pC discharges

3x3 INSULATION TESTING APPROACH

Evolution and Rationale

- Models 4B, 5A, and 6A, Interim Baseline, Hybrid Prepreg, 3-D Cigar Roll
  - Limit AR Hipot withstand testing to a maximum of two external turn pairs
  - Perform Hipot after PD testing
  - Do not take central turn to outside turn pairs to withstandvoltage level
  - Initiate 10 kVrms, 1 hr AC Life Test
    - Performed on 4B after failure
    - Performed on 5A after 15,000 cycles
    - Equivalent to 7.2 life cycles at 30,000 cycles and peak local stress levels between turns >8 kV/mm or > 3 times allowed
- Table1 on Next Vugraph Presents a Summary of the 3x3 Electrical Insulation Testing Matrix

TPX

MARINE DIVISION

3x3 Insulation Test Program

Table 1. Electrical Testing Evolution and Matrix for 3x3 Models

MODEL	DIELECTRIC PROPERTIES			DC HIPOT AR/15,000/Failure				PARTIAL DISCHARGE To 10 kVrms in 0.5 kVrms steps Average & Peak pC			AC LIFE TEST Selected Turn Pairs at 10 kVrms for 1 hr 7.2 LC at 6 kVrms/mm
	C pF	Loss %	IR Ω	10 kVdc 5s	20 kVdc 15s	16 kVdc 60s	40 kVdc Withstand Maximum	All pairs	Selected pairs	Selected pairs & <2000 pC	Selected Turn Pairs
1-CDR Baseline	√	√	√	√				√			
3-CDR Baseline with Araldite	√	√	√			√	All pairs (1 Fault)		√		
2-Slip Plane Option	√	√	√		√	√	Only after cycling			√	
4B-Interim Baseline	√	√	√		√	√	All ext. pairs until two faults			√	√ After Failure
5A-Hybrid Prepreg	√	√	√		√	√	All ext. pairs until two faults			√	√ After 15,000 cycles
6A-3-D Cigar Roll	√	√	√		√	√	All ext. pairs until two faults				

TPX

MARINE DIVISION

3x3 Insulation Test Program

FABRICATION AND MANUFACTURABILITY ASSESSMENT

MODEL	STRENGTH	WEAKNESS	MANUFACTURING ISSUES
1-CDR BASELINE	Easy to tape dry glass Easy to assemble layers on to G-10 barrier sheets	Difficult to insert glass bundle fillers & jam into void	•Assembly of IL-L barriers (barrier strips are not considered for turn-turn)
2-KAPTON SLIP OPTION (USING XMPI ADHESIVE)	Taping Kapton and overwrap dry glass not difficult	Difficult to control slipping of glass tape at model ends Difficult to insert glass bundle fillers & jam into void	•Curing XMPI during drying cycle requires >185 C° •Kapton to VPI glass bonding •Insertion of roving bundles
3-CDR BASELINE/ARALDITE	Easy to tape dry glass Easy to assemble layers on to G-10 barrier sheets	Araldite forming & short pot life Difficult to judge how much filler putty to use to avoid pushing into glass and blocking impregnation	•Finding high pot life putty •How ot "caulk" voids without clogging glass •Epoxy fillers block VPI
4-INTERIM BASELINE	Easy to tape 1" Kapton,no adh Easy to work with 3-D 14 mil tape	Difficult to control slipping of glass tape at model ends	•How to take Tackified filler around radii •Is it ok to have Kapton w/o adhesive? •Bonding of VPI to 3-D tape
5-HYBRID PREPREG	Tackified/preform fillers work very well	Taping wet/prepreg/Kapton a "nightmare" Getting butt lap of dry glass over Kapton; some slip	•Optimization of prepreg and VPI curing processes •Can't predry pack for optimum VPI without kicking off prepreg •Only ITER approach may be viable but not TPX compatible •"Dry" prepreg not "wet"
6-3-D CIGAR ROLL	Tackified/preform fillers work very well	Cigar roll seam overlap control Used Kapton tape to tape roll and to control end wrap;	•How to apply roll and seam •How to get tight wrap around conduit; conduit slip

TPX

MARINE DIVISION

3x3 Insulation Test Program

Table 1. Summary of 3x3 Insulation Model Designs

Model	Insulation System	Corner Roving	VPI System	Conduit Insulation Build mils	Insulation Build L-L & T-T mm	Model Length L (Metal Flat) inches	Model Cross Section H x W inches
1-CDR Baseline	TTI Satin weave wrap 3/4"x.010" with G-10 L-L barriers	Glass bundle	Shell 826	45.6	2.672 L-L 2.316 T-T	5.375	2.937 x 2.914
2-Slip Plane Option	Kapton H .001" with XMPI adhesive with TTI Plain weave wrap 3/4"x.008"	Glass bundle	Shell 826	30.9	1.570 L-L & T-T	9.938	2.820 x 2.820
3-CDR Baseline with Araldite	TTI Plain weave wrap 3/4"x.008" with G-10 L-L barriers	Araldite Epoxy Resin Putty	Shell 826	25.9	1.671 L-L 1.316 T-T	9.938	2.816 x 2.791
4A-Interim Baseline with 3-D Overwrap	Kapton H .001" w/o adhesive and Techniweave 3-D 1"x.014" wrap	3-D Shape Dry (16)	Shell 826	32.5	1.651 L-L & T-T	4.812	2.824 x 2.834
4B-Interim Baseline with 3-D Overwrap	Same as 4A	3-D Shape Tackified (16)	Shell 826	36.9	1.875 L-L & T-T	4.812	2.857 x 2.854

3x3 Insulation Test Program

Table 1. Summary of 3x3 Insulation Model Designs (Cont.)

Model	Insulation System	Corner Roving	VPI System	Conduit Insulation Build mils	Insulation Build L-L & T-T mm	Model Length L (Metal Flat) inches	Model Cross Section H x W inches
5A-Hybrid Prepreg with 3-D Overwrap	CNF Plain weave 1"x.007 with CTD 112P prepreg and Kapton H 1"x.007" on top with Techniweave 3-D 1"x.014" overwrap	3-D Shape Tackified (16)	CTD 101K (No mold preheat)	30.6	1.554 L-L & T-T	4.812	2.824 x 2.826
5B-Hybrid Prepreg with 3-D Overwrap	Same as 5A	3-D Shape Tackified (12) Dry (4)	CTD 101K (No mold preheat) 101K	31.3	1.590 L-L & T-T	4.812	2.828 x 2.830
6A-3-D Cigar Roll	Techniweave 3-D cloth 3.75"x.032" with .016 seam tabs	3-D Shape Tackified (8) Dry (8)	Shell 826	30.6 L-L 27.1 T-T	1.554 L-L 1.377 T-T	4.812	2.825 x 2.804
6B-3-D Cigar Roll	Same as 6A	3-D Shape Tackified (9) Dry (7)	Shell 826	29.6 L-L 26.3 T-T	1.504 L-L 1.336T-T	4.812	2.819 x 2.799

TPX

MARINE DIVISION

3x3 Insulation Test Program

Table 2. Summary of Dielectric Performance of TPX 3x3 Insulation Models

Models	Test Conditions	Capacit. (ε) at 1 kHz	Loss Tangent at 1 kHz	Insulation Resist. at 1000 V	Partial Discharge Performance kVrms		DC Hipot Performance (50 μA, Max. Trip Sensitivity = Appr. 10 μA) kVdc				
1, 3, 2 (order of testing)	Number of Thermal & Mech Load Cycles	pF	%	TΩ	100 pC Onset Minimum	1000 pC Pk Level Minimum	20 kVdc 15 s	16 kVdc 60 s	Turn-Turn Withstand Minimum	Turn-Turn Faults	Average Stress kV/mm
1-CDR Baseline/ Roving Filler	AR	196 (5.50)	0.31	>100	4.8	9.0	10 kVdc	-	-	-	>4.3 (Withstand)
	1 Thermal	196	0.29	>100	4.5	7.0	10 kVdc	-	-	-	>4.3 (Withstand)
	2 Thermal & 7500 cycles	195	0.30	>100	4.5	7.0	10 kVdc	-	-	-	>4.3 (Withstand)
	3 Thermal & 15000 cycles	195	0.32	>100	4.0	7.0	10 kVdc	-	-	-	>4.3 (Withstand)
3-CDR Baseline/ Araldite Filler	AR	531 (5.06) 5-4 Short	0.41 5-4 Short	1.8 5-4 Short	4.0 5-4 Short	5.5 5-4 Short	P	P	>22 (for all turn pairs)	29 5-4 Short	17.3 (Fault)
	2 Thermal & 15000 cycles plus Failure	425	0.58 (29.9 from turns 5-4)	<0.2	2.5	>5.0	P(1-2) F(other turn pairs)	P(1-2, & 6-9) F(other turn pairs)	<21 (for all turn pairs)	5 to 12 (T-T pairs) 8-21 (L-L pairs)	3.8-9.1 (T-T pairs) 4.8-12.6 (L-L pairs) (Faults)
2-Slip Plane Option/ Roving Filler	AR	517 (5.21)	0.21	20	5.0	7.0	P	P	-	-	12.7 (Withstand) -
	2 Thermal & 15000 cycles	516	0.28	1.5	3.5	5.5	P	P	27.5 to 38.5 (for all turn pairs)	-	17.5 to 24.5 (Withstand)
	3 Thermal & 15000 cycles plus Failure	439	0.25	3.0	2.5	3.0	P	P	29.5 to 38.1 (for all turn pairs)	21.8 5-2 pair (with 5000 μA trip)	13.9 (Fault)

TPX

MARINE DIVISION

3x3 Insulation Test Program

Table 2. Summary of Dielectric Performance of TPX 3x3 Insulation Models (Cont.)

Models	Test Conditions	Capacit. (ε) at 1 kHz	Loss Tangent at 1 kHz	Insulation Resist. at 1000 V	Partial Discharge Performance kVrms		DC Hipot Performance Based on 50 μA, Max. Trip Sensitivity kVdc				
4B, 5A, 6A (order of testing)	Number of Thermal & Mech Load Cycles	pF	%	TΩ	100 pC Onset Minimum	1000 pC Pk Level Minimum	20 kVdc 15 s	16 kVdc 60 s	Turn-Turn Withstand Minimum	Turn-Turn Faults	Average Stress kV/mm
4-Interim Baseline/3-D	AR	192 (4.7)	0.23	100	6.5	9.5	P	P	28 to 38 (for all turn pairs)	-	>14.9 (Withstand)
	2 Thermal & 15000 cycles	192	0.58	30	4.5	5.0	P	P	31-40 (for all turn pairs)	-	>16.5 (Withstand)
	3 Thermal & 15000 cycles plus Failure	164	0.34	50	2.5	3.0	P (all pairs except 1-2)	P	31-35 (for pairs 2-3, 7-8, 3-6)	20(1-2) 26(1-4) 22-34(for 7 pairs at ends)	10.7 (Fault)
5-Hybrid Prepreg/3-D	AR	240 (4.95)	0.45	30	5.0	6.0	P	P	26-40 (for all turn pairs)	-	>16.7 (Withstand)
	2 Thermal & 15000 cycles	240	0.42	30	3.5	6.0	P (all pairs except 5-2 short)	P (all pairs except 5-2 short)	28-40 (for 5 pairs 2-1, 4-1, 6-9, 5-4, 5-8)	28-36 (for 6 pairs at ends) (5-2 shorted)	18.0 (Fault)
Note: Gross failure.	3 Thermal & 15000 cycles plus Failure	-	-	-	-	-	F	-	-	7-16 (all pairs fail) (5-2 shorted)	4.5 (Fault)
6-3-D Cigar Roll	AR	283 (5.51)	0.26	120	3.5	5.5	P	P	<23 (for 4 pairs only 2-1, 2-3, 8-7, 8-9)	23-32 (for same 4 pairs, lead to adjacent turn, ext. puncture)	<1 Creep (Failure for >25 mm path)
	2 Thermal & 15000 cycles	282	0.27	>100	Fault s at 4.5-5.5	<800 pC at failure	Fault all pairs; 6	Not tested	No withstand	6 Shorted 6 pairs 4.4-9.2	<3

TPX

MARINE DIVISION

3x3 Insulation Test Program

Table 3. Summary of 1 Hour, 60 Hz Life Test for TPX 3x3 Models 4B, 5A and 6A

MODEL	TEST SEQUENCE	CONFIGURANTION OF TEST LEADS		TEST VOLTAGE	PARTIAL DISCHARGE LEVELS		TEST DURATION		FAILED TURN PAIRS
		HV Turn	GD Turns	kVrms	pCav	pCpk	hrs	LC	
4B-Interim Baseline	After mech. failure	7	4 & 8	7.0	5.5	300 to 1500	1.0 Pass	7.2	Withstand
	After mech. failure	3	2 & 6	10.0	18.0	3000 to 6000	0.2 Fail	1.4	3-6 Short
5A-Hybrid Prepreg	After 15,000 cycles	5	All outside turns	10.0	35.0	1200 to 2400	0.5 Fail	3.6	5-2 Short
	After mech. failure (Model too damaged for life testing)	-	-	-	-	-	-	-	-
6A-3-D Cigar Roll	After 15,000 cycles								
	After mech. failure								

Note: Number of life cycles, LC represented by the test is defined as:

(1) LC = (Test Duration(s) x 60 Hz)/30,000 (cycles/LC).

3x3 Insulation Test Program

Table 4. Summary of Capacitance Characteristics for 3x3 Models at 1 kHz

MODEL	VPI	RELATIVE DIELECTRIC CONSTANT	CAPACITANCE AS RECEIVED (AR)			CAPACITANCE WITH SHORTS (WS)	RATIO (WS)/(AR)
			pF	pF/mm	pF/mm Normalized (For 1.63 mm Turn to Turn Spacing)	pF	
1-CDR Baseline	Shell 826	5.50	195	1.43	2.19	No Shorts After 15,000 cycles	-
3-CDR Baseline with Araldite Filler	Shell 826	5.06	531	2.10	1.93	452	0.851
2-Kapton Slip Plane Option	Shell 826	5.21	517	2.05	1.98	439	0.849
4B-Interim Baseline/3-D	Shell 826	4.70	193	1.58	1.82	164	0.850
5A-Hybrid Prepreg	CTD 101K with CTD 112P Prepreg	4.95	240	1.96	1.87	No Shorts After 15,000 cycles	-
6A-3-D Cigar Roll	Shell 826	5.51	284	2.32	2.09		

Note: Average Normalized Capacitance (AR) is: 2.07 pF/mm +/-6% for fully bonded Models 1,3,6A
1.89 pF/mm +/-4% for Kapton slip Models 2,4B,5A(Prepreg)

Table 5. Correlation of Failure Cracks and Hipot Failure for Model 3-CDR Baseline with Araldite Fillers

TURN PAIR	OBSERVED CRACK	WITHSTAND 16 kVdc, 1min TEST	FAILURE VOLTAGE kVdc	TYPE OF FAILURE
1-2 Turn-Turn	No	P	21 WS	Ext Leads
2-3 Turn-Turn	Yes	F	7	Internal
4-5 Turn-Turn	Yes	F	Short	(AR Test Fault)
5-6 Turn-Turn	Yes	F	7.5	Internal
7-8 Turn-Turn	Yes	F	6	Internal
8-9 Turn-Turn	Yes	F	9.5	Internal
1-4 Layer-Layer	No	P	19.5 WS	Ext Discharge
2-5 Layer-Layer	Yes	F	14.5	Internal
3-6 Layer-Layer	Yes	F	15.2	Internal
4-7 Layer-Layer	Yes	F	13	Internal
5-8 Layer-Layer	Yes	F	14.2	Internal
6-9 Layer-Layer	No	P	19.5	Internal

TPX

MARINE DIVISION

3x3 Insulation Test Program

Table 6A. Correlation of Failure Cracks and Hipot Failure for Model 2-Kapton Slip Plane Option/Roving Fillers

TURN PAIR	OBSERVED CRACK	WITHSTAND 16 kVdc, 1min TEST	FAILURE VOLTAGE (See Note) kVdc	TYPE OF FAILURE
1-2 Turn-Turn	Yes	P	31, 33	Ext. Leads
2-3 Turn-Turn	Yes	P	34.5, 35	Internal, Ext. Leads
4-5 Turn-Turn	Yes	P	37.5, 40	Internal,WS
5-6 Turn-Turn	Yes	P	37.1, 40	Internal, WS
7-8 Turn-Turn	Yes	P	33.2, 38	Internal, Ext. Surface
8-9 Turn-Turn	Yes	P	29, 33	Ext. Surface, Ext. Leads
1-4 Layer-Layer	Yes	P	31.5. 35	Ext. Surface, Ext. End
2-5 Layer-Layer	Yes	P	36.1, 35.1	Internal, 5-2 Fault
3-6 Layer-Layer	No	P	37.5, 40	Internal, WS
4-7 Layer-Layer	Yes	P	38, 40	Internal, Ext. End
5-8 Layer-Layer	Yes	P	36.5, 40	Internal, WS
6-9 Layer-Layer	No	P	38.1, 40	Internal, WS

Note: First Hipot breakdowns performed at 50 µA trip and before PD testing. Second breakdowns at 5000 µA trip after PD testing.

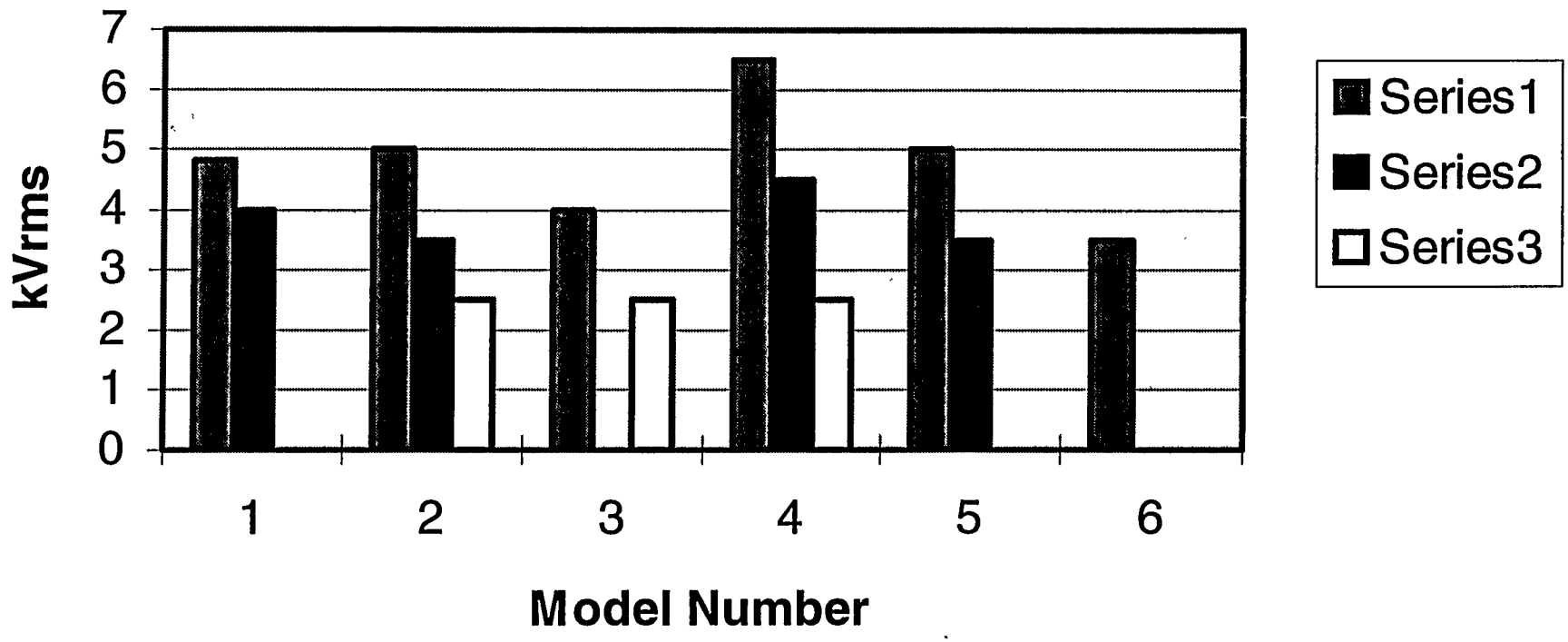
Table 6. Correlation of Failure Cracks and Hipot Failure for Model 4B-Interim Baseline with 3-D Tape/Fillers

TURN PAIR	OBSERVED CRACK	WITHSTAND 16 kVdc, 1min TEST	FAILURE VOLTAGE kVdc	TYPE OF FAILURE
1-2 Turn-Turn	Yes	P	20	Internal
2-3 Turn-Turn	No	P	34 WS	Ext. Leads
4-5 Turn-Turn	Yes	P	30.5 WS	End Turns
5-6 Turn-Turn	Yes	P	33.5 WS	End Turns
7-8 Turn-Turn	No	P	31 WS	Ext. Leads
8-9 Turn-Turn	Yes	P	26	Internal
1-4 Layer-Layer	Yes	P	32	Internal
2-5 Layer-Layer	Yes	P	26 WS	End Turns
3-6 Layer-Layer	No	P	34 WS	Ext. Lead-Turn
4-7 Layer-Layer	No	P	33 WS	End Turns
5-8 Layer-Layer	No	P	22 WS	End Turns
6-9 Layer-Layer	Yes	P	33 WS	End Turns

Comparison of Dielectric Performance of 3x3 Models

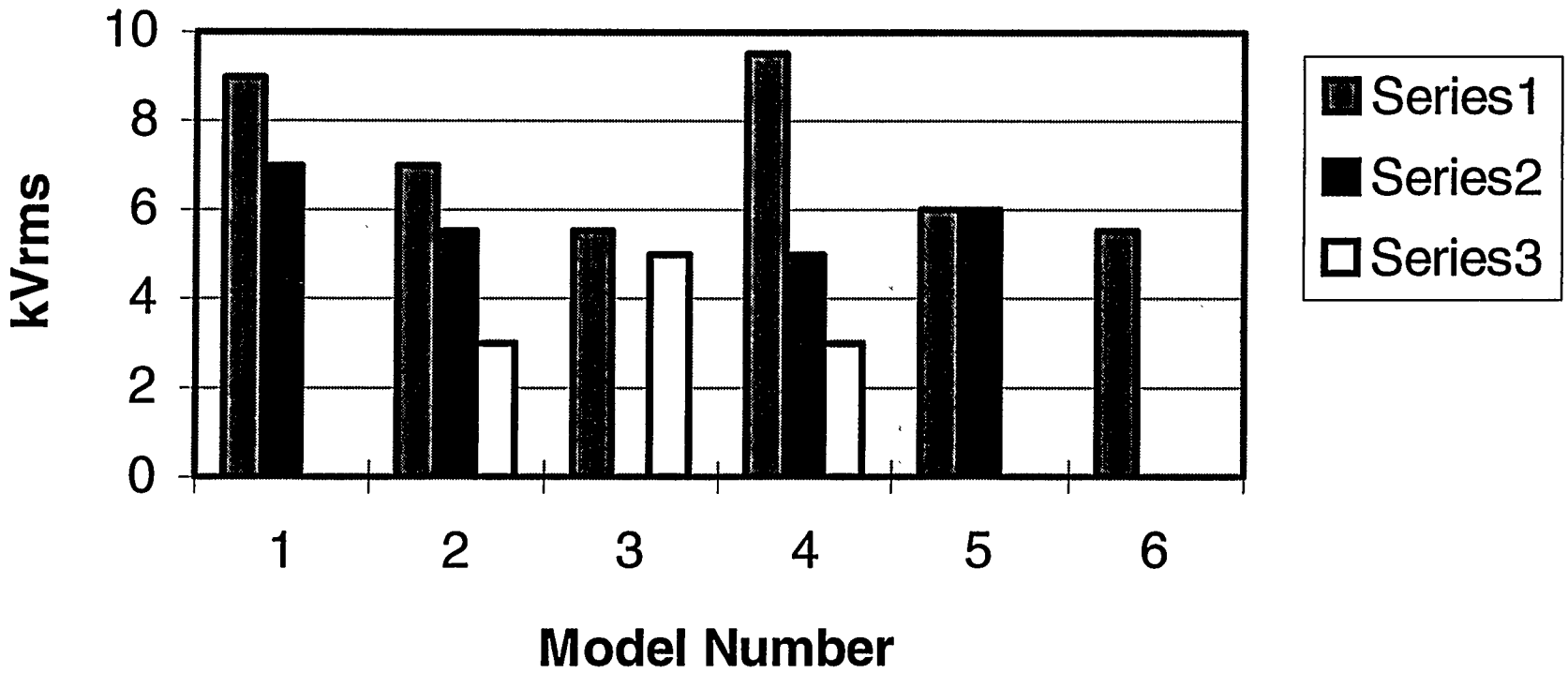
- Data inTable 2 is presented in Bar Graph Form.
  - The X-axis represents the six Insulation Models 1-6. The three Bar Groups (Series 1,2,3) at each Model Number refer to values measured As Received, after 15,000 Mechanical Cycles, and after Mechanical Failure.
  - Loss Tangent is presented in Bar Graph form for As Received and after 15,000 Mechanical Cycles only. The four Bar Groups (Series 1,2,3,4) are the test frequencies 0.1, 0.4, 1,10 kHz.
    - Loss Tangent given in Table 2 is for 1 kHz only

Partial Discharge Onset (100 pC)



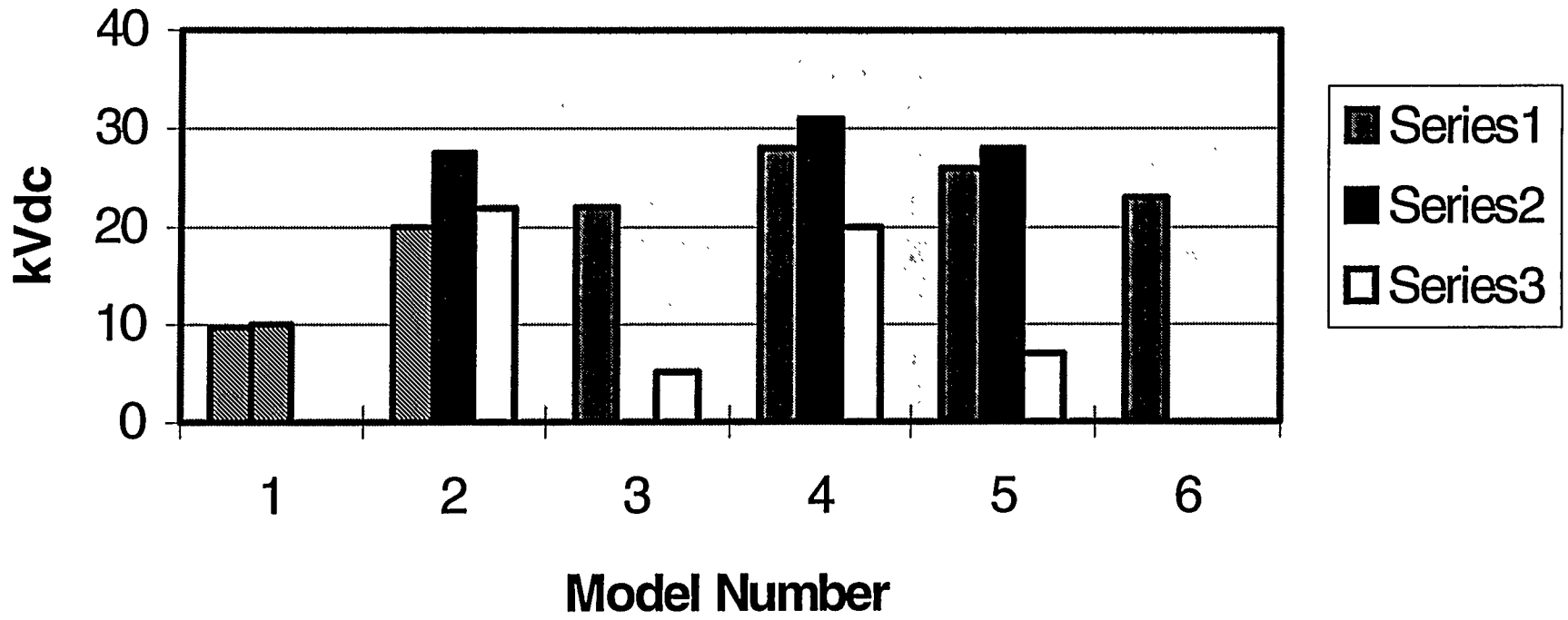
3x3 Insulation Test Program

Minimum Voltage at 1000 pC Level



3x3 Insulation Test Program

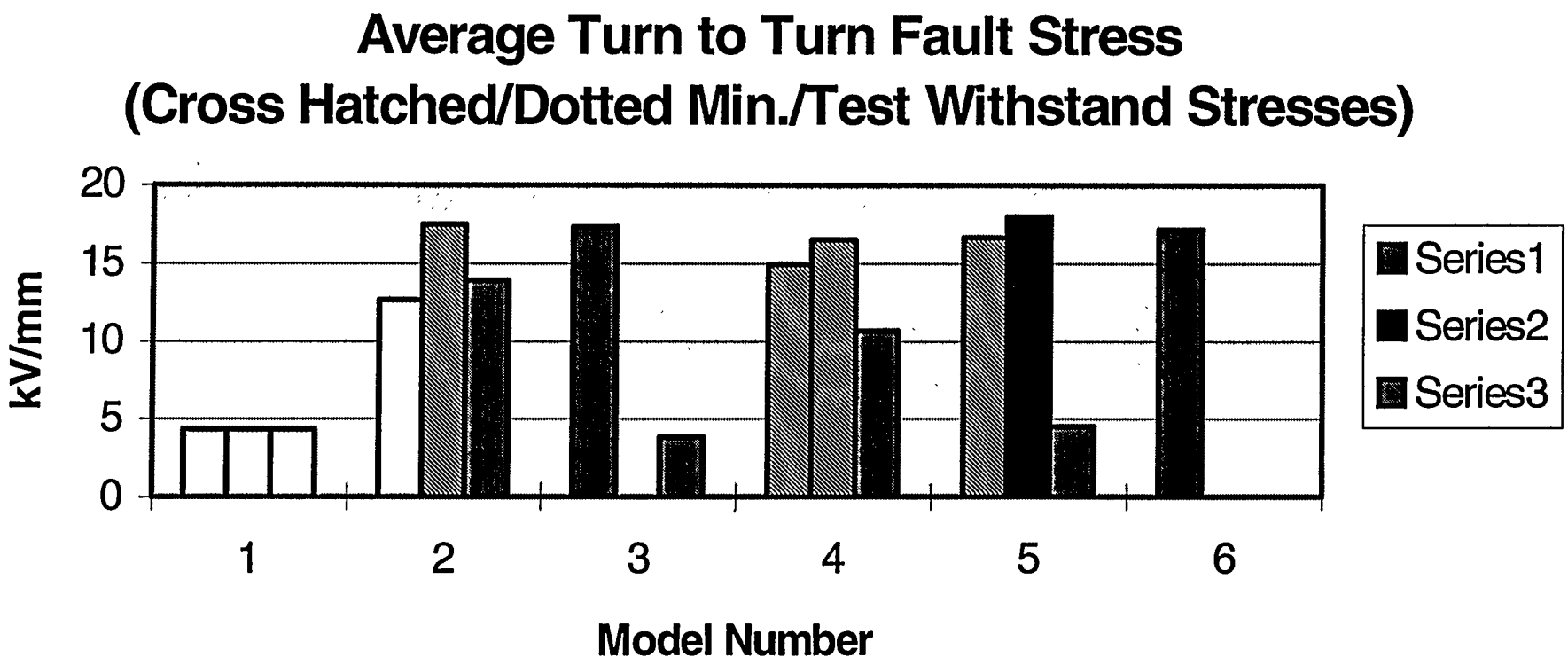
Minimum Turn to Turn DC Withstand (Cross Hatched for Fixed Test Voltage)



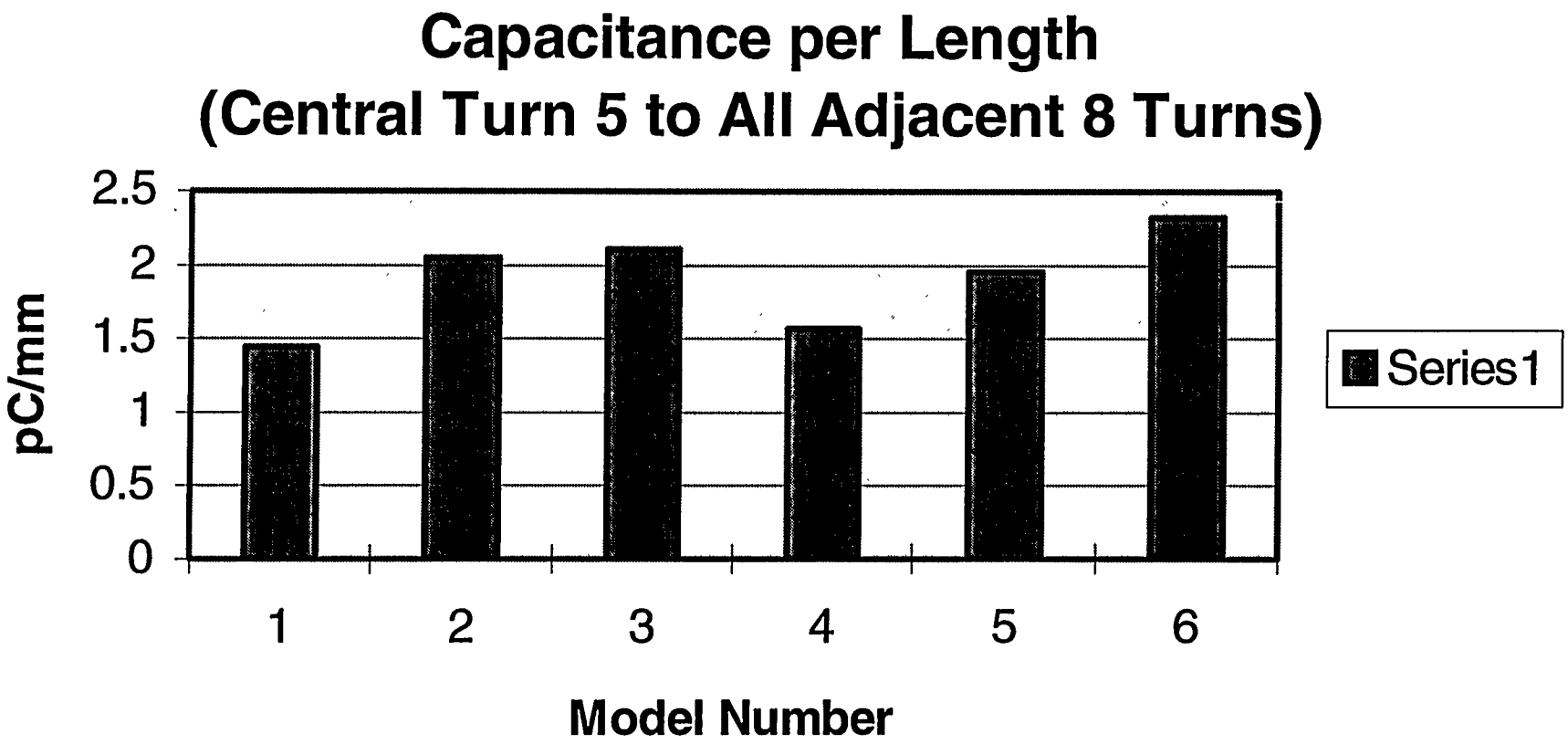
TPX

MARINE DIVISION

3x3 Insulation Test Program



3x3 Insulation Test Program

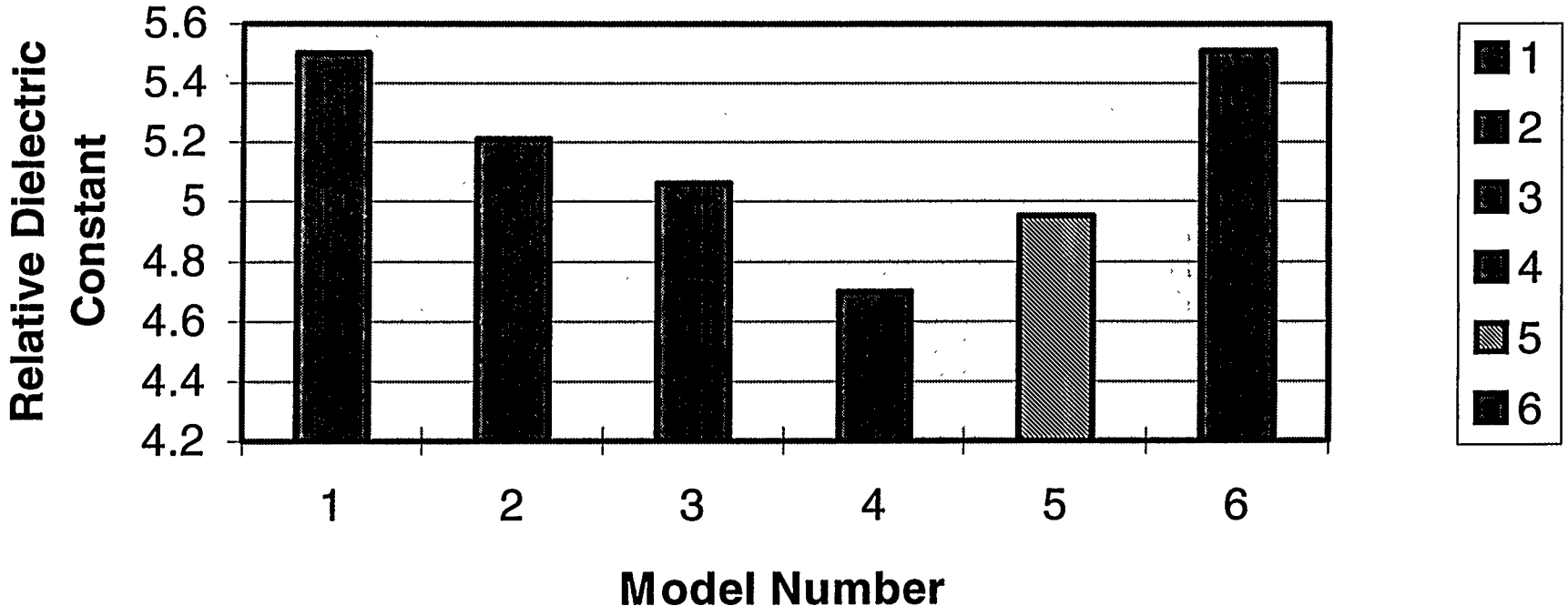


TPX

MARINE DIVISION

3x3 Insulation Test Program

Predicted Average Dielectric Constant (Solid Shell 826; Cross Hatched CTD 101K)

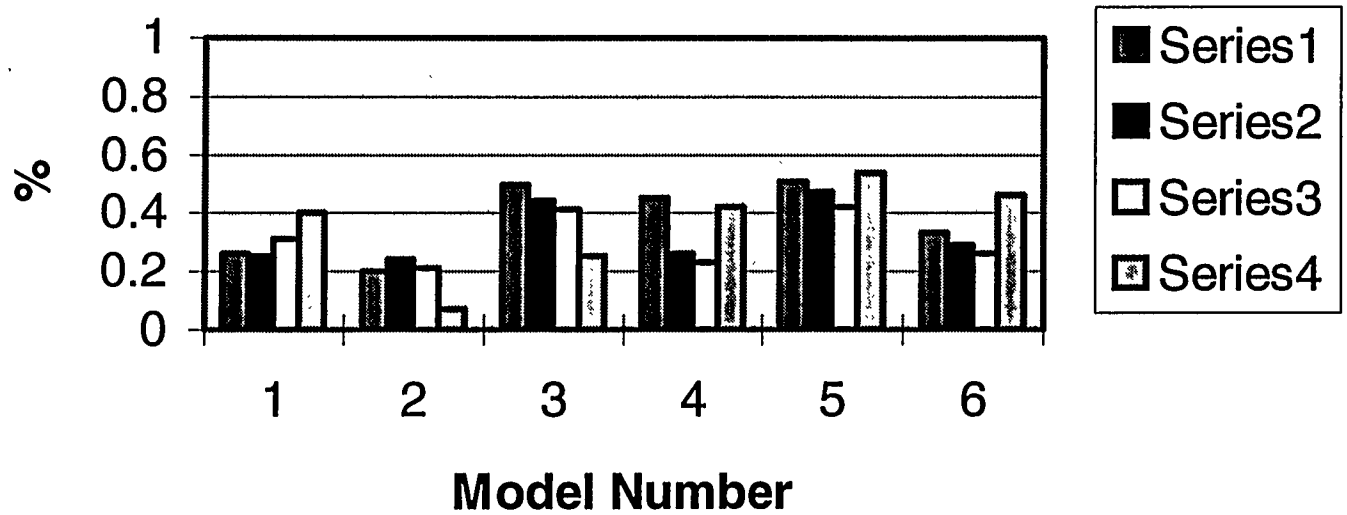


TPX

MARINE DIVISION

3x3 Insulation Test Program

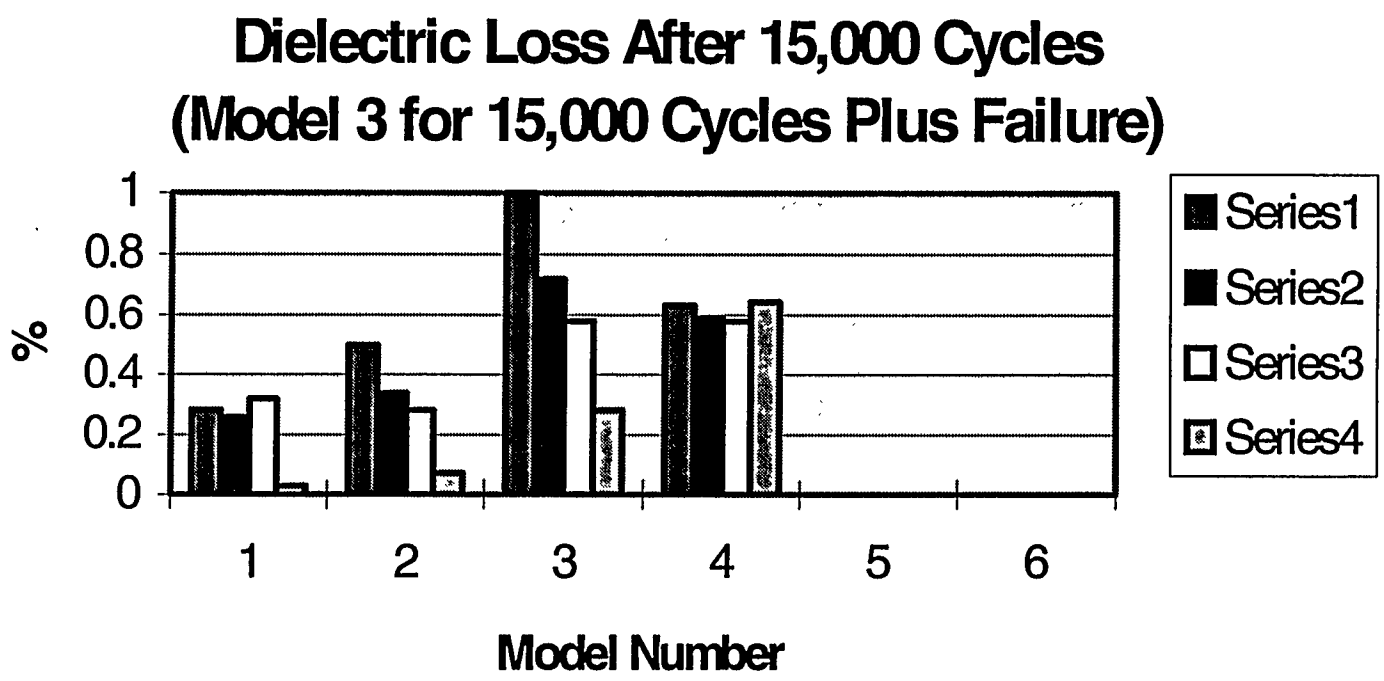
Dielectric Loss As Received



TPX

MARINE DIVISION

3x3 Insulation Test Program



LOSS TANGENT TESTING

- Measures effect of conducting impurities in insulation resulting in resistance and potentially damaging heating under long term electric stress
- What is measured is the Loss Tangent which is given by the ratio Xc / R, ie capacitive reactance to pure resistance
  - Loss Tangent (or Dissipation Factor) is a function of applied frequency
- Pure insulating materials may have Loss Tangent < 0.005%
  - Epoxy-Glass systems have Loss Tangents on the order of 0.1-0.5%
  - Kapton has Loss Tangents of 0. 3% at 0 degC at 100 Hz
- For TPX operation at 30,000 electrical life cycles a Loss Tangent < 0.8% should be acceptible
  - Dielectric heating should not be an issue for TPX
- Should continue to monitor Loss Tangent during insulation development as quality check on Epoxy-Glass impregnation and conducting contamination

TPX 3x3 Insulation Mechanical Test Program

R. J. Hillenbrand
Advanced Electromechanical Systems Department

August 2, 1995

TPX 14-950719-WEC-JHillenbrand-02

APPROVED:

P. A. Sanger
Westinghouse TPX Chief Scientist

APPROVED:

D. R. Potter
Westinghouse TPX Engineering Manager

Westinghouse Electric Corporation
Electronic Systems Group

401 East Hendy Avenue, Sunnyvale, California 94088-3499

CONTENTS

Page

ABSTRACT vii

1. INTRODUCTION AND OBJECTIVE 1-1

1.1 GENERAL DESCRIPTION OF THE PROGRAM 1-8

1.2 CONCLUSIONS 1-9

2. DESCRIPTION OF THE MECHANICAL TESTS 2-1

2.1 LOAD SELECTION 2-1

2.1.1 Shear Stresses in the CS Assembly 2-3

2.1.2 Vertical Compressive Load in the CS Assembly 2-5

2.1.3 Mechanical Test Load Values 2-6

2.2 MECHANICAL TEST CONFIGURATION 2-7

2.2.1 Sample Preparation 2-7

2.3 TEST SETUP 2-10

3. MECHANICAL COMPRESSION TESTING 3-1

3.1 SUMMARY OF 3X3 TEST RESULTS 3-3

3.2 SAMPLE 1 TESTING 3-3

3.3 DISCUSSIONS REGARDING SAMPLES 2-6 3-9

LIST OF FIGURES

Page

Figure 1 — 3x3 Test Sample Configuration for Mechanical Testing 1-3
Figure 2 — End View of 3x3 Sample Prepared with Electrical Connection Points .. 1-4
Figure 3 — Side View of a Typical 3x3 Sample 1-5
Figure 4 — End View of 3x3 Sample Mounted with G10 Load Carrying Block and Extensiometer 1-6
Figure 5 — Side View of 3x3 Sample With Extensiometer Mounted 1-7
Figure 6 — Nomenclature 1-8
Figure 7 — 3x3 Sample Prepared for Testing 2-9
Figure 8 — Test Setup Schematic 2-11
Figure 9 — Load Deflection Characteristics of Sample 1 3-5
Figure 10 — Damage to Sample 1 After 15,000 Cycles 3-6
Figure 11 — Acoustic Emission During Cyclic Testing on Sample 1 3-6
Figure 12 — Load Deflection at Failure - Sample 1 3-8
Figure 13 — Comparative Results of Sample Dissection 3-10
Figure 14 — Dissection of Sample 4b - Interim Baseline w/3d Wrap & Roving 3-11
Figure 15 — Dissection of Sample 1 - CDR Baseline [at 15,000 Cycles] 3-12
Figure 16 — Dissection of Sample 1 - CDR Baseline [After Internal Failure] 3-13
Figure 17 — Dissection of Sample 2 - Slip Plane Option 3-14
Figure 18 — Dissection of Sample 3 - CDR Baseline with Arolidite Filler 3-15
Figure 19 — Load Compression Test Results 4-4

LIST OF TABLES

Page

Table 1 — 3x3 Coil Sample Configurations 1-2

Table 2 — Vertical Compressive Loads Applied During 3x3 Testing 2-7

Table 3 — Comparison of Expected Worst Case Loads with Test Simulations 2-8

Table 4 — 3x3 Testing Sequence 3-1

Table 5 — Summary of Mechanical Results 3-3

Table 6 — Comparative Finite Element Results 3x3 Vs. 6x10 Coil 4-2

Table 7 — Approximate Single Cycle Material Limits at 4°K 4-5

Table 8 — Stresses / Approximate Single Cycle 4°K Limits 4-6

STC Report 95-8TM4-TPXAC-R6

Contract Required
August 2, 1995

3X3 COIL TEST PROGRAM

R. J. Hillenbrand
Advanced Electromechanical Systems

Westinghouse Science & Technology Center
1310 Beulah Road
Pittsburgh, PA 15235-5098

ABSTRACT

Uniaxial compressive testing was performed on 3x3 arrayed TPX coil conductor samples in order to: 1) characterize and assess the different insulation systems being considered for the TPX coil systems as to the type of mechanical and electrical damage that would occur in operation of full size coils, 2) assess the validity of the finite element analysis of the coil.

Electrical testing was used to determine to what degree the electrical integrity was compromised by the mechanical degradation and is reported under separate cover.

Highly stressed areas showed distress consistent with the analysis, and subsequent electrical testing indicated electrical distress in some of the samples.

1. INTRODUCTION AND OBJECTIVE

The purpose of the 3x3 sample test is to characterize the different insulation systems being considered for the TPX coil systems for the purpose of differentiating between them electrically and to provide verification for the finite element analysis as a tool.

Electrical testing will determine to what degree the electrical integrity is compromised by the mechanical degradation of the insulation system after characteristic cyclic loading and after loading to incipient mechanical failure.

Mechanical testing is intended to simulate loading characteristics typical of those experienced in the coil pack providing characteristic physical coil degradation. The mechanical tests will identify structural failure mechanisms in the coil consistent with cooldown and through compressive loading and coupled with comparative analysis will establish the relation between highly stressed areas identified in the analysis and the areas showing deterioration from mechanical testing, thereby providing experimental basis to compare various insulation systems and to correlate the mechanical analysis with the test results.

The sample used for tests in this test series consists of a 3x3 aligned array of coil conductors insulated in a manner consistent with the systems being evaluated for use with the TPX coils and listed in table. The make up of the samples is as indicated in the Table 1.

The conduit is Inconel 908 having dimensions consistent with the intended construction of the CS coil system.

Mechanical testing during this test series consisted of cooling each test sample to cryogenic temperatures and then cyclically loading the sample in compression across the conduit as suggested by Figure 1. Photographs of a typical sample are

given in Figures 2 to 5. The nomenclature used to describe components in the winding pack are given in Figure 6.

Table 1 — 3x3 Coil Sample Configurations

Name Insulation System	Conduit Insulation System	Filler Material	Barriers Plate	Nominal Sample Length
Sample #1 CDR Baseline	2D S-glass Double thick	Glass Roving-Epoxy	G11- Micarta	150 mm (6 inches)
Sample #2 Option 1(e)-R Slip Plane Option	Kapton @ the conduit 2D weave overwrap	Glass Roving-Epoxy	None	250 mm (10 inches)
Sample #3 CDR Baseline w / Araldite	2D S-glass	Araldite Filled Epoxy (Low therm. expansion)	G11- Micarta	250 mm (10 inches)
Sample #4a Option 1(e) Interim Baseline	Kapton @ the conduit 3D weave overwrap	3D weave S-2 Glass	None	130 mm (5 inches)
SPARE Sample #4b Option 1(e) Interim Baseline	Kapton @ the conduit 3D weave overwrap	3D weave S-2 Glass	None	130 mm (5 inches)
Proposed Sample #5a Hybrid Prepreg	Kapton - Interleaved with 2D Glass Prepreg 3D weave Overwrap	3D weave S-2 Glass	None	130 mm (5 inches)
SPARE Sample #5b Hybrid Prepreg	Kapton - Interleaved with 2D Glass Prepreg 3D weave Overwrap	3D weave S-2 Glass	None	130 mm (5 inches)
Sample #6a Cigar Roll	3D weave S-2 Glass Overwrap	3D weave S-2 Glass	None	130 mm (5 inches)
SPARE Cigar Roll	3D weave S-2 Glass	3D weave S-2 Glass	None	130 mm (5 inches)

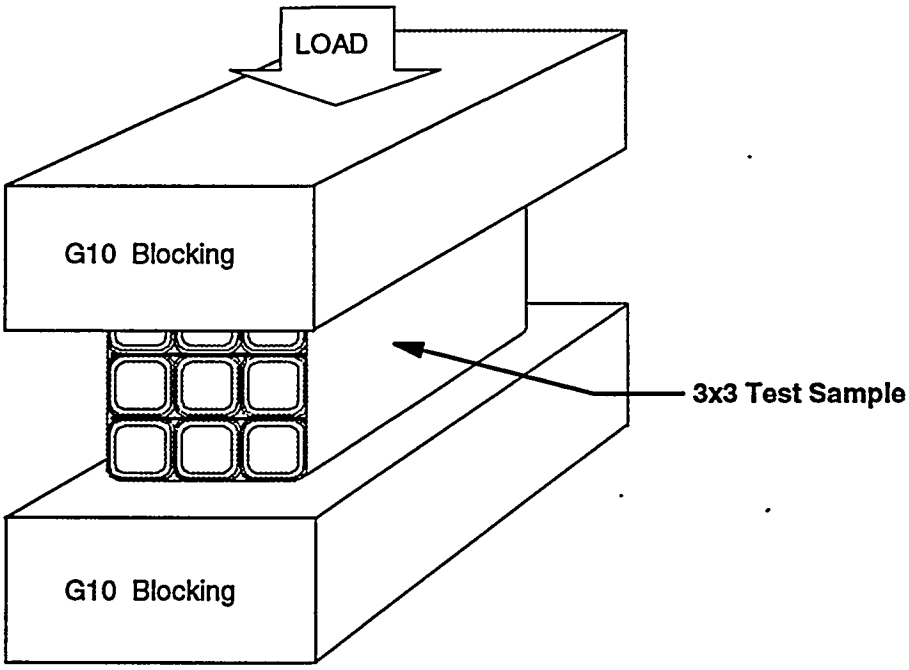


Figure 1 — 3x3 Test Sample Configuration for Mechanical Testing

Figure 2 — End View of 3x3 Sample Prepared with Electrical Connection Points

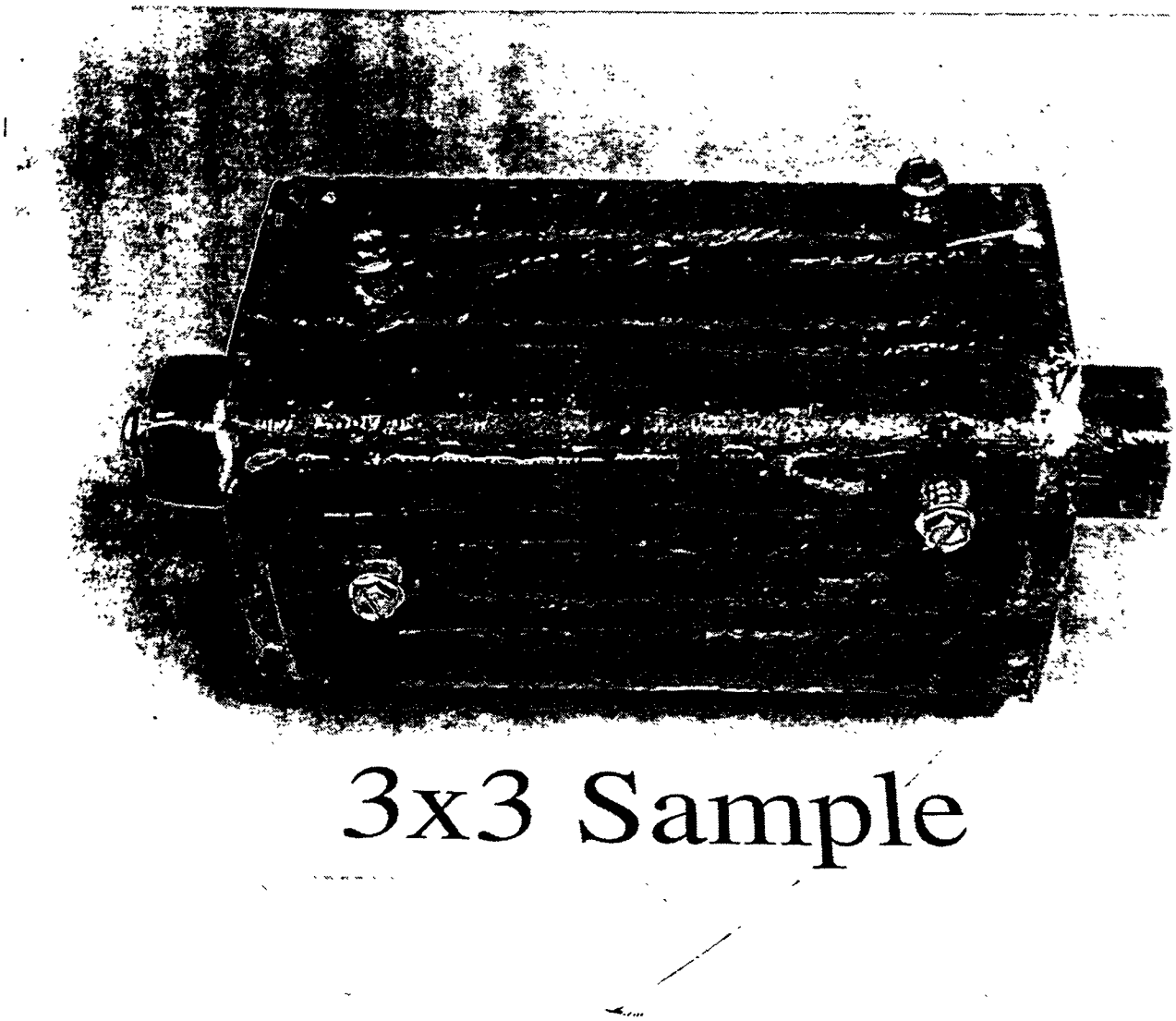


Figure 3 — Side View of a Typical 3x3 Sample

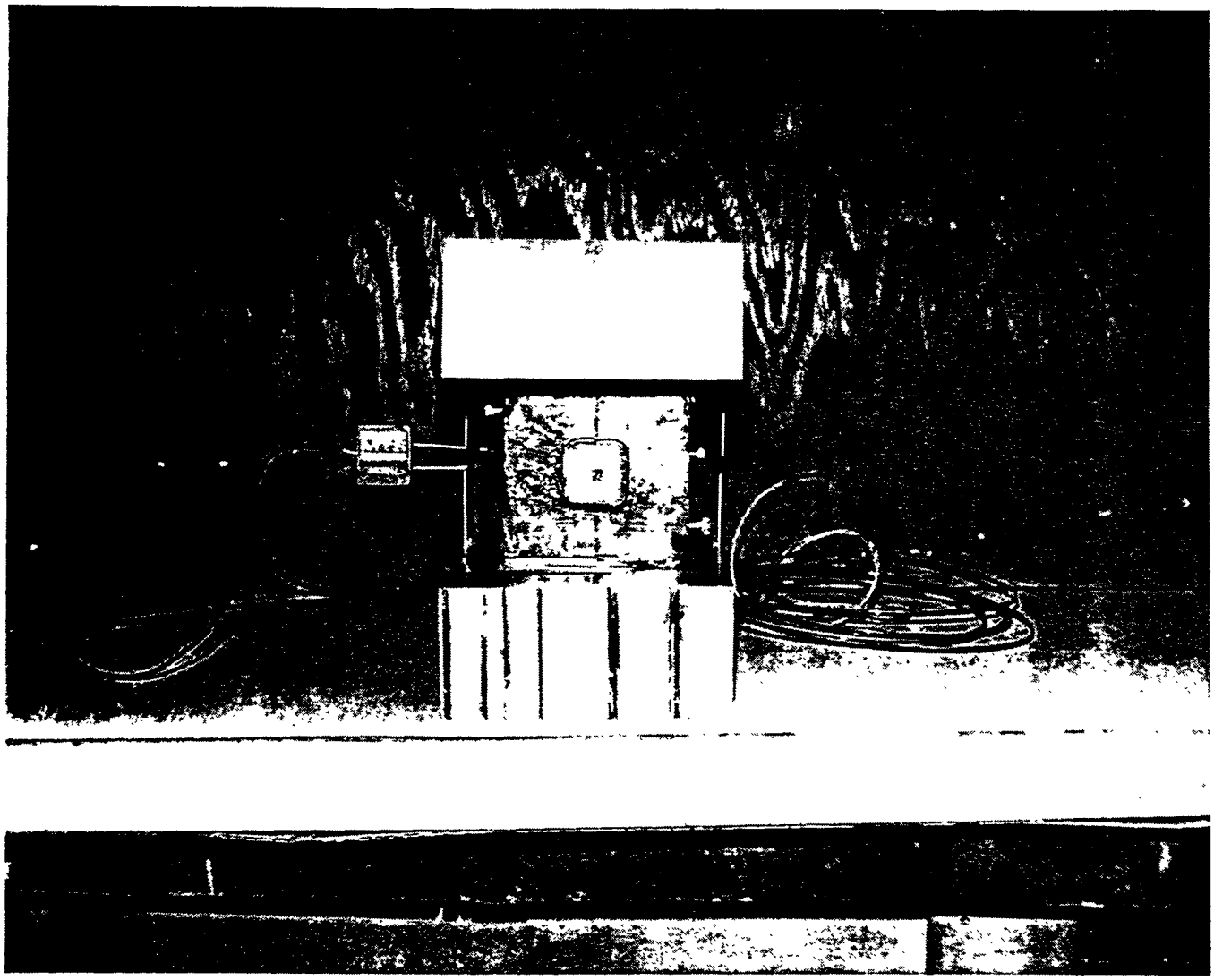


Figure 4 — End View of 3x3 Sample Mounted with G10 Load Carrying Block and Extensiometer

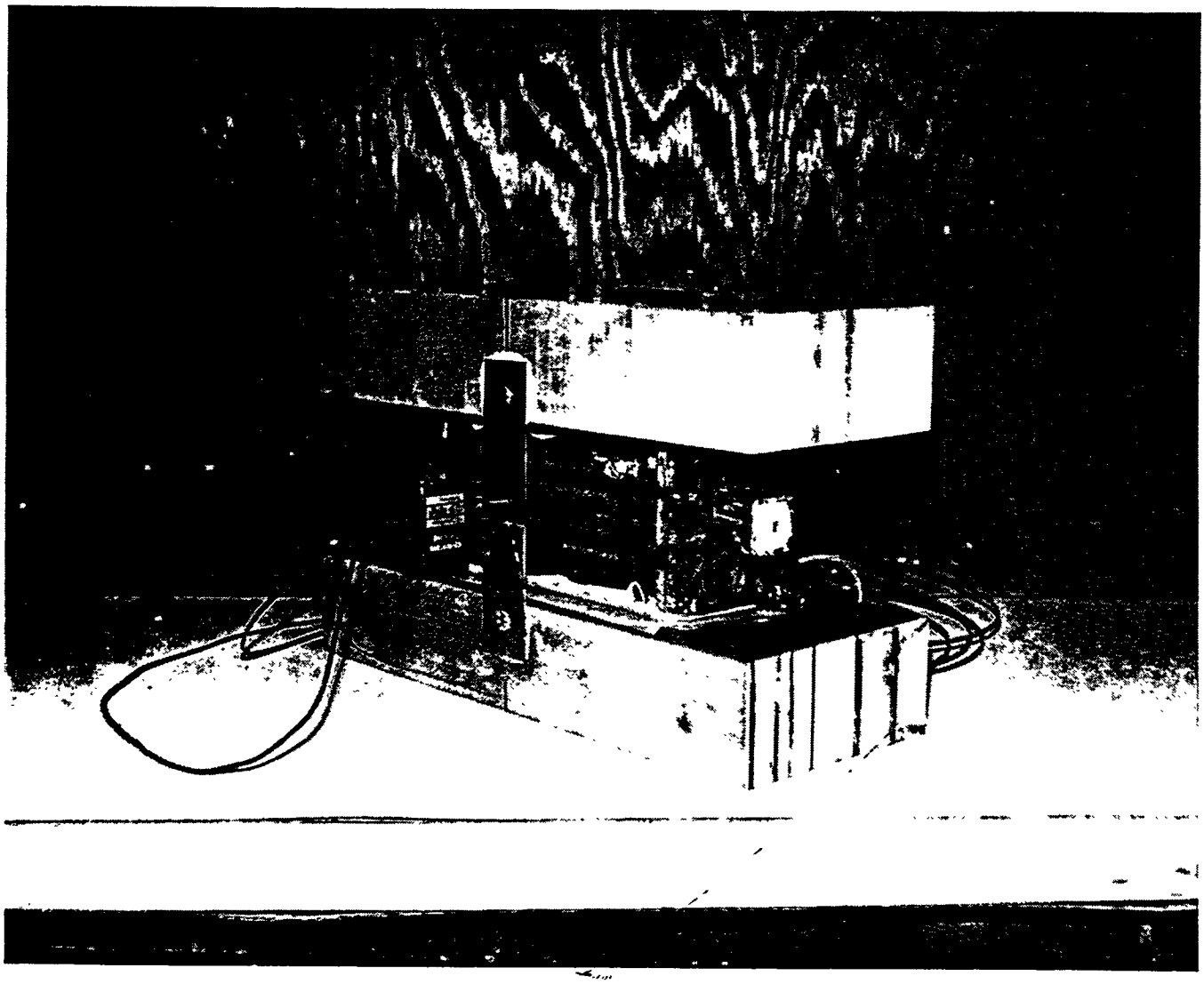


Figure 5 — Side View of 3x3 Sample With Extensiometer Mounted

1.1 GENERAL DESCRIPTION OF THE PROGRAM

During the testing program a total of six configurations were tested. The first three configurations had one sample each, and the remaining three had two samples each. The first sample was approximately 150mm (6 inches) long, the following two were approximately 250 mm (10 inches) long and the remaining samples were 130 mm (5 inches) long with two samples per configuration, one for test, one as a spare.

The electrical tests were done at the end of each warmup when the samples has reached complete thermal equilibrium with the room. The electrical tests determine if the mechanical degradation in the coil is causing damage to the electrical integrity of the coil.

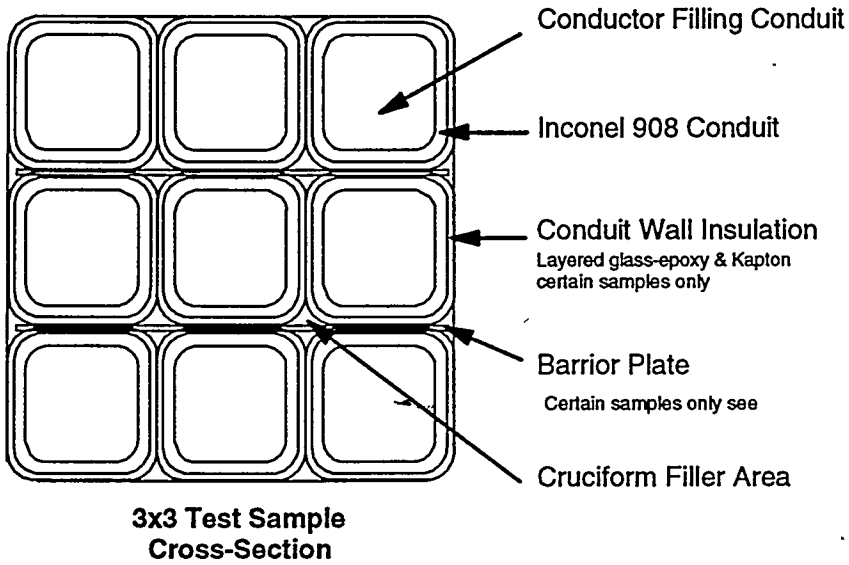


Figure 6 — Nomenclature

1.2 CONCLUSIONS

From a mechanical prospective the 3x3 test program has two specific objectives:

1. Provide a basis for evaluating the results of the finite element analysis, and
2. create significant characteristic mechanical degradation in the coil that discriminating information can be obtained on the relationship between mechanical degradation and electrical degradation for different insulation systems.

The 3x3 coil sample tests accomplish this.

1. The character and magnitude of the stresses predicted by the finite element analysis of the 3x3 test are consistent with the physical degradation observed in the test samples thereby providing FEA model validation.
2. The physical degradation of the 3x3 sample on test is consistent with degradation which is indicated by the finite element analysis of the 6 x 10 CS coil under combined thermal cooldown, EM loading and mechanical preload, thereby providing validation for the test loads ability to introduce characteristic mechanical damage.

Specifically, due to cyclic testing the filler material in the cruciform and crescent areas of the 3x3 test sample crack and debond in a manner consistent with the stress levels and stress character predicted by the finite element analysis of the test sample. This same general pattern of stress is predicted for the 6 x 10 coil under full baseline loads[1]. Under these loads the critical stresses in the filler of the 6 x 10 coil would be (36%) higher than the peak critical stresses in the test sample during cyclic load. As result the same general character of degradation as experienced in the test is expected in the real 6x10 coil.

The test also indicates that in the old baseline design the failure of the insulation barrier sheet is imminent at about the baseline load level. While the 3x3

[1] Base line loads refer to the load set used in the finite element analysis and consist of cooldown from room temperature, vertical load equivalent to 25 MN on the actual coil.

barrier failed at double the load level applied for 15,000 cycles, the analysis of the 6 x 10 indicates that it will achieve the critical stress level in this component at closer to the baseline load conditions.

The failure of the insulation barrier in the cruciform area of the 3x3 sample provides a breakdown path from layer to layer for electrical testing. This leaves the electrical integrity of the conduit wrap insulation at the corner of conduit to protect against layer to layer electrical breakdown. This conduit insulation like the filler pieces are also stressed mechanically during the test cycle.

The character and magnitude of the conduit insulation interlaminar shear during cyclic loading will be very similar to the stresses predicted for the 6x10 coil and no gross interlaminar degradation is visible. The actual coil is subjected to overall tensile loads in the hoop direction that the test sample cannot duplicate without considerable difficulty therefore while the shear is duplicated the overall stress state of the insulation is not.

The most critical conduit wrap stress in terms of its apparent proximity to predicted failure points is the conduit wrap interlaminar shear at the corner of each cruciform. The maximum interlaminar shear stress at the corner of the 3x3 test from the linear elastic finite element analysis is 82 MPa. The value predicted for the 6 x 10 is 96 MPa. The shear stress limit predicted for the insulation is as low as 50 MPa depending on the interlaminar direct load. At this corner the interlaminar direct stresses increase up to 50 MPa compression as the cyclic portion of the load is applied and released. The compressive load is applied coincident with the highest shear. Data indicates that the compression raises the shear strength limit by about 50%. The 3x3 test does not visually indicate that shear failures are occurring in conduit wrap. Similarly at the highest applied loads the 157 MPa shear predicted for this corner do not appear to fail the insulation. Again the direct compressive load of about 100 MPa causes the strength to increase to the point where delamination does not occur. The compressive loads in the 6x10 coil will be higher than the stresses in the 3x3 based on the finite element analysis and as a result even more favorably influence the shear stresses limits.

Laminar tensile stress in conduit wrap in the region of the conduit corner is also a concern. It appears less critical from the point of its proximity to its limit, however the 3x3 test sample does not reproduce this stress well and failure in this mode could be the most significant type of insulation failure. The finite element analysis of the 6x10 original baseline indicates that the direct tension in the wall of the insulation will be as high as 88 MPa. Strengths even considering fatigue should be more than twice this level. This is considered the most significant shortfall in the 3x3 test program.

2. DESCRIPTION OF THE MECHANICAL TESTS

2.1 LOAD SELECTION

The worst case operating loads on the CS coil were selected as the loads that would be used for mechanical testing. This decision was based on the types of loading that can be expected in the coil packs during operation. Consideration was given to loads on the central solenoid coils packs, PF5, 6 and 7, and the TF coils. In addition the different loading scenarios were considered including disruption and fault. This encompasses a wide variety of loading conditions due to variations in coil geometry, mechanical support and applied electrical field.

When the loading patterns were compared for the various coils the following similarities in loading become apparent:

1. Each coil is subject to internal stresses due to thermal contraction;
2. Each coil has areas where through compression exists;
3. Each of the PF coils display some degree of tensile load along its length (hoop load);
4. PF5, PF6, PF7 and the TF coils experience some bending; and
5. The CS coils experiences some shear associated with differential radial load.

To characterize the stresses in each of the coils or due to each of the loadings would require multiple tests and to reproduce the character of the hoop stresses could require large axisymmetric models. The objective of the 3x3 test series suggests simple tests which result in characteristic insulation damage and is intended to capture the most critical internal coil stresses that are representative of the loadings discussed.

The stresses of interest in the coil insulation are those related to the conduit insulation and those related to filler material. The cruciform filler is of particular interest, because the cruciform filler area is highly stressed. Degradation in this area has been shown to lead to mechanical and electrical breakdown. Stresses in the ground wall further complicate the stress field in the rest of the coil but in the interest of correlating with the analysis the less critical groundwall was not included in the 3x3 mechanical testing program.

In comparing the various external coil loadings the CS magnets appear to have the highest mechanical and electromagnetic loads (except for bending) and will be subject to the worst case thermal stresses. The analysis and design work still in progress will more clearly define these stresses. In the interest of downselecting to an insulation system, a selection of the test load and configuration was made on the information available. The thermal stresses are worst for the CS (and PF5) coils, because the conduit material is made from Inconel 908 which has a greater mis-match in thermal contraction when compared with the insulation system than the 316 Stainless Steel used for the conduit in the other coils. The conclusion as to the worst case mechanical loading is based on results of load studies published by MIT[1]) and worst case summaries published by (W)STC[2] . Some ambiguity exists as to the worst hoop loads because of the incomplete analysis and design particularly related to the support of the PF5, PF6 and PF7 coils.

For the CS magnets the loadings of concern include:

1. Internal thermal contraction stresses due to differential thermal contraction of the various materials in the composite coil;
2. Vertical compression of the central solenoid pack due to preload;

[1] Radovinsky,A.L., "The Worst Fault Load Cases on coils of the TPX PF Set due to a Vertical Plasma Disruption Followed by a System Dump with Shorted PF Coils Terminals at the Twenty Three Equilibra,"TPX-950327-MIT-ARadovinsky-01

[2] Krefta,M.P., "Worst Case Electromagnetic Loading", TPX.STC.MPK.BH.M006.02.02.95 and TPX.STC.PAS.BH.M006.02.22.95.

3. Vertical compression of the central solenoid pack due to the vertical component of the electromagnetic forces (Lorentz forces) on the central solenoid pack;
4. Hoop loads due to the radial component of the magnetic loads (Lorentz forces) on the coil;
5. Shear loads due to the variation of the radial component of the magnetic loads inside the conductor pack; and
6. Mechanical shear load due to differential radial loads between different coils in the stack.

Given the above it was decided that the 3x3 model testing would be done at liquid nitrogen temperature nominally simulating the cooldown stress field in the CS coil, then the sample would be loaded to worst case vertical compressive load in cyclic fashion for 15,000 cycles, and then finally would be loaded in a similar compressive fashion to incipient structural failure.

Hoop load simulation was not included because of difficulty of the simulation combined with the fact that a finite element based comparison of the stress fields due to hoop loading and vertical compressive loading indicates that the vertical compressive loading produces more critical stresses.

2.1.1 Shear Stresses in the CS Assembly

Mechanical shear across the entire coil was not included in the test series because the average level of shear stress caused by the differential shear loading is relatively low with respect to the shear load capability of the insulation. This conclusion was based on bounding calculations at the time of the test definition. Ultimately detailed finite element calculations will be used to establish the local stresses caused by the shear loads. The program plan calls for detail calculations of the loads with a "smeared properties overall structural model" then a detailed stress analysis of the coil with the loads applied.

The maximum shear stress can be bounded on the high side without a structural model for both normal operation and fault conditions by assuming that the differential loads between coil packs is resolved as a stress between them.

The maximum shear load between coils due to a normal operating scenario occurs due to Load Case 1 PF1-PF2. This is reported in (W)STC report[1] as equivalent to 2.85 MN of hoop load which is equivalent to 2.85 MN/radian of radial line load. The shear stress between the coils can be upper bounded by multiplying the line load by the circumference (2π) and dividing that by the interface area. Disruptions will not raise the level of this load.

Worst Case Differential Coil to Coil Shear = 2.85 MN Hoop Load / (Entire coil - 6 turns)
Coil Mean Radius = 31.893 in = 810.08 mm / (LLNL DWG-9414002B)
Conductor Width = 0.92 in = 23.4 mm

Shearing Line Load :
2.85 MN / Radian
2.85 MN x 1e03 (m/mm) / 810.08 mm = 3.52 MN / m

Shearing Load :
2.85 MN x 2 x Pi = 17.90708 MN

Average Shear Stress:
Line Load x 2 x Pi / (2 x Pi x radius x coil width) = Average Stress
2.85 MN x 1e06 (mm^2/m^2) / (810.08 mm x (23.3mm/turn x 6 turns)) = 25.09 MPa (3639 psi)

Based on tests reported at TIM #3 minimum shear strengths in the insulation appears to be about 50 MPa at 4 K with 0 normal tension or compression. While 25 MPa is significant if the coils have similar hoop stiffness the stress can be no higher than half of this value and coil to coil shear compliance will lower this further. Therefore it was concluded that the maximum coil to coil shear during normal operation will be less than 12.6 MPa.

The worst case differential layer-to-layer shear during a fault is reported as 97 kN hoop force/turn[2], where PF3U attempts to pull out of the pack and is re-

[1] Krefta,M.P., "Worst Case Electromagnetic Loading", TPX.STC.MPK.BH.M006.02.02.95.
[2] Radovinsky,A.L., "The Worst Fault Load Cases on coils of the TPX PF Set due to a Vertical Plasma Disruption Followed by a System Dump with Shorted PF Coils Terminals at the Twenty Three Equilibra,"TPX-950327-MIT-ARadovinsky-01

strained on the top and bottom. The worst case line load at the coil to coil interface will be 0.097 MN/turn-radian x 60 turns = 5.82 MN/radian. The symmetry of the situation suggests that half of the load will be reacted on the top half of the coil and the other half on the bottom resulting in a surface traction at both locations of 2.91 MN/radian. Approximately the same as calculated for the worst case normal operation stress.

2.1.2 Vertical Compressive Load in the CS Assembly

The worst case vertical compressive load was identified from a document written by Al Corpuz (W)Sunnyvale dated 8 March 95 to A. Radovinsky at MIT where Corpuz presents examples of design algorithms which suggest that the vertical preload will approximate the maximum coil-to-coil vertical separation force and it will apply at the same time as the maximum EM vertical clamping load. The document indicates that the peak CS coil vertical clamping load due to combined preload and EM force is expected to be 30.22 MN. Approximately 10 MN (9.15) of that load is a steady preload load provided by the vertical preload structure and 20 MN (21.07) caused by the peak Lorentz forces during normal operation load case #10 at the midplane of PF1. (Later information suggests that LC #15 or #16 replaces #10 as worst but with about the same max load and location.) This ignores the increase which occurs during disruption which raises the maximum vertical EM load to 23 MN and presumably will result in a combined maximum of about 33 MN.

The loading cycle was picked to initiate a fatigue pattern in the material consistent with the pattern expected during normal worst case coil life and then to extend the damage beyond normal operation by overloading the specimen. The number of cycles was picked to provide the correct order of magnitude for load applications so as to initiate the pattern of fatigue expected in the operating coil, recognizing that fatigue is a logarithmic phenomena and therefore 15,000 cycles should provide a moderately similar level and character of fatigue (as long as crack growth

is in a stable regime) as the 30,000 cycles of required life. Fatigue data for epoxy-glass composite suggests that when compared on the basis of fatigue damage, the difference between 15,000 load cycles and 30,000 load cycles is equivalent to about 12% difference in load. Application of Miners Rule suggests that if damage is occurring in a linear fashion, the final load application (actually on the order of 10 applications) at twice the load applied in the cyclic test (2 x (Preload + EM)) will result in substantially more damage than would occur due to an additional 15,000 cycles. Current swing in the central solenoid coil can potentially result in load reversals that effectively double the number of load cycles. This could raise the number of cycles that the solenoid will see in its lifetime to 60,000. Studies of the temporal operating scenarios for the TPX CS indicate that for the worst case loadings the load swing is small by comparison to the overall cyclic load making the effect of the load swing negligible and allowing 30,000 cycles to be considered life.

2.1.3 Mechanical Test Load Values

The vertical preload of 10 MN applied evenly over the CS coil with a mean radius 0.81 m (LLNL DWG-9414002B) and a conduit with of 23.4 mm works out to be an average pressure load of approximately 14 MPa or 2,000 psi over the six conduits.

Worst Case Verticle Compression = 10 MN over the Entire coil - 6 turns
Coil Mean Radius = 31.893 in = 810.08 mm
Conductor Width = 0.92 in = 23.4 mm

Vertical compressive Line Load :
10 MN x 1e03 (m/mm) / (2 x Pi x 810.08) mm = 1.96 MN / m = 1.12E+04 Lb/in

Average Vertical Compressive Stress:

$$\frac{2.85\ \text{MN} \times 1e06\ (\text{mm}^2/\text{m}^2)}{(2 \times \text{Pi} \times 810.08\ \text{mm} \times (23.3\text{mm/turn} \times 6\ \text{turns}))} = 14.01\ \text{Mpa} \quad (\ 2032\ \text{psi}\ )$$

The 20 MN EM vertical clamping load caused by the Lorentz forces represent an additional load of approximately 28 MPa or 4,000 psi. As a result the loads applied to the individual test samples are given in Table 2.

Table 2 — Vertical Compressive Loads Applied During 3x3 Testing

	Test Loads					
	Preload Simulation		EM Ld. Simulation		Preload+EM Load	
Sample length	Lbf	MN	Lbf	MN	Lbf	MN
6 inch = 0.152 m	33600	0.15	67300	0.299	100900	0.449
10 inch = 0.254 m	56100	0.249	112200	0.499	168300	0.748
5 inch = 0.127 m	28000	0.125	56100	0.249	84100	0.374

Test Load = Pressure x Sample Length x 3 Conduit x Conduit Width

Preload Pressure =	2032	psi	=	14.01	Mpa
EM Pressure =	4064	psi	=	28.02	Mpa
Conduit Width =	0.92	inches	=	0.023	meters

During testing the preload is used as a steady state bias while the EM portion of the load is cycled on and off for 15,000 cycles.

The final test load consists of load to "failure". The failure is defined by observation of the load deflection plot and acoustic noise level. The load to failure tests consists of raising the load slowly to the point at which a noticeable offset or significant nonlinearity occurs in the load deflection curve and/or acoustic emission indicates catastrophic damage is occurring. Table 3 below shows a comparison of the loading applied to the 3x3 samples and the worse case loadings expected on the coils. Loading applied to each sample are indicated in a later table.

2.2 MECHANICAL TEST CONFIGURATION

2.2.1 Sample Preparation

When received for mechanical testing the 3x3 test sample dimensions have already been recorded, and the sample has been marked to identify individual conductors by number. The top of the sample is identified as that side adjacent to conduits numbered 1, 2 and 3. Alignment is important because some of the samples

have a barrier plate between layers and also because the sample must always have the same orientation during testing. Figure 7 shows the sample prepared for testing.

Table 3 — Comparison of Expected Worst Case Loads with Test Simulations

3x3rpt.xls

Expected Worst Case Coil Loadings	Test Simulation
Cool Down, Glass Transition --> Room Temperature, One time	Cool Dn. Gl. Transition --> Room Temp, One time
Compressive Preload applied at RT. F(Vert./ Preload) = 0 –>14 Mpa one cycle	Load Compression at RT. F(Vert) = 0 MPa -->14 MPa 2-6 cycles / set up
Cool Down RT. –> 4 °K - 30 cycles ?	Cool Down RT. –> 77 °K - 3 cycles
Peak Loads during LC #16, Max. Vertical Compression at 4°K F(Vert./ Normal Operation) = 14 --> 42 Mpa, 15000 cycles F(Radial / NO) = 0 --> 27 KN / Turn Hoop Load F(Vert./ Disruption) = 14 --> 48 Mpa, 15000 cycles F(Radial / Disruption) = 0->27 KN. / turn, hoop load	Load Compression @ 77°K F(Vert.) = 14MPa –> 42 MPa, 15000 cycles F(Vert.) = 14 MPa --> 84 MPa approx.10 cycles
LOADS NOT SIMULATED: Max. Differential Radial shear @ 4 K -LC#1 Shear Stress PF1-PF2 < 12.6 MPa, 30000cycles. Bending Load @ 4°K, To Be Determined Max. Radial Electromagnetic Force @ 4°K, LC#1 PF3 F(Vertical) = 18.3 MN w/preload , 30000 Cycles F(Radial) = 45.6 KN. / turn, hoop load	

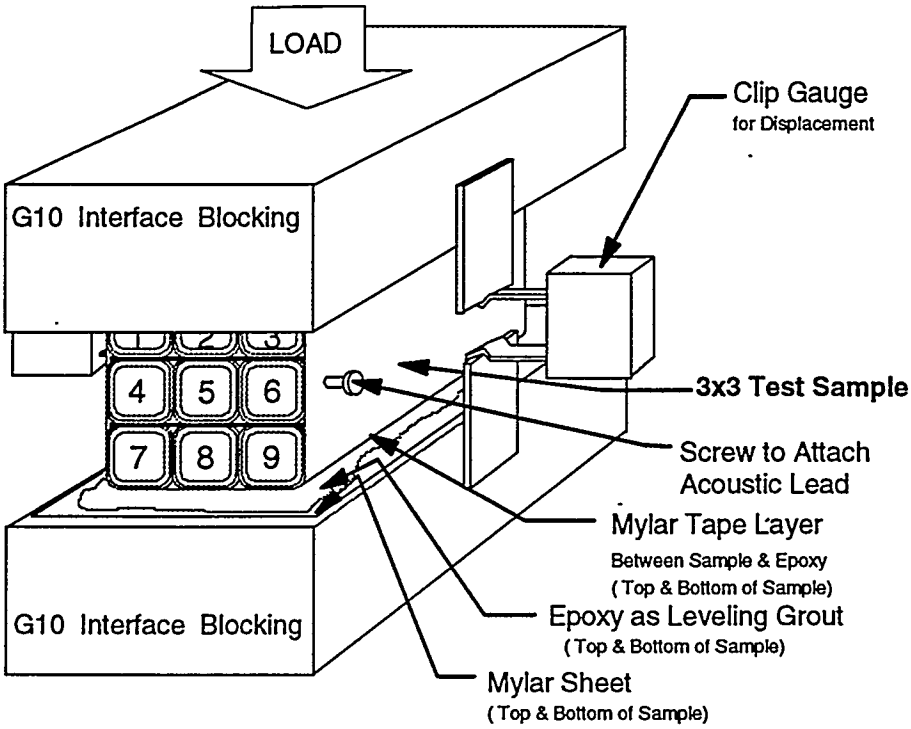


Figure 7 — 3x3 Sample Prepared for Testing

The sample is prepared for compression testing by attaching 51 mm (2″) thick G11 test sample interface blocks to the top and bottom of the sample so as to provide proper alignment in the test machine and assure that the load is evenly distributed over the top and bottom surfaces. G11 material is selected as it will act as an elastic foundation against the sample in the absence of groundwall. Before attaching the sample to the blocks any resin flashing or burrs on the top and bottom surface of the sample that interfere with proper parallel alignment of the blocks is removed using a fine file.

The test sample interface blocks are attached to the top and bottom of the sample using epoxy grout to level the surface and provide fine adjustment for paralleling the blocks. At the beginning of the process the top and bottom of the sample are covered with 0.05mm (0.002")″ Mylar tape to provide for easy removal of the epoxy grout at the end of the test and to prevent the electrical test attachment holes from filling with epoxy. A two part epoxy kit is mixed so as to have a cure which

from filling with epoxy. A two part epoxy kit is mixed so as to have a cure which provides a working time of about a half of an hour. This results in an interface which will have some plasticity when first placed in the test machine. The epoxy is troweled on to the sample, a sheet of Mylar is applied over the resin, and the blocks are pressed to the Mylar. The sample is centered on the blocks based on markings on both the sample and the blocks. The blocks are then adjusted using a metal gauge to assure that their faces are parallel to each other. The epoxy is then allowed to set for about an hour before the sample is placed in the test rig and cycled slowly up to the preload level.

While the epoxy sets a thermocouple is embedded in one of the outside conduits using one of the holes which were drilled into the sample for electrical testing. The thermocouple is pressed into the hole so that it contacts the dummy copper conductor inside the conduit, and putty is placed in the hole after the thermocouple to seal out the liquid nitrogen that would otherwise enter the hole during testing.

2.3 TEST SETUP

After the epoxy has initially set up to a plastic state, the test sample is placed in the test apparatus and aligned in the platens of the apparatus. Figure 8 shows the test setup. The loading apparatus consists of a large commercial MTS hydraulic load compression test machine capable of 1e06 Lb (4.4 MN) force. The nitrogen bath is located in such a fashion that that the load can be applied through the sample while it is submerged in liquid nitrogen as is indicated in the figure.

While still at room temperature a mild compressive load is applied to the sample to align the sample-interface blocks in the test machine. The epoxy still being plastic will adjust for misalignment. While the sample is held in place with the light load, two deflectometers are installed on the test sample as indicated in Figures 4 and 5 so that compressive deflection can be recorded along with load from the crosshead of the test machine. (On the first series of 7,200 cycles on sample #1 only one deflectometer was installed.)

hour at 77°K the sample is allowed to slowly return to room temperature. The preload is not maintained during warm up.

The second cooldown usually occurs the following morning. Sample one was the exception because the second cycle occurred after an initial 7200 mechanical cycles. In either case prior to cooldown to 77.4°K (-320.4° F) the mechanical compressive load is slowly brought back to the 14 MPa level. Sometimes several up and down cycles are applied to assure that the sample alignment is correct and shows a linear behavior. During this second cooldown a constant pressure of about 14 MPa is maintained on the sample, and acoustic emission is recorded. Following cooldown mechanical cyclic load testing is commenced. The third cool down is accomplished in a similar manner.

After cooldown the preload simulation level of 14 MPa is reestablished accurately, then the sample is cycled from that load to the maximum load and back at a rate of between 0.5 cycles per second and 2 cycles per second until the desired number of cycles are obtained. During this cycling load deflection and acoustic emissions are recorded. Load deflection is recorded at a minimum of every 1,000 cycles while acoustic emission is recorded every cycle. The general procedure discussed above is repeated as outlined in Table 4 until all cyclic testing is complete. Load to "failure" is accomplished by preparing the sample as done for the cyclic tests. When the sample has been cold for one hour, the preload level is established as done for the cyclic tests. The load is then ramped up slowly to load levels which are incrementally higher than the maximum load used in the cyclic portion of the test. The load is ratcheted up with each succeeding load cycle until significant nonlinearity is observed in the load verses deflection curve or until significant acoustic emission indicates unusually high distress. A loud snap is an indication that a significant failure has occurred or flattening of the load verses deflection curve indicates incipient failure. During some of the tests the load vs. deflection curve appears to flatten only to appear linear up to that point in succeeding cycles.

After there are indications that the sample has been damaged as significantly as possible without crushing it, the sample is removed from the mechanical

test apparatus and is electrically tested. After electrical test it is sectioned at its mid-point.

3.1 SUMMARY OF 3X3 TEST RESULTS

Table 5 below summarizes some of the results of the mechanical 3x3 tests.

Table 5 — Summary of Mechanical Results

3x3test.wk4

24-May-95

		Sample #1 CDR Baseline	Sample #2 Slip Plane Option	Sample #3 CDR Baseline W/Araldite	Sample #4b Interim Baseline 3d Wrap& Rov	Sample #5a Hybrid Prepreg	Sample #6 Cigar Roll
Apparent Compressive Modul ①②							
Cycle 4	(Gpa)	9.6	7.9	9.7	8.1	9.7	9.1
Cycle 15000	(Gpa)	9.2	7.6	9.3	7.8	9.2	9.0
Percent decrease		3.5%	3.3%	3.8%	4.2%	5.8%	1.0%
Apparent Deformation ③							
Pressure Load	(Mpa)	44.7	41.3	41.8	42.6	42.7	42.6
Cycle 4	(cm)	0.034	0.038	0.031	0.038	0.031	0.034
Cycle 15000	(cm)	0.036	0.039	0.032	0.039	0.033	0.034
Mechanical Compressive Failure							
Cycle Number		15006	15038	15009	15021	15016	15005
Failure Pressure	(Mpa)	87.2	73.8	76.4	85.9		62.9
Def. at "Failure"	(cm)	0.071	0.089	0.069	0.089		0.086
Buckling Load	(Mpa)	89.9				86.2	
Def. at Buckling	(cm)	0.113				0.101	
Original Sample Dimensions:							
Length (Sample)	(mm)	152	254	254	127	127	127
Length (Conduit)	(mm)	137	252	252	122	122	122
Width	(mm)	74.0	71.6	70.9	72.5	71.8	71.8
Height	(mm)	74.6	71.6	71.5	72.6	71.7	71.2

1) Apparent Compressive Modulus = E = Load x height / (Loaded cross-section area x measured deformation)

2) Comparative apparent modulus (E) from finite element analysis (GPa) 10.8

3.2 SAMPLE 1 TESTING

Sample #1 is referred to as the CDR baseline because the insulation materials used are most similar to the configuration which was identified in the conceptual design phase of the program. The one major difference is that the conduit wall insulation is approximately twice the planned thickness of 1.62 mm (0.064").

Sample 1 was tested as described in Table 5. When the sample was cooled to 77°K acoustic emission was monitored. Several times during in the cooldown cycle some snapping was heard with a distinct report shown on the acoustic emission chart. This could have reflected cracking inside the sample. However, after observing several cooldowns, it was decided that the relative thermal contraction in the fixturing and test set up, and the boiling of the liquid nitrogen caused sufficient background noise that the signal could not be relied upon to reflect damage activity inside the sample.

Loading the sample to preload force levels of 0.15 MN corresponding to nominal pressures of 14 MPa was done at both room temperature and 77°K. Six cycles were applied to the sample in establishing the preload bias at cold temperature. Significant nonlinear load deflection was observed up to the preload point, and some indication was present that the test setup continued to take a set beyond the alignment set provided for at room temperature. After the first assembly several steps were taken to minimize this effect. 1) Additional attention was paid to the initial alignment, 2) the epoxy grout thickness was minimized, and 3) more time was provided at room temperature for the setup to align itself at "preload" pressures. The curve did appear smooth and nominally repeatable. While the preload force was maintained an additional load of 0.299 MN corresponding to approximately 28 MPa was applied in a cyclic fashion on top of the preload to represent the vertical compressive electromagnetic force. This results in a peak force of 0.449 MN or approximately 42 MPa. When the pressure is calculated based on the conduit length as opposed to the sample length, a more precise value of 44.7 MPa is obtained.

Beyond the preload range the sample behaved in a nice linear repeatable fashion. The curves show nothing remarkable in the first several loadings to 44.7 MPa (101e03 lb.) where early weaknesses might be expected to show up. Subsequent loadings to this level behave in a similar fashion. Figure 9 shows the load deflection characteristics of sample 1 at load cycles 4, 5, 6, 7,520, 7,521, 12,300, 13,500 and 15,000. The results are smooth linear and reasonably similar in slope. Data from Table 5 indicates that the modulus decreases by about 3.5% over 15,000 cycles.

This softening of the structure is likely due to crack growth and weakening of the insulation which bonds the conduit together into a structure.

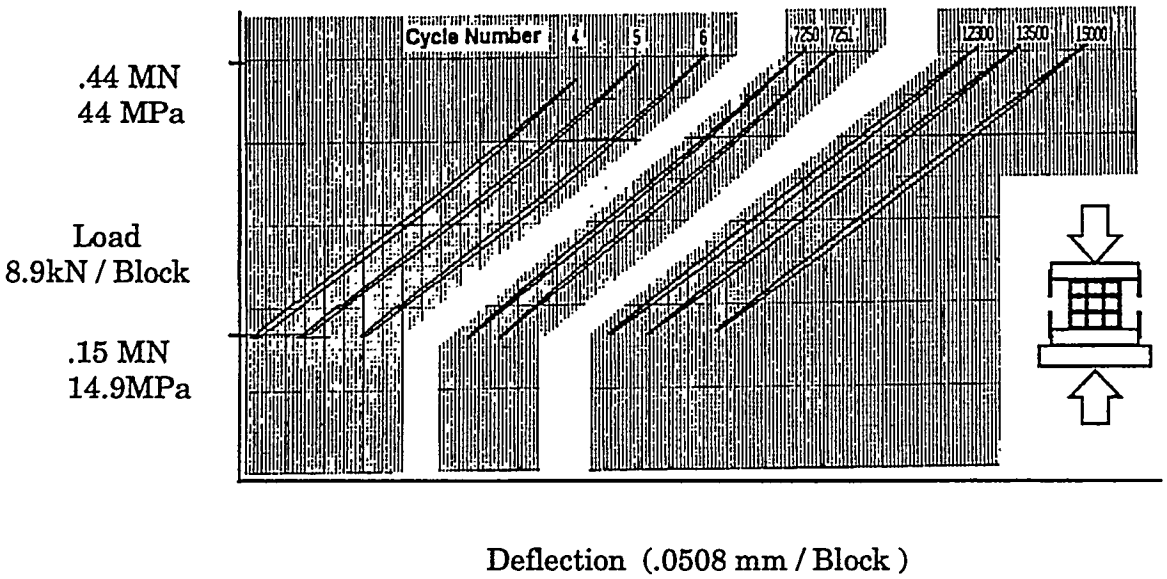


Figure 9 — Load Deflection Characteristics of Sample 1

All of the load deflection results are included in Appendix 1. When the sample was sectioned after 15,000 cycles, cracks could be observed in the cruciform area as depicted in Figure 10. The pictures in Figures 14-18 show the area in more detail.

During the cyclic loading period acoustic measurement of the noise emitted by the sample is recorded. Figure 11 shows a trace of that acoustic signal. The noise emitted can be heard when standing next to the test apparatus. A distinct sound is emitted as the load swings up, and a second is emitted as the load returns to the preload bias level. The acoustic equipment counts the number of emissions it hears during a specified time period which are above a threshold level and produces a proportional output based on that count. For these tests no particular significance

placed on the absolute value of the signal, however, the logarithmic decay of the signal to a constant level is taken to signify that the damage accumulation is stable and linear.

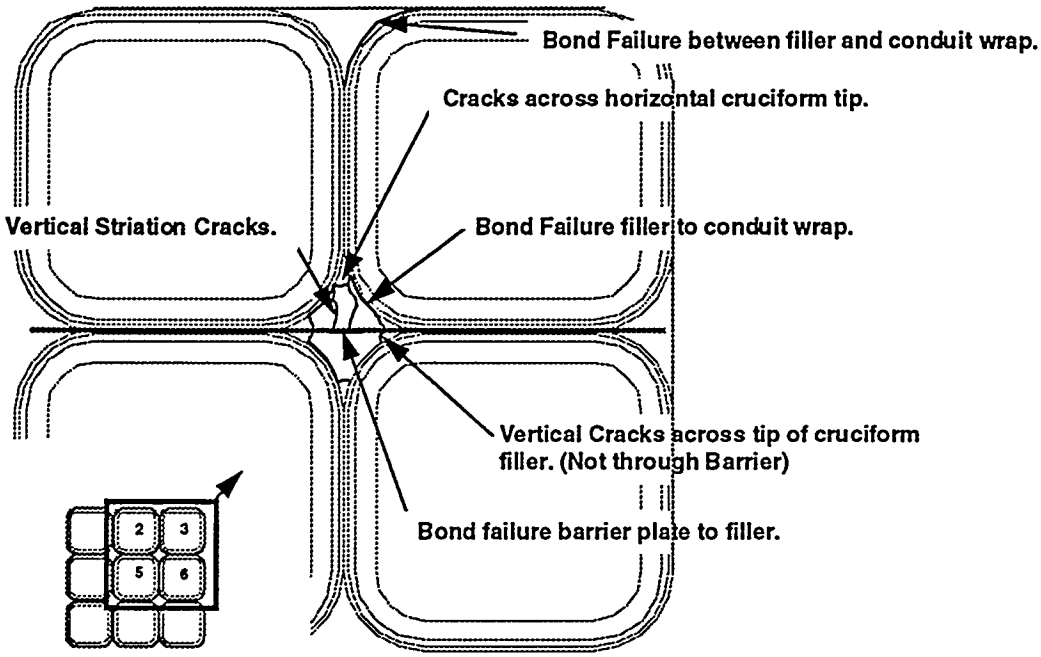


Figure 10 — Damage to Sample 1 After 15,000 Cycles

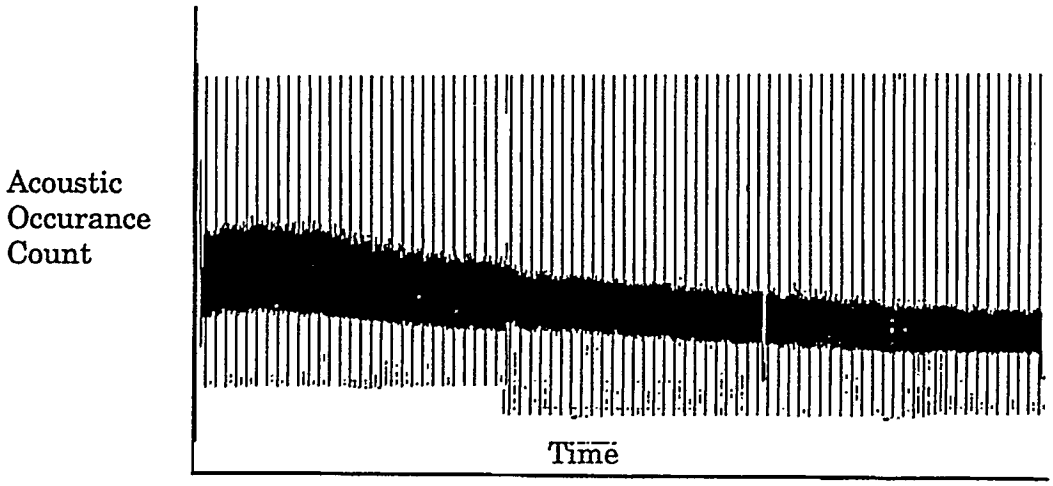
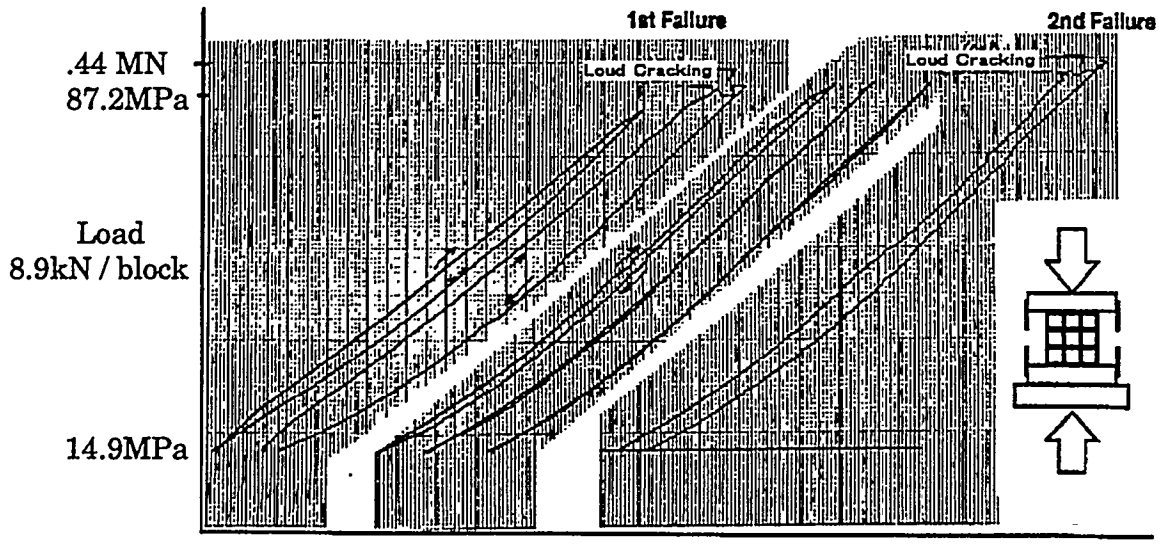


Figure 11 — Acoustic Emission During Cyclic Testing on Sample 1

After the 15,000 cycles shown as steps 3 and 7 in Table 4 were accumulated and electrical testing alluded as step 9 was performed, the sample was cut in half. While half the sample was dedicated to damage assessment the other half of the sample was dedicated to loading to "failure". The 75 mm (3 inch) long half sample was placed back in the test apparatus and cooled to 77°K. The preload load bias was reestablished, and the load was successively raised from the 44.7 MPa pressure at which the 15,000 cycles had been accumulated to a pressure of 87.2 MPa (as calculated using the conduit area). This pressure results from a load of 0.449 MN. A total of 16 cycles were applied to the sample in ratcheting up to the "failure" load. The last several load deflection curves are shown in Figure 12. During the last cycle and the sixth from last cycle, a loud snapping noise was heard to come from the test sample, and the noise was accompanied by a constant load strain. These events are believed to be associated with failure of the barrier plate. They were taken to signify that the sample was about to undergo a structural collapse. The load deflection characteristics are not nearly as clean as at the lower loads. The roughness in the curves is believed to reflect significant damage being done to the insulation with each cycle. The change in the slope at the lower end of the curves may reflect gaps having formed inside the sample which cause the sample to stiffen as load causes them to reclose. This would indicate that the metal conduit has taken a permanent set. After the final load to failure the sample was warmed and sectioned for damage assessment.

The portion of the sample sectioned after "failure" was found to have cracking fundamentally similar in character to the section taken at after 15,000 cycles except that on the "failed" sample 1) cracking at the horizontal apexes of the cruciform now proceeded all the way through the barrier plates, 2) the cracks were open wide enough to infer that there is permanent set in the conduit, and 3) vertical cracks were propagating up vertically between the conduit.

Electrical testing which would have taken place as step 15 from Table 4 was skipped, because the sample had been sectioned eliminating the insulation at the end of the sample necessary to prevent very early breakdown under test.



Deflection (0.1016 mm/ Block)

Figure 12 — Load Deflection at Failure - Sample 1

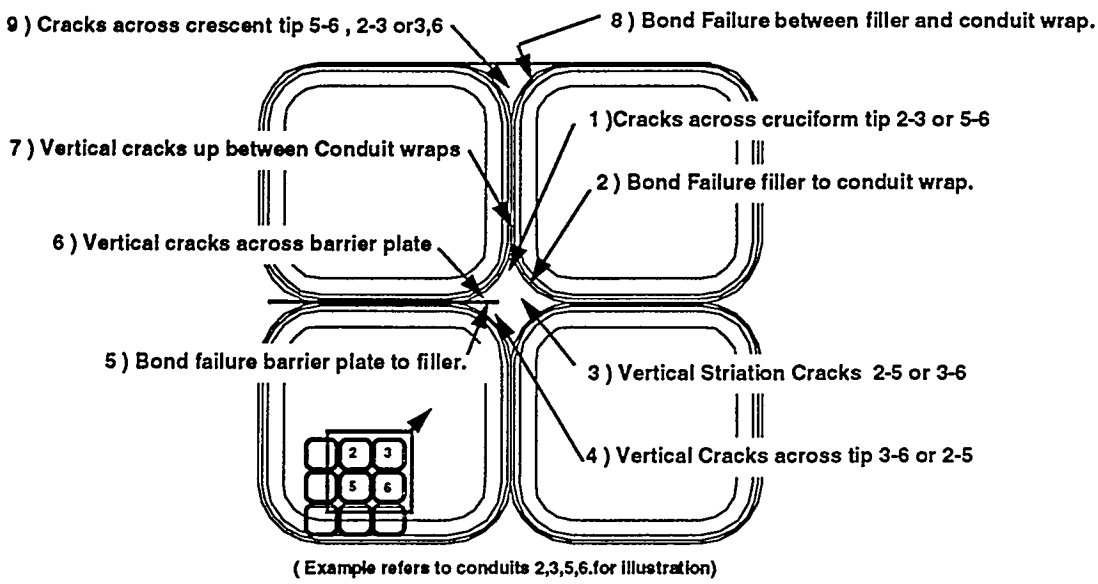
The acoustic noise measurements support the idea that significant damage is occurring to the sample as its being loaded to "failure". Judging from the noise most of the damage occurs the first time that the sample is loaded to a new higher level.

The sample section which had not been loaded to "failure" had a remaining sample length of 44 mm (1.75 inches) after removal of the section for examination. (Conduit length in this sample section was 38 mm (1.5 inches)). The remaining piece was cooled to 77°K and loaded to the point of crushing in one cycle. The sample appeared to undergo a rapid onset buckling at a pressure load of about 89.9 MPa applied over the conduit area.

The failure mode suggests that the conduit side walls bulge outward during compression stretching the cruciform area. Weak areas break first possibly resulting in the vertical cracking shown in Figure 16. Eventually the barrier plates fail and the columns of conduit begin to separate. As the vertical cracks between conduit grow the three high stack of conduit begin to behave more and more like a column structure. This particular failure clearly is a function of the three high, aligned conduit configuration. The failure mechanisms apply to the CS coil up to the point where large deformations effects come into play.

3.3 DISCUSSIONS REGARDING SAMPLES 2-6

The remaining samples behave in a fashion similar to sample #1. As indicated in Table 4 samples 2-6 were not sectioned after 15,000 cycles but only after the final loading to failure in order to permit electrical measurements throughout the process. The results of the final dissection are depicted in Figure 13. Actual photos of the cracks depicted in Figure 13 are shown in Figures 14 to 18.



Sample #		1) Cracks across cruciform tip (Horiz.)	2) Bond failure filler to conduit wrap	3) Vertical striation cracks in filler	4) Cracks across cruciform tip (Vert.)	5) Bond failure barrier plate to filler	6) Vertical cracks across barrier plate	7) Vertical cracks between conduit wrap	8) Bond failure filler to conduit wrap	9) Cracks across crescent tips.
	# of Locations Examined	8	16	4	8	4	8	8	6	8
1	CDR Baseline @ 15000 cyc	88	81	100	100	75	0	0	50	0
1	CDR Baseline @ Failure	100	94	100	100	50	75	50	67	38
2	Slip Plane Option	88	56	50	100	-	-	63	50	63
3	CDR Baseline w/Arolidite	38	56	100	63	0	63	25	67	0
4b	Interim Baseline 3d matl.	88	50	100	38	-	-	50	33	50
5a	Hybrid Prepreg		Buckling Failure Before Dissection							
6	Cigar Roll	Sample Failed Electrically, Testing Discontinued								

Figure 13 — Comparative Results of Sample Dissection

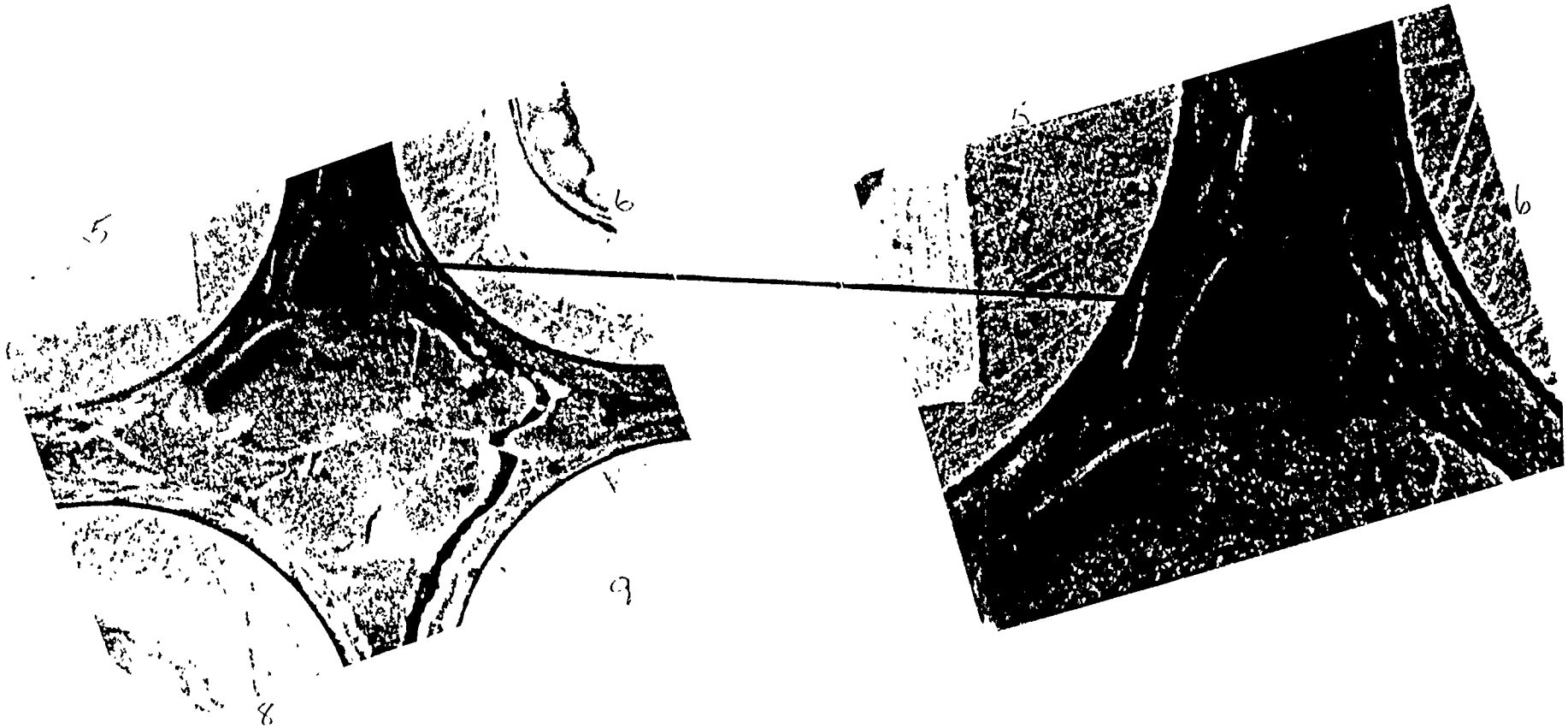


Figure 14 — Dissection of Sample 4b - Interim Baseline w/3d Wrap & Roving

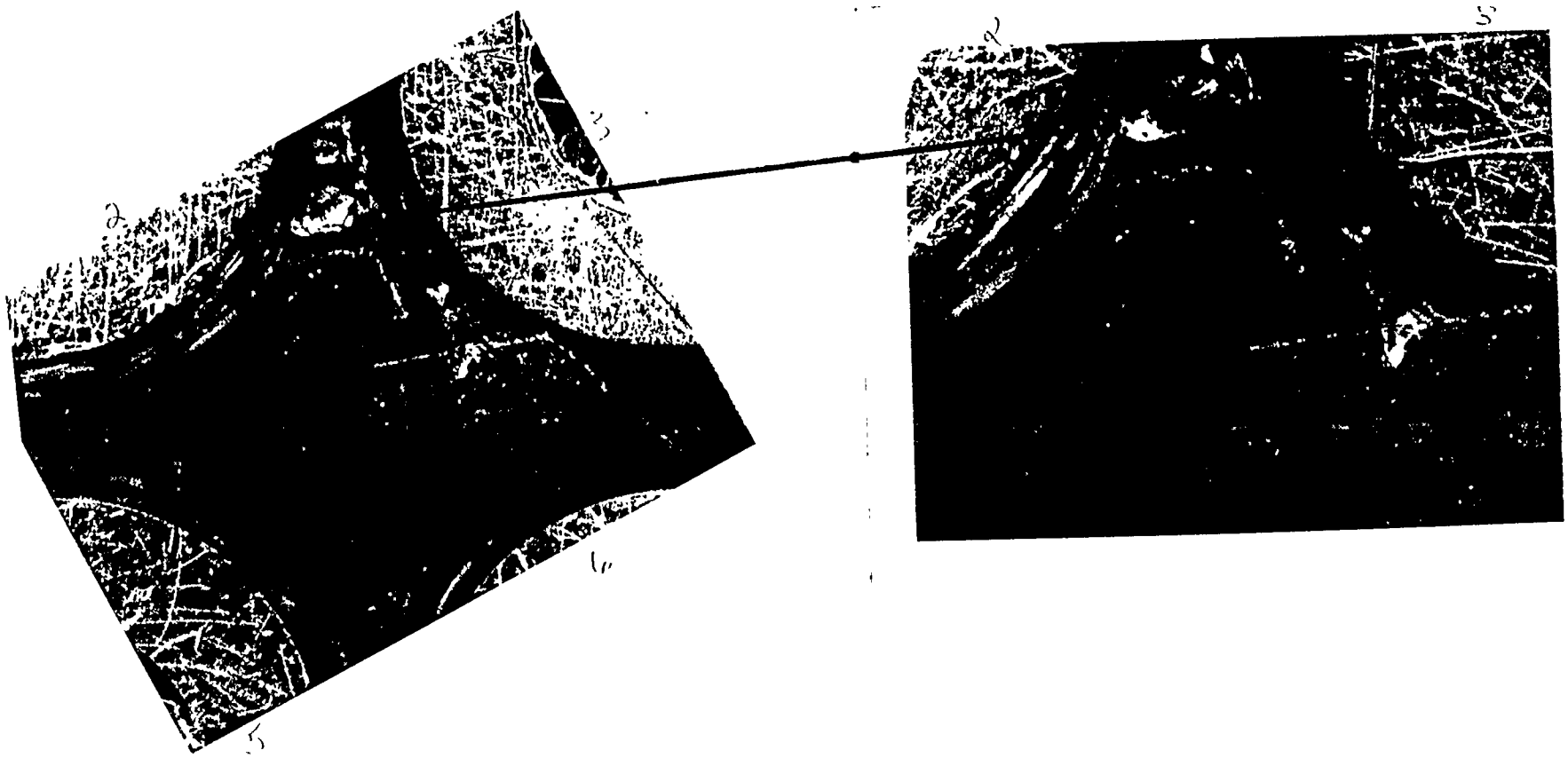


Figure 15 — Dissection of Sample 1 - CDR Baseline [at 15,000 Cycles]

Figure 16 — Dissection of Sample 1 - CDR Baseline [After Internal Failure]

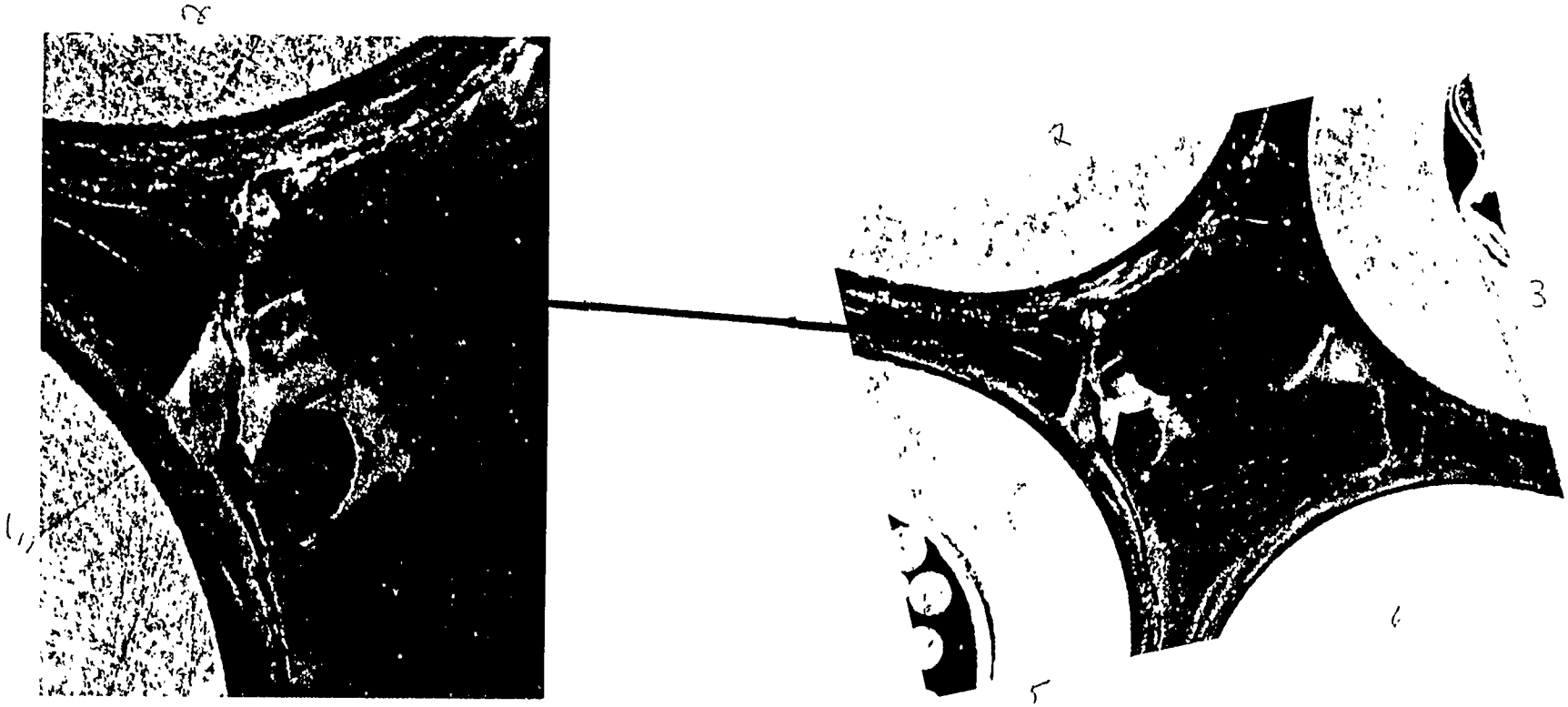


Figure 17 — Dissection of Sample 2 - Slip Plane Option

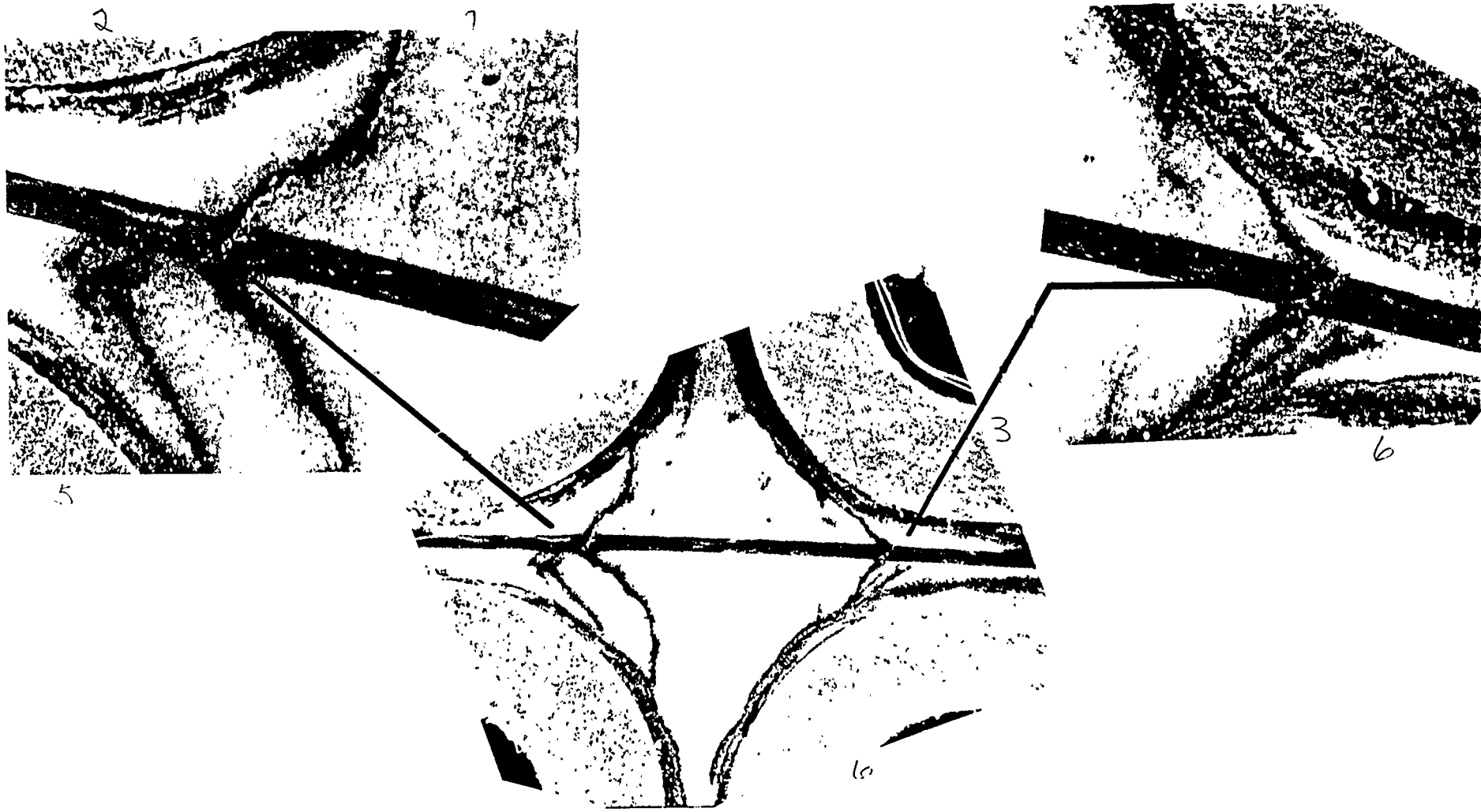


Figure 18 — Dissection of Sample 3 - CDR Baseline with Arolidite Filler

4. COMPARATIVE FINITE ELEMENT ANALYSIS

One of the primary objectives of the 3x3 testing program is to provide verification for the finite element analysis of the coils. In pursuit of this objective a Finite Element model of the 3x3 compressive test was constructed. The model used material properties that reflect test sample 1 (CDR Baseline). The results from the analysis of the 3x3 sample are compared with results of a 6x10 unaligned coil having the same CDR baseline insulation system. The analysis of the sample was done to reflect the loads placed on the sample during test. The 6x10 analysis which is used for comparison purposes had a set of load conditions which were identified as the baseline load set. This load set consisted of cool down from room temperature to 4°K, 25 MN of vertical compression at the boundary and EM loads which reflected equlibria Load Case 1.

The comparison of the critical mechanical stresses during test as compared with the stresses during operation is the most significant factor in assessing the applicability of the test to the actual loading situation . The stresses of interest occur primarily in the conduit insulation and cruciform as this area is highly stressed mechanically and is the area that will be challenged during electrical test. Table 4.1 shows a comparison of the some of the most significant stresses predicted by the linear elastic finite element models. Three cases are tabulated: a) stresses of 6x10 worse case loading, b) stresses in 3x3 sample at 84 MPa. The third case corresponds to the load at which most 3x3 samples failed and can be used in an overall assessment of the test. The conduit wrap stress values ignore stresses which would be adjacent to the ground wrap location as those stresses are not likely to be a factor in the testing program described here. With the exception of the previous statement, the stresses presented in this table are maximum values of stress aligned with the

principal material directions and for each of the various components of interest. They are for direct comparison purposes. These peak values do not necessarily apply at the same location in a component, and therefore cannot be judged to act in combined fashion.

Table 6 — Comparative Finite Element Results 3x3 Vs. 6x10 Coil

Units = N/m²		CDR Baseline 6x10 coil		3x3 coil @ 42 MPa 15000 mech. cycles		3x3 coil @ 84 MPa Expected Failure	
		Laminar	Inter-Lam.	Laminar	Inter-Lam.	Laminar	Inter-Lam.
Conduit Wrap Insulation							
	Tension	60E+6	60E+6	20E+6	20E+6	Same as For	
Cool down	Compression	-59E+6	-108E+6	-40E+6	-23E+6	15000 cycles	
	Shear	-	69E+6	-	21E+6		
Cool Down & Vertical Id	Tension	88E+6	44E+6	27E+6	20E+6	53E+6	39E+6
Plus EM Load for 6x10	Compression	-90E+6	-142E+6	-90E+6	-108E+6	-177E+6	-217E+6
	Shear	-	96E+6	-	82E+6	-	157E+6
Cruciform Filler Material		Fiber Dir.	Inter-Fiber	Fiber Dir.	Inter-Fiber	Fiber Dir.	Inter-Fiber
	Tension	82E+6	150E+6	28E+6	78E+6	Same as For	
Cool down	Compression	0	-107E+6	0	-30E+6	15000 cycles	
	Shear	-	75E+6	-	26E+6		
Cool Down & Vertical Id	Tension	116E+6	136E+6	25E+6	100E+6	31E+6	114E+6
Plus EM Load for 6x10	Compression	0	-105E+6	0	-112E+6	-20E+6	-214E+6
	Shear	-	93E+6	-	24E+6	-	27E+6
Barrier Insulation Sheet		Laminar	Inter-Lam.	Laminar	Inter-Lam.	Laminar	Inter-Lam.
	Tension	61E+6	109E+6	26E+6	34E+6	Same as For	
Cool down	Compression	-93E+6	109E+6	-54E+6	-30E+6	15000 cycles	
	Shear	-	71E+6	-	1E+6		
Cool Down & Vertical Id	Tension	93E+6	91E+6	48E+6	17E+6	109E+6	34E+6
Plus EM Load for 6x10	Compression	-68E+6	-141E+6	000E+0	-131E+6	000E+0	-239E+6
	Shear	-	63E+6	-	997E+3	-	997E+3

The degree to which the stresses in the test sample approximate the stresses in the actual coil indicate the degree to which the tests replicate the actual coil stresses. Some of the stresses are replicated well others are not. Where a poor replication exists we must convince ourselves that the stress is not important, because it represents a noncritical failure mechanism, or because the limit is far from the material limit.

One of the objectives of the 3x3 program was to aid in the selection of the baseline insulation system. Unfortunately the mechanical aspects of the 3x3 pro-

gram did not provide any strong discriminators based on mechanical performance. The other two aspects of the program, electrical performance and finite element analysis, have provided stronger guidance for a final selection. Nevertheless, the following observations can cautiously be made:

a) The compressive modulus of both samples with no bond between the conduit and the Kapton was lower than the other fully bonded samples.
b) The ultimate failure of the sample appeared to be due to buckling of the three conduit high column. Bonded samples appear to collapse at a higher pressure.
c) Sample #5a failed suddenly and without the expected early warning signs of eminent collapse. Post failure examination revealed numerous areas where full impregnation between the Kapton layers was not achieved and could be responsible for this behavior (shown in Figure 19).
d) Sample 6 started exhibiting signs of collapse much earlier than the other samples. Due to the early and unexpected collapse of sample #5a, premature termination of the testing may have occurred. In addition further investigation in this sample was not pursued due to extensive electrical failures on the sample.
e) The drop in compressive modulus after 15,000 cycles was the least with the sample 6, the most with sample 5 while the other samples were nested together in the middle of these two extremes.

Reviewing the comparison tables we can see that the thermal stresses in the model are approximately one-third the values to be expected in the coil. When the combined loading is applied, the match-up improves particularly for the conduit wrap shear and exceeds or matches all important stresses at the observed sample failure stress. However, the match-up falls short on conduit wrap insulation tensile stresses induced by the hoop reaction from both the radial EM force and the thermal contraction mismatch.

One measure of the criticality of the stresses is its proximity. The tensile stresses mentioned above are far from their ultimate limit which makes them less

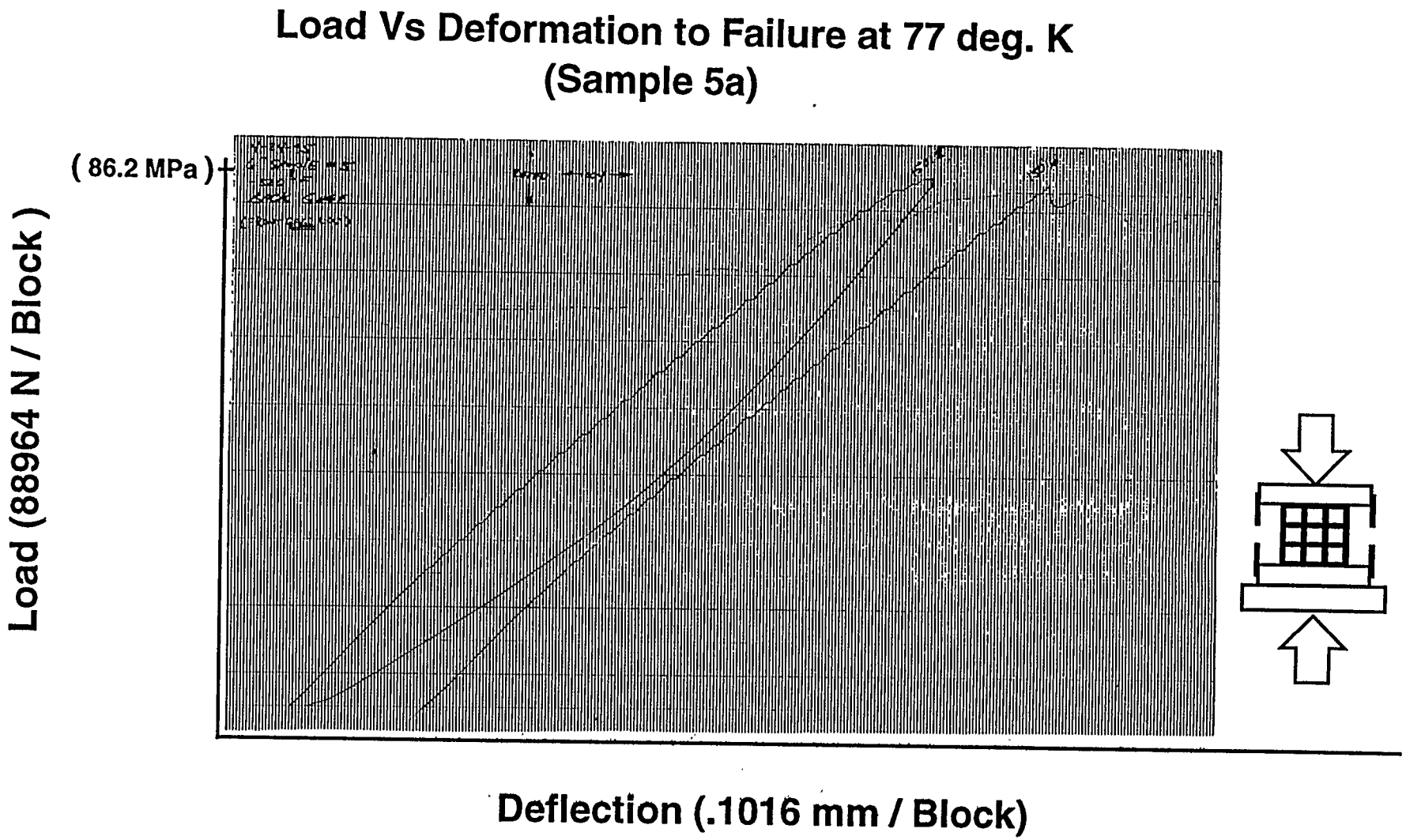
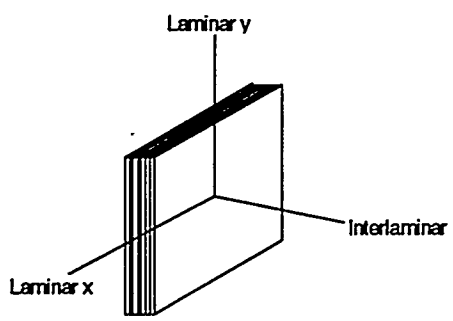


Figure 19 — Load Compression Test Results

critical than the shears which are at or near their limit. The cyclic nature of the load situation is known to affect the limit. However, the simplistic evaluation (to be refined in later work) ignores fatigue and simply compares the stress with the single cycle limit. Table 7 shows estimated values for the single cycle materials limits. These limits are then compared to calculated coils stresses and show in Table 8 where each stress is divided into its limit as a fractional measure of capability used up in the coil. Ideally all fractions should be greater than one. The limits are provided as rough estimates for the purpose of rough criticality assessment. Definitive material characterization must be performed in later phases of the program. It is clear that the key interlaminar limits are significantly exceeded as evidenced by values less than one particularly for the corner fillers and for interlaminar tension and shear in the conduit wrap.

Table 7 — Approximate Single Cycle Material Limits at 4°K

Material	Fiber Dir or Laminar x Compressive Strength (Mpa)	Fiber Dir or Laminar x Tensile Strength (Mpa)	Laminar y Compressive Strength (Mpa)	Laminar y Tensile Strength (Mpa)	Inter-fiber or Interlaminar Compressive Strength (Mpa)	Inte-rfiber or Interlaminar Tensile Strength (Mpa)	Crossfiber or Laminar Shear Strength (Mpa)	Inter-fiber or Interlaminar Shear Strength (Mpa)	Laminar Shear Strength (Mpa)
Conduit Wrap	400	400	400	400	560	40		60	
Roving Filler	40	600			40	60		34	
G10-cr	600	600	600	600	840	60		90	
Resin	40	69						34	



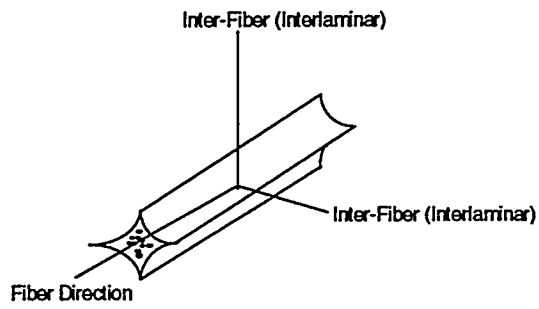


Table 8 — Stresses / Approximate Single Cycle 4°K Limits

3x3stres.xls		CDR Baseline 6x10 coil		3x3 coil @ 42MPa 15000 mech. cycles		3x3 coil @ 84MPa Expected Failure	
		Laminar	Inter-Lam.	Laminar	Inter-Lam.	Laminar	Inter-Lam.
Conduit Wrap Insulation							
	Tension	6.7	0.7	20.0	2.0	Same as For	
Cool down	Compression	6.8	5.2	10.0	24.3	15000 cycles	
	Shear	-	0.9	-	2.9		
Cool Down & Vertical ld	Tension	4.5	0.9	14.8	2.0	7.5	1.0
(Plus EM Load for 6x10)	Compression	4.4	3.9	4.4	5.2	2.3	2.6
	Shear	-	0.6	-	0.7	-	0.4
Corner Filler Material		Fiber Dir.	Inter-Fiber	Fiber Dir.	Inter-Fiber	Fiber Dir.	Inter-Fiber
	Tension	7.3	0.4	21.4	0.8	Same as For	
Cool down	Compression	-	0.4	-	1.3	15000 cycles	
	Shear	-	0.5	-	1.3		
Cool Down & Vertical ld	Tension	5.2	0.4	24.0	0.6	19.4	0.5
Plus EM Load for 6x10	Compression	-	0.4	-	0.4	2.0	0.2
	Shear	-	0.4	-	1.4	-	1.3
Barrier Insulation Sheet		Laminar	Inter-Lam.	Laminar	Inter-Lam.	Laminar	Inter-Lam.
	Tension	9.8	0.6	23.1	1.8	Same as For	
Cool down	Compression	6.5	7.7	11.1	28.0	15000 cycles	
	Shear	-	1.3	-	90.0		
Cool Down & Vertical ld	Tension	6.5	0.7	12.5	3.5	5.5	1.8
Plus EM Load for 6x10	Compression	8.8	6.0	-	6.4	-	3.5
	Shear	-	1.4	-	90.3	-	90.3

An important objective of the 3x3 test program was to confirm the high stress fields portrayed by the finite element analysis. From Table 8, one of the pronounced damage areas would be expected to be the corner fillers failing in tension and shear. The pictures in the previous section exhibit this pattern of damage. The conduit wrap would also be expected to fail in shear at the corners of the conduit. Unexpectedly this failure mode was not observed in the 3x3 samples.

TPX Magnet Insulation Large Scale Verification Test Program

R. J. Hillenbrand, J. F. Roach, and P. A. Sanger
STC Advanced Electromechanical Systems Department

August 18, 1995

TPX 14-950818-WEC-PSanger-01

APPROVED:

P.A. Sanger
Westinghouse TPX Chief Scientist

APPROVED:

D. R. Potter
Westinghouse TPX Engineering Manager

Westinghouse Electric Corporation
Electronic Systems Group

401 East Hendy Avenue, Sunnyvale, California 94088-3499

CONTENTS

ABSTRACT ..... **vii**

SUMMARY ..... **viii**

1. OBJECTIVE AND PROGRAM OVERVIEW **1-1**

2. OVERVIEW OF TESTING PROGRAM **2-3**

3. SUCCESS CRITERIA **3-6**

3.1 MECHANICAL CRITERIA: 3-6
3.2 ELECTRICAL: 3-9

4. DETERMINATION OF THE MECHANICAL LOADING FOR THE 5X5 TESTING PROGRAM **4-10**

4.1 DETERMINATION OF THE NUMBER OF LOAD CYCLES FOR THE TPX CONDUCTOR PACK 4-11
4.2 THE TPX MAGNET SYSTEM EM LOAD CASES 4-13
4.2.1 CS Coil EM Loading Cases *4-14*
4.2.2 PF5 Loading Cases *4-15*
4.2.3 PF6 Loading Cases *4-15*
4.2.4 PF7 Loading Cases *4-16*
4.2.5 TF Coil Loading Cases *4-16*
4.3 TPX COIL EM LOAD MAGNITUDES 4-16
4.4 FEA STRESS RESULTS FROM THE CS COIL PACK ANALYSIS 4-18
4.5 DETERMINATION OF THE LOADS FROM FEA ANALYSIS OF THE 5X5 TEST SAMPLE 4-21
4.5.1 5x5 CS Coil Test Loads *4-21*
4.5.2 FEA Stress Results for the 5x5 Test Sample *4-23*
4.6 3X2 TEST LOADS 4-26
4.7 5X5 TF CONDUCTOR PACK TEST LOADS 4-27
4.8 DETERMINATION OF THE NUMBER OF TEST LOADING CYCLES 4-28

5. TESTING CRITERIA AND TEST VOLTAGES FOR TPX 3X2 AND 5X5 INSULATION R&D MODELS **5-31**

5.1 ASSUMPTIONS 5-31
5.2 DEVELOPMENT OF TESTING CRITERIA 5-32
5.2.1 Turn-Turn Peak Operating Voltage *5-32*
5.2.2 Turn-Ground Peak Operating Voltage *5-33*
5.2.3 Peaking Factor for Local Stress Enhancements at Conduit in Kapton Wrap *5-33*
5.2.4 Peaking Factor for Vacuum/Helium Partial Discharge Simulation in Air Test *5-33*
5.3 TEST VOLTAGE TO OERATING VOLTAGE CORRELATIONS 5-36
5.3.1 Turn-Turn Test Voltages *5-36*
5.3.2 Turn-Ground Test Voltages *5-37*
5.4 SELECTION OF TESTING VOLTAGES FOR 5X5 AND 3X2 MODELS 5-38

6. DESCRIPTION OF CONDUCTOR TEST SAMPLES AND FABRICATION PROCESS **6-40**

6.1 TEST SAMPLE CONFIGURATIONS 6-40

6.2 FABRICATION AT EVERSON ELECTRIC COMPANY 6-43
6.2.1 Conductor Preparation Procedures *6-43*
6.2.2 Insulation and Mold Assembly *6-44*
6.2.3 Impregnation Procedures *6-46*
6.3 AS RECEIVED SAMPLE CHARACTERISTICS 6-47

7. MECHANICAL TESTING PROGRAM 7-48

7.1 OVERVIEW OF TESTING 7-49
7.2 THERMAL LOAD CYCLING 7-50
7.2.1 Results of Thermal Testing of Sample A1 ..... *7-52*
7.3 MECHANICAL COMPRESSION TESTS 7-55
7.3.1 CS 5x5 Tests *7-55*
7.3.2 TF 5x5 Compression Tests *7-69*
7.3.3 3x2 Bending Tests. (Sample #C1&C2) *7-69*
7.3.4 3x2 Bending Tests *7-74*

8. ELECTRICAL TEST RESULTS 8-77

9. CONCLUSIONS 9-83

FIGURES

FIGURE 2-1 SCHEMATIC REPRESENTATION OF THE TEST PROGRAM. 2-4
FIGURE 2-2 SCHEMATIC REPRESENTATION OF THE TEST LOADS. 2-5
FIGURE 3-1 ILLUSTRATION OF THE LIMITING CASES FOR CRACKING IN THE UNIT CELL OF THE WINDING PACK REPRESENTED BY THE 5X5 TEST SAMPLES. 3-7
FIGURE 3-2 ILLUSTRATION OF BOTH UNACCEPTABLE (LEFT) AND ACCEPTABLE (RIGHT) DELAMINATIONS AND CRACKING IN THE 5X5 SAMPLE USED IN THE VERIFICATION TESTING PROGRAM 3-8
FIGURE 4-1 FLOW CHART INDICATING METHOD FOR DETERMINATION OF CS SAMPLE TEST LOADS. 4-11
FIGURE 4-2 COMPRESSIVE FORCE BETWEEN CS 1U AND 1L DURING LC #16 4-29
FIGURE 4-3 COMPRESSIVE FORCE BETWEEN CS 1U AND 1L DURING LC #16 DIVIDED INTO TEMPORAL COMPONENTS. 4-30
FIGURE 6-1 CROSS SECTIONAL CONFIGURATIONS OF 3X2 AND 5X5 SAMPLES SHOWING EXTENDED CONDUCTORS (MARKED WITH AN "X") AND IDENTIFICATION OF CONDUCTORS FOR INSULATION TESTING. 6-41
FIGURE 6-2 END PREPARATION OF INCOLOY 908 CONDUCTORS. 6-43
FIGURE 6-3 INSULATED B1 AND B2 5X5 SAMPLES AND PARTIAL INSTALLATION IN MOLD. 6-45
FIGURE 6-4 PARTIAL ASSEMBLY OF THE 5X5 MOLD SHOWING VACUUM/PRESSURE PORT END FLANGE, C-CLAMPS, AND CLAMPING BAR. 6-46
FIGURE 7-1 — COOLDOWN TEST RIG 7-51
FIGURE 7-2 SAMPLE A1 - SECTION 1 - AS MANUFACTURED 7-53
FIGURE 7-3 SAMPLE A1 - SECTION 2 - AFTER 19 THERMAL CYCLES. 7-54
FIGURE 7-4 CS 5X5 SAMPLE PREPARED FOR TESTING 7-55
FIGURE 7-5 TEST SETUP SCHEMATIC 7-57
FIGURE 7-6 USAGE OF SAMPLE A1 7-59
FIGURE 7-7 SCHEMATIC OF THE PARAMETERS FOR MEASURING THE MODULUS OF THE SAMPLE 7-60
FIGURE 7-8 MODULUS AND CHANCE IN MODULUS FOR THE CS 5X5 COIL SAMPLE 7-61
FIGURE 7-9 SAMPLE A1 - SECTION 3 - AFTER 31000 COMPRESSIVE LOAD CYCLES. 7-63
FIGURE 7-10 CHARACTERIZATION OF CRACKING IN - SAMPLE A1 - SECTION 3 THE CRACKING PRESENT DOES NOT VIOLATE THE RULES SET FORTH IN SECTION 3 AND THE STRUCTURE APPEAR TO REMAIN MECHANICALLY ROBUST. FIGURE 7.10 IS INTENDED TO CHARACTERIZE THE CRACKING OBSERVED FROM THE SECTION A1-3. 7-64
FIGURE 7-11 SAMPLE A1 - SECTION 4 - AFTER 155000 COMPRESSIVE LOAD CYCLES 7-65
FIGURE 7-13 SAMPLE A1 - SECTION 5 - AFTER COMPRESSIVE FAILURE 7-68
FIGURE 7-14 CHARACTERIZATION OF CRACKING IN - SAMPLE A1 - SECTION 5 7-69
FIGURE 7-15 TF 5X5 SAMPLE PREPARED FOR TESTING 7-68
FIGURE 7-16 3X2 SAMPLE PREPARED FOR TESTING 7-74
FIGURE 8-1 — MODEL 5X5 A2 UNDER HIPOT TESTING 8-77
FIGURE 8-2 GROUNDPLANE FOIL ELECTRODE ON 5X5 SAMPLE B2 8-78

TABLES

TABLE 4-1 ANTICIPATED COIL LOADS 4-13
TABLE 4-2 MAXIMUM VALUES OF THE WORST CASE COIL LOADS[4] 4-17
TABLE 4-3 FEA ANALYSIS LOAD CASE TABLE 4-19
TABLE 4-4 FEA MAXIMUM STRESS RESULT SUMMARY FOR THE CS COIL ASSEMBLY* 4-20
TABLE 4-5 FEA STRESS RESULTS SUMMARY FOR THE CS 5X5 TEST 4-25
TABLE 4-6 COMPARISON OF WORST CASE CS COIL STRESS AND 5X5 TEST SAMPLE STRESS 4-26
TABLE 4-7 COMPARISON OF WORST CASE TF COIL STRESS AND 5X5 TEST SAMPLE 4-28
TABLE 5-1 PEAK TF AND PF OPERATING VOLTAGES (V) 5-31
TABLE 5-2 PASCHEN BREAKDOWN FOR HELIUM AND AIR 5-34

TABLE 5-3 RECOMMENDED TEST VOLTAGES FOR 5X5 MODEL ACCEPTANCE TESTING 5-38
TABLE 6-1 DESIGN CONFIGURATIONS OF 3X2 AND 5X5 TEST SAMPLES 6-41
TABLE 6-2 VPI IMPREGNATION PROCEDURES FOR THE 3X2 AND 5X5 MODELS 6-47
TABLE 6-3 AVERAGE DIMENSIONS AND INSULATION SPACINGS OF 3X2 CS AND 5X5 PF AND TF MODELS AS RECEIVED 6-48
TABLE 7-1 VERIFICATION TESTING PROGRAM & SEQUENCE 7-50
TABLE 7-2 VERTICAL COMPRESSIVE LOADS APPLIED DURING CS 5X5 TESTING 7-59
TABLE 7-3 MODULUS AND CHANCE IN MODULUS FOR THE CS 5X5 COIL SAMPLE 7-61
TABLE 7-4 VERTICAL COMPRESSIVE LOADS APPLIED DURING TF 5X5 TESTING 7-72
TABLE 7-5 STIFFNESS FROM COMPRESSIVE TESTS OF TF 5X5 COIL 7-73
TABLE 7-6 3X2 TEST RESULTS 7-76
TABLE 8-1MEASURED DIELECTRIC CHARACTERISTICS AT 20 KHZ 8-79
TABLE 8-2 ELECTRICAL CONNECTIONS FOR HIPOT TESTING A2 AND B2 SAMPLES 8-80
TABLE 8-3 SUMMARY OF HIGH VOLTAGE TEST RESULTS FOR SELECTED CONNECTIONS 8-81
TABLE 8-4HIPOT FAILURE OF A2 AND B2 SAMPLES AFTER ALL MECHANICAL TESTING 8-82

ABSTRACT

The results of the TPX magnet insulation and impregnation R&D large scale verification test program are presented. The principle objective of the large scale verification test program is to demonstrate that the CPDR electrical insulation design meets the performance requirements of the TPX magnet coil system. The mechanical and electrical criteria for judging the success of the test program in demonstrating compliance with TPX requirements are discussed. Mechanical testing loads for the 5x5 PF and TF compression samples and the 3x2 CS bending samples are identified. The electrical testing criteria is developed and the acceptance test voltages determined. The fabrication of the 3x2 and 5x5 samples at Everson Electric is discussed. The mechanical and electrical test results are presented. The 3x2 and 5x5 passed all Hipot, AC partial discharge, and AC life cycle electrical endurance tests applied the turn-to-turn and turn-to-ground insulation without a single failure in the as received condition and after all thermal and mechanical cycles had been completed. Based upon the electrical results, the CPDR insulation system based upon the Kapton slip insulation alternative to the TPX CDR baseline performed well. The 3-D materials used for conductor wrap and for void fillers performed well under life cycle mechanical loading. The test results support the CPDR electrical insulation system design as judged from the mechanical and electrical sucess criteria established for acceptance and verification.

SUMMARY

This document contains the rationale developed at the May 3 Technical Interchange Meeting for the acceptance test voltages for DC Hipot, AC partial discharge, and AC life cycle testing of the 3x2 CS bend models, the 5x5 TF model with regimented conductor pack, and the 5x5 CS model with offset conductor pack. The acceptance test voltages are determined from the peak operating voltages for TF and PF coils for pancake-pancake (turn-turn) insulation and turn-ground insulation. The test voltages are developed by applying peaking factors on average electric stress, including peaking factors for: (1) local electric field enhancements due to dielectic constant mismatch and conduit curvature predicted by electrostatic analysis by J. F. Roach and D. C. Johnson at WEC-STC, (2) nonuniform voltage distribution within PF winding packs predicted by A. L. Radovinsky at MIT, and (3) peaking factor to account for helium partial discharge during life cycle testing in air. The selected acceptance test voltages are 10 kVdc, 1 min Hipot withstand and 6 kVrms, 15 min AC life cycle for turn-turn insulation and 16 kVdc, 1 min Hipot withstand and 10 kVrms, 15 min AC life cycle for turn-ground insulation. Samples must pass the 1 min DC Hipot tests at 50 μA maximum leakage current setting without power supply trip. AC life cycle tests will monitor peak and average pC discharge levels periodically during the 15 min life test. These test levels will verify the peak operating/fault electric stresses to margins >13 times operating and >2 times line lead fault for turn-turn insulation, and to margins >3 for turn-ground insulation. The large turn-turn margin for operating voltage is due to the fact that the peak pancake-pancake operating voltage for all TF and PF coils is only 628 V so that testing at 10 kVdc/6 kVrms naturally results in very large margin over operating stess.

1. OBJECTIVE AND PROGRAM OVERVIEW

Objective: To demonstrate by the test of a representatively sized sample that the preliminary insulation design of the important coil insulation features meet the requirements of the TPX coils.

The objective of this test program can only be evaluated within the total design process of the insulation system for the TPX Magnet Systems and vitally complements and is complemented by the structural and electrical analysis of the magnet winding pack design. The analytical modeling alone cannot validate the insulation design due to the limited data on material properties particularly mechanical strength limits as well as due to the difficulties in modeling the micro and macro cracking of these composite structures. The inabilities of a sub-sized test to simulate the actual mechanical loading to be found in the magnets requires that modeling be used to provide the linkage to the operating conditions.

In subsequent sections, the key elements of this objective will be expanded and descriptions of how they are to accomplished provided. The interpretation of "meet" is embodied in the success criteria of part 2. The requirements of the insulation system for the TPX magnet systems must be represented by the test loading conditions defined in Parts 3 and 4. In part 5 the meaning of "representatively sized sample" and "important coil features" are defined. The test conditions and evaluation methods are defined in Part 6 and include identification of the limitations of the tests to simulate the actual loading conditions.

The approach presented herein incorporates the lessons learned from the earlier testing of the 3x3 conduit arrays. These lessons are summarized as follows:

1) The sample configuration must match to the goals of the test. We found that one sample could not used for both electrical and mechanical testing. In this program separate samples are dedicated to electrical and mechanical test respectively. The insulation of the ends of the samples are critical to valid and interpretable electrical measurements. As a result cutting the sample to investigate the mechanical condition at the various steps in the process is prohibited.

2) Single axis compressive tests does not adequately simulate all the important stresses to be experienced in the TPX magnets. In particular stresses along the length of the conductor and those stresses created by bending moments on the winding pack are poorly represented. As a result the large scale verification test program introduces a three point flexure test of a 3x2 conductor array for this purpose.

3) Partial discharge measurements are not sufficient to expose weaknesses in the design and demonstrate design capability. Expansion of the partial discharge test into a 60 Cycle AC Life test allows linkage of the partial discharge characteristics to the actual magnet system requirements and provides definitive limits of performance. Therefore the test program to follow focuses on 60 cycle AC life and ultimate breakdown voltage as the principal test criteria.

2. OVERVIEW OF TESTING PROGRAM

The Large Scale Verification program is based on testing of six conductor arrays: two representing a CS coil (5x5 CS samples), two representing a TF coil (5x5 TF samples) and two 3x2 arrayed samples directed at the effects of stresses in the insulation which exist in the actual coil but will not be represented by the other tests. Two samples of each type are provided so that one sample can be used for assessment of mechanical damage and the other used for assessment of electrical insulation system degradation after mechanical cyclic loading. Each of the two samples are subjected to the same series of mechanical tests but differing assessment criteria. The mechanical assessment is based on visual identification of cracking in sectioned samples and reduction of stiffness in the sample. The electrical assessment is based on electrical discharge and high potential tests.

The test program has two points where the coil is evaluated. The first is at the end of one lifetime of cyclic loading. The second is at the end of four additional mechanical lifetimes. At the end of the first lifetime, the sample must meet the mechanical and electrical acceptance criteria described in earlier sections of this report dealing with acceptance criteria. At the end of the four additional lifetimes the same assessment criteria will be applied however no pass fail judgment will be made and the results will be used only for determination of margin. After the final assessment, the 5x5 mechanical samples are re-tested to failure. This final test provides additional information for determining the margin in the strength of the coil.

The testing sequence is depicted in Figure 6.1. The program involves testing of sections of simulated 5x5 conductor packs under uniaxial compressive loading similar to the 3x3 tests and bending tests of 3x2 aligned conductor packs.

The 5x5 tests will simulate through compressive loads in both the PF and TF coils. Both aligned array and unaligned array configurations will be tested in order to simulate both the TF coil configuration and the PF coil configuration respectively. The 3x2 tests will simulate direct load in the conduit wall insulation at the outer bending fibers and bending induced interlaminar shear. In the 3x2 sample the direct stress in the conduit wall insulation will match the worst case laminar conduit wall insulation direct stress from any coil and the shear will be based on the worst case insulation shear induced by bending of the TF, PF5, PF6 or PF7 coil.

Figure 6.2 shows sketches of the loading configurations. A detailed table of the testing sequence and loading cycles are shown in Table 6.1 and are based on discussion is section 3.

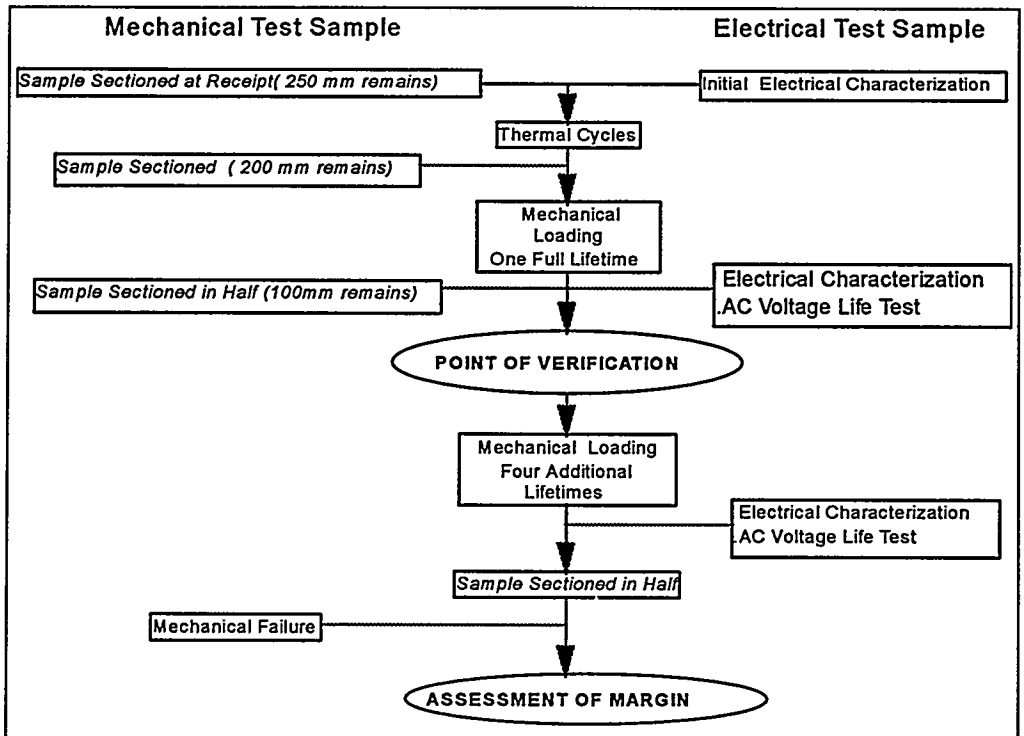


Figure 2-1Schematic representation of the test program.

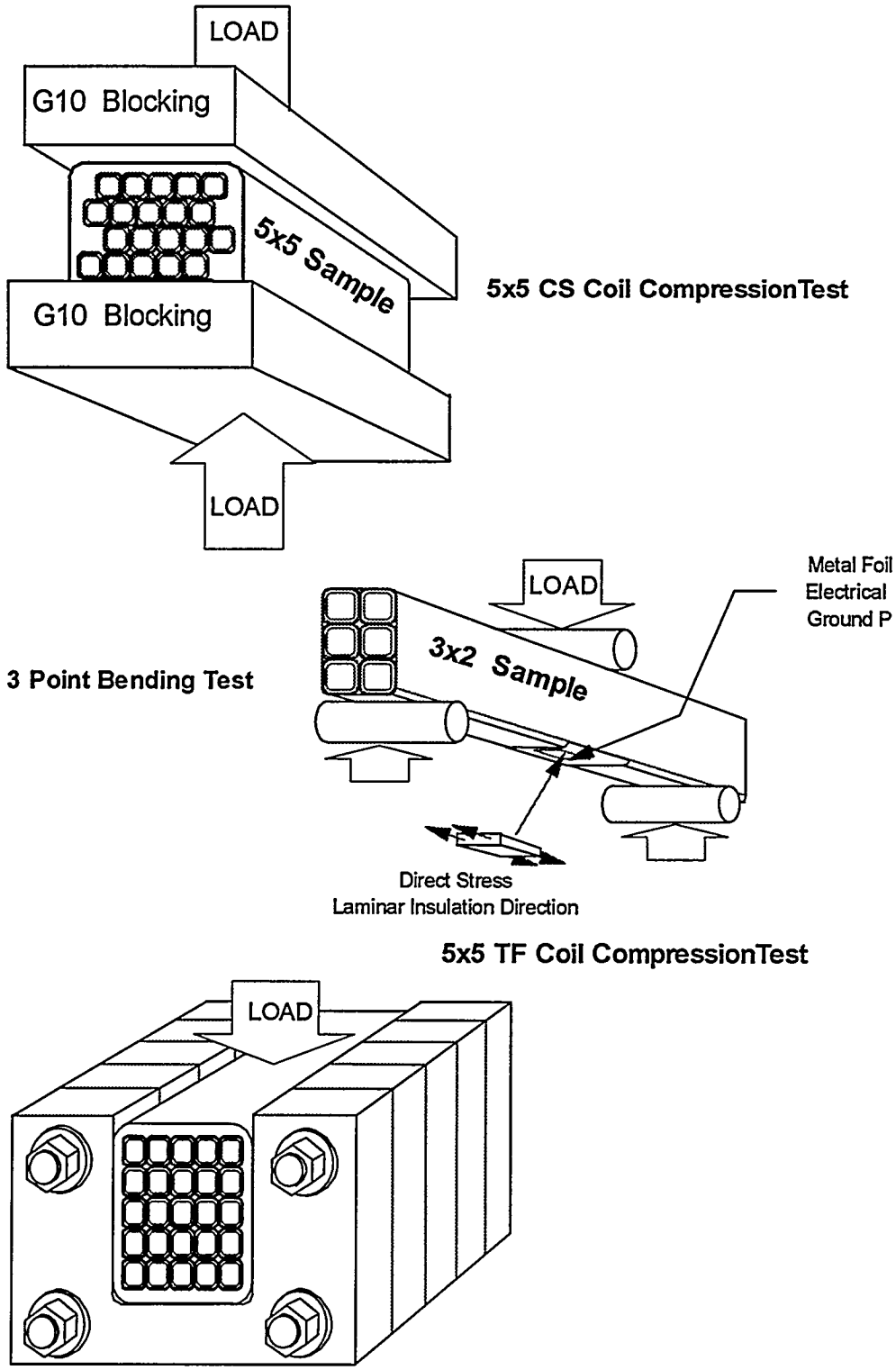


Figure 2-2 Schematic representation of the test loads.

3. SUCCESS CRITERIA

Unlike its predecessor, the 3x3 array testing, which explored the parameters and characteristics of the TPX insulation system, the large scale insulation verification test program is a demonstration of meeting the TPX requirements and not an experiment. Therefore the testing is divided into two phases with the first phase rigidly defined on the verification of requirements. Subsequently, in the second phase, testing will be performed that will explore the ultimate limits of the insulation system. The verification phase requires concrete evaluation criteria against which successful satisfaction of the requirements can be measured. The conditions of the testing form an essential ingredient of the criteria and for this program, satisfaction of requirements will be verified after ONE lifetime of test loads (both electrical and mechanical) suitably selected to represent the worst case normal operating loads of the TPX magnet systems (see part 3.0). Consensus on the following success criteria for the TPX insulation system was reached at the May 3 Technical Interchange Meeting:

3.1 MECHANICAL CRITERIA:

1. The force deflection curve of the sample shall not change by more than 10%.
2. No cracks extending completely across the glass/epoxy overwrap in the through thickness direction shall be allowed (see below for clarification of allowable cracks)
3. No continuous in-plane delamination greater than the dimension of the insulation unit cell shall be observed (see sketches for further clarification).

Based on the 3x3 array testing, cracking of the test assemblies is expected. Many of these cracks have not been found to impair the electrical and mechanical integrity of the insulation system. For the purposes of this test and except for cracks identified in criteria 2, continuous cracks that extend past the unit cell around each conductor and therefore involving multiple conductors are unacceptable. The term "unit cell" is used to describe the assembly of the conductor, the kapton, the 3D tape conduit wrap and the upper and lower corner fillers. To violate this criteria, then cracking must include the bond between adjacent 3D tape wraps and two corner fillers. The basis for this interpretation is indicated from the 3x3 tests where mechanical integrity is compromised when cracking has progressed to this extent. Additionally the inter-conductor bond and the two corner filler represent the chain of mechanical components providing mechanical integrity. Once these three links of the chain are cracked, the failure of the entire chain is imminent. Two limiting cases of this interpretation are shown shown in Figure 1. These cases would constitute failure while less cracking would be acceptable. The evaluation of the mechanical integrity of the assembly will be performed on cross section cut from the assembly, polished to a metallurgical finish and 100% inspected at a magnification such that the intersection of four conduits (includes two corner filler) completely fills the field of view.

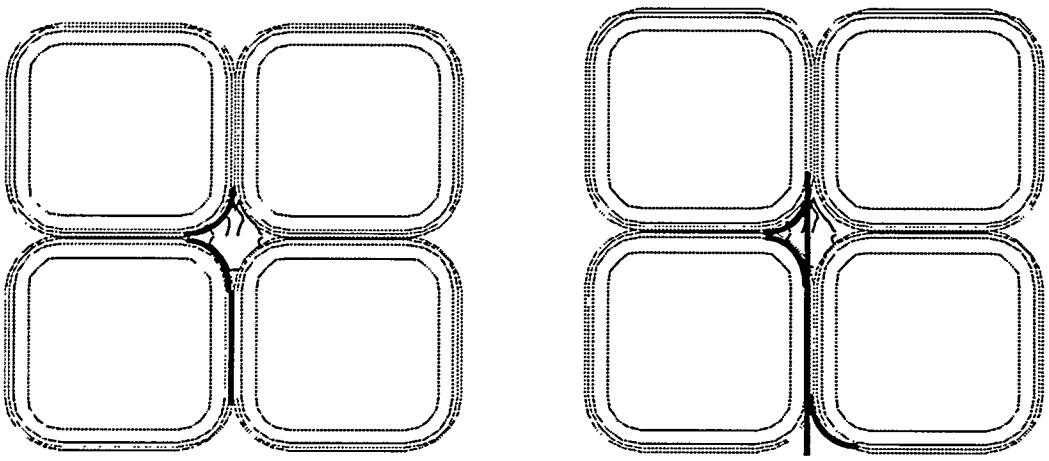


Figure 3-1 Illustration of the limiting cases for cracking in the unit cell of the winding pack represented by the 5x5 test samples.

It is intended that the first two criteria apply to the ground wall insulation as well. A looser interpretation of allowable cracking is allowed for the transition pieces of the coil design. Figure 2 illustrates acceptable and unacceptable cracks relative to the transition pieces. It is clear that through thickness cracks in the ground wall are unacceptable. However extensive delamination along boundaries with the transition pieces can be tolerated to the extent that the criteria 1 and 2 are not violated.

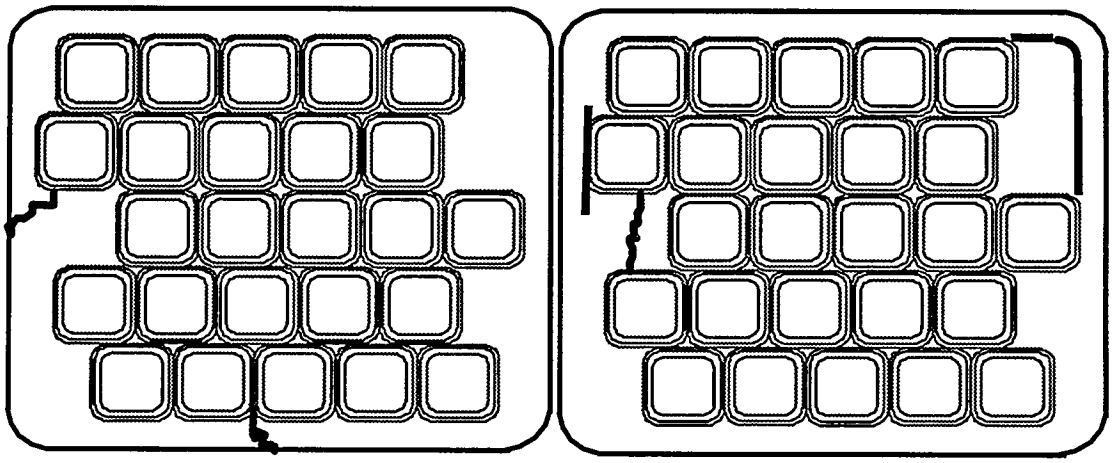


Figure 3-2 Illustration of both unacceptable (left) and acceptable (right) delaminations and cracking in the 5x5 sample used in the verification testing program

The following circumstances have also been considered: In this type of composite structure following thermal cooldown and cyclic loading, micro-cracking and crazing within the composite structure is considered likely. It is expected that high quality impregnation will be attained both in the sample and in the magnets. Nevertheless porosity and lack of impregnation may occur. Based on 3x3 tests both of these conditions are deemed allowable **provided** that the electrical and other mechanical criteria are met.

3.2 ELECTRICAL:

1. The turn to turn insulation shall hold off 10 kV for 1 minute without arc discharge following a conditioning of 15 minutes at 6 kV rms.
2. The groundwall insulation shall hold off 16 kV for 1 minute without arc discharge between any turn and the ground plane following a conditioning of 15 minutes at 10 kV rms.

The above criteria will be tested with an instrument set to trip at a leakage current of 50 microamps.

The above criteria both electrical and mechanical will be expanded upon in subsequent sections. Particular attention is given to the establishment of load levels and definition of the mechanical and electrical lifetimes.

4. DETERMINATION OF THE MECHANICAL LOADING FOR THE 5X5 TESTING PROGRAM

The purpose of the testing program is to demonstrate the adequacy of the insulation system. The general approach is to introduce mechanical damage in the test samples which is equivalent to the damage that the coil is expected to see in service and show that the coil still has reserve mechanical and electrical integrity. The approach for doing this is to identify the worst case load histories that each of the coils will be subjected to, determine the associated mechanical stresses and then subject coil test samples to mechanical loadings similar in character to the loadings that the coil will see in service and which will produce the same level of *critical* stress. The critical stresses are those which are 1) closest to their limits and 2) judged to relate to significant types of failures. The short coming with this approach is that it is impractical to completely match the coils triaxial loading conditions and complex stress histories. The worst case stresses anticipated for the coil are based on Finite Element Analysis of worst case load conditions and the matching stresses for the tests are also identified with Finite Element Analysis. The loading that the actual coil sees and the load that will be applied to the test samples can both be characterized by:

1) the magnitude of the load,
2) the shape of the load cycle, and
3) the number of load applications.

The magnitude for the test load is set by the fundamental load that the real coil will see and the stress correlation discussed above. The shape consists of a triangular alternating load pulse superimposed on a steady mean load or bias. The

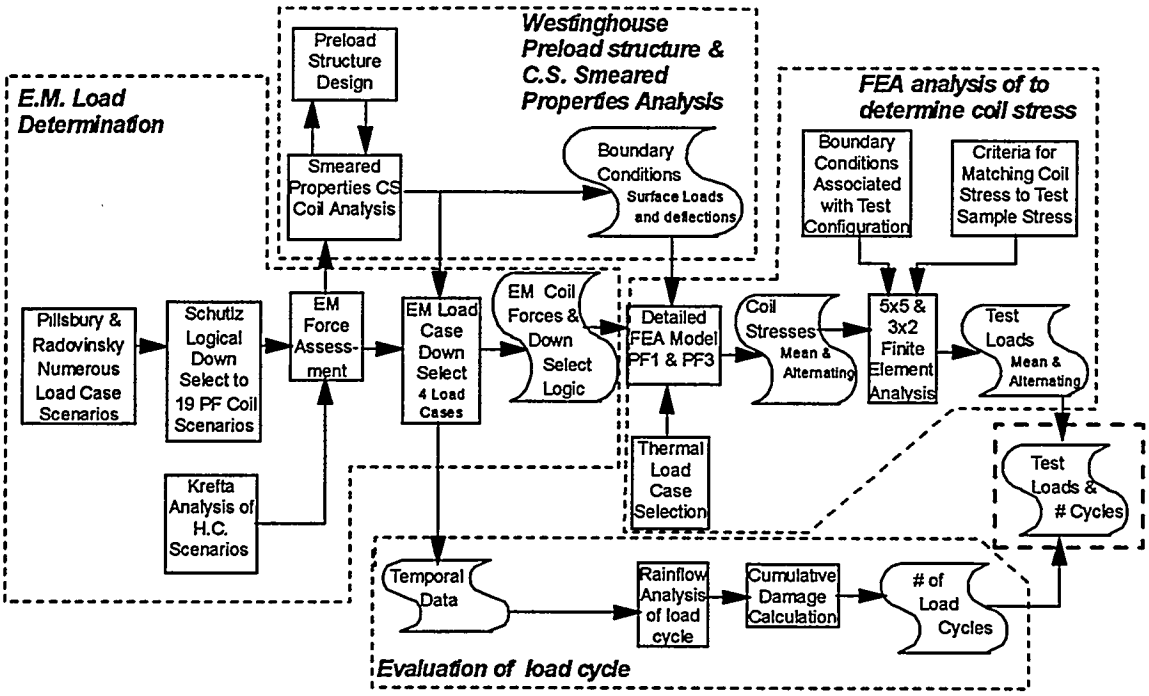


Figure 4-1 Flow chart indicating method for determination of CS sample test loads.

alternating portion is imposed for the desired number of cycles corresponding to the actual number of load applications and the shape of the HC scenario load pulse. The complexity of the load shape on the actual coil is compensated for by increasing the number of test load cycles during test, thereby matching total damage. Figure 3.1 shows the procedure used to arrive at the CS load cycle for verification testing.

Loads for the tests related to PF 5,6, and 7 and TF were established in a generally similar manner. Some variation exists in the details and they are discussed later in this document and in the documentation of the stress analysis effort for those coils.

4.1 DETERMINATION OF THE NUMBER OF LOAD CYCLES FOR THE TPX CONDUCTOR PACK

Of the three characteristics of the loading on the actual coil the number of load application cycles is the most easily determined. This data is combined later in the report with the shape of the load pulse to determine the number of cycles which must be applied during the test to cause the same total damage that the real coil will see in service. The damage done during each of the cycles will be a function of the temporal character and magnitude of the applied load.

The number of cycles of each load predicted for the actual coil is specified by the general requirements document. Rev 0 of this document indicates that the magnets should be designed for an operating life of 10 years. Section 2.4 specifies that the coil design should provide for 300 cool down / warm up cycles over a ten year life. That requirement appears excessive and 20 cycles are planned for the test. Section 2.4 also specifies that the PF coils withstand 30000 EM load cycles, that the TF system withstand 6000 EM cycles and section 1.10 specifies that up to half of all normal operation scenarios end in disruption. Therefore the PF EM duty cycle will be 15000 cycles normal operation and 15000 cycles of normal operation ending in disruption. The same 50-50 split applies to the TF coils however the forces are not as significantly affected. The general requirements document also indicates that faults resulting in more significant forces will occur infrequently, however, the actual frequency is not spelled out and no cyclic load applications are intended at fault magnitude during the test program. At the end of the testing cycle the sample will be taken to failure to determine the remaining margin.

In order to construct the test load set, it is necessary to know the alternating and mean components of the stresses. The more significant portion of the damage done to the coil will be done by the repeated load applications and this condition must be duplicated on test. While the information above describes the number of load cycles in a simple fashion the actual application of the loads combines them in a fashion which is described in Table 3.1. This table describes the loadings discussed above along with the manufacturing cool down load preload and the vertical clamping preload which is applied to the CS coil only.

Table 3.1 shows the general loading cycles that the coil is subject to (across the top) and the loadings which are active during each of the loading cycles (down the left side). It highlights the steady S(m) and alternating S(alt) component of the expected coil loads *assuming that stresses are zero at glass transition temperature(T(g))*.

The table highlights the importance of the EM load cycle. The number of EM load cycles makes them by far the most significant loading provided that the magnitude is at least similar to the other load conditions. The following section will reveal that the EM loads provide the highest portion of the loading,

Table 4-1 Anticipated Coil Loads

Loads active during Loading Cycle	Loading Cycles: Cool down T(g) -> RT S(m) S(alt)	Mechanical Preload S(m) S(alt)	Cool down RT -> 4K S(m) S(alt)	EM Load S(m) S(alt)
Cool down T(g) -> RT	1 Cycle	x	x	x
Mechanical Preload		1 Cycle	x	x
Cool down RT -> 4K			30-300 Cycle	x
EM Load Normal Operation				15000 Cyc
Disruption				15000 Cyc
Fault				1 Cycle

Note that the alternating component listed above has a steady offset component. Therefore rather than an arithmetic mean of the alternating load, S(m) is the minimum of the alternating component of the load.

4.2 THE TPX MAGNET SYSTEM EM LOAD CASES

The differing equilibria conditions provide different magnitude and temporal character for the differing EM loads. The EM loads that the coil is subject to are complex in nature and numerous load scenarios exist. The details have been dealt with by Pillsbury[1], Schultz[2], Radovinsky[3] and others and are referred to in the discussion as equilibria load cases. The screening rules presented by J. Schultz[2] have been fundamentally adopted to reduce the number of load cases scenarios to manageable level. The only rule disregarded was the screening out of disruptions not having more than 10% higher force than normal operation. The remaining cases pertaining to the PF coils have been further screened by M. Krefta[4] and A. Corpuz of (W) and Tom Schultheiss of NG. The CS coil load screening done by Krefta and Corpuz included the effects of the CS structure provided by means of the (W)

[1] Pillsbury, R.D., Jr., "Poloidal Field Coil System Forces for the Twenty-three Equilibria in TPX," 11/17/94 TPX Report#14-941117-MIT-RPillsbury-01.
[2] Schultz, J., "Selection of the Scenario Points for FEA Analysis," 4/20/95 950420-MIT-JSchultz-01
[3] Radovinski,A.L., "The Worst Fault Load Cases on the Coils of the TPX PF Set due to a Vertical Plasma Disruption Followed by a System Dump with shorted PF Coils terminals at the Twenty - Three Equilibria," TPX-950327-MIT-Radovinsky-01.
[4] Krefta, M., Corpuz, A,"Final Downselection to the Worst Case Electromagnetic Loading of the PF Coils" TPX. No. 14-950707-WEC-MKrefta-01.

smeared properties FEA model. It is essential to include the structural interaction for the load determination because the external loads due to coil to coil and coil to structure interactions are in many cases the most significant loadings on the coil pack. In the following discussion Schultz's numbering system has been adopted to distinguish between specific worst case conditions. Load cases numbers are also sighted and these refer to equilibria scenarios reported by Pillsbury and Radovinski.

4.2.1 CS Coil EM Loading Cases

In summary the initial multiplicity of equilibria scenario cases were reduced by J. Schultz to 23 of which 19 applied to the PF coil system. For identification purposes the 23 cases identified by Schultz are referred to J. Schultz or JS load cases.

The first nine J. Schultz cases apply to the CS coil and of that nine, three drive the design of the CS structural support system (cases 2,8,9). The CS smeared properties analysis includes the design features dictated by the three loads cited and then incorporates the other six loads as necessary to identify the boundary loadings on each coil during the worst case loads. Of these six loads two can be disregarded after examination. Case 4 deals with coil to structure shear and is superseded by coil to coil shear in the coil pack which is higher in magnitude but similar in character. Case 5 is hoop compression and is significantly lower than hoop tension. Case 5 requires that the coil be checked for buckling but the load case will not be carried forward for further detailed analysis. This leaves four cases for detailed CS coil analysis. Schultz cases 1,3,6 and 7 listed below and in Table 3 along with the force magnitudes.

JSCase 1. MAX VERTICAL COMPRESSIVE FORCE DURING NORMAL OPERATION OR DISRUPTION occurring on PF1, during equilibria LC#16

JSCase 3. MAXIMUM COIL TO COIL SHEAR FORCES occurring on PF2 during equilibria LC#1 NORMAL OPERATION

JSCase 6. MAXIMUM RADIAL FORCES during NORMAL OPERATION OR DISRUPTION occurring on PF3, during equilibria LC#1 (PREBLIP)

JSCase 7. MAXIMUM RADIAL FORCES occurring on PF3U during a FAULT (i.e., short circuit of PF3U), following equilibria LC#1 (PREBLIP)

However, case 3 can be eliminated as a separate analysis by replacing the shear stress in case 1 with the one from case 3 as suggested in Table 3. Reducing to 3 the total number of loadings scenarios which will be carried into the detailed finite element analysis of the CS coil. These are J.Schultz cases 1,6 and 7.

4.2.2 PF5 Loading Cases

J.Schultz Cases 10 through 13 deal with PF5. Case 10 is hoop compression and like case 5 we check that instability is not a problem then ignore the stress because the values are low compared with the load cases which put the coil in tension. The remaining cases appear to produce small forces compared to the central Solenoid. However bending due to the coil support is a concern. JS Case 11 causes the maximum radial forces and occurs during equilibria load case #1 under normal operation. JS Case 12 causes maximum centering vertical load also during equilibria load case #1 normal operation. JS Case 13 causes maximum vertical launch during equilibria LC#14. The launch slightly exceeds the centering therefore both equilibria load cases #1 and #14 are of interest, leaving two load cases for analysis.

JSCase 11. MAX RADIAL LOAD DURING NORMAL OPERATION occurring on PF5, equilibria LC#1

JSCase 12. MAX VERTICAL LOAD DURING NORMAL OPERATION occurring on PF5, equilibria LC#14

4.2.3 PF6 Loading Cases

J.Schultz Cases 14 through 16 deal with PF6. JS Case 14 causes the max radial force during normal operation and equilibria load case #9. J. Schultz case 15 is the maximum vertical centering force during equilibria load case #19 while JS case 16 is the maximum launch force and will not be analyzed because it is small compared with the centering force, leaving two load cases for analysis equilibria, load case # 9 and equilibria load case #19.

JSCase 15. MAX RADIAL LOAD DURING FAULT occurring on PF6 , following equilibria LC#19

JSCase 16. MAX VERTICAL CENTERING LOAD DURING N.O. occurring on PF6, following equilibria LC#9

4.2.4 PF7 Loading Cases

J.Schultz Cases 17 through 19 deal with PF7. Case 17 causes the max radial force during normal operation of equilibria load case #18. JS case 18 is the maximum vertical centering force during equilibria load case #18 while JS case 19 is the maximum launch force occurring during equilibria LC#19. The maximum vertical launch can be discarded because it is small compared to the centering force which will cause the same characteristic stresses. This leaves two load cases for analysis equilibria load case #17 and #18.

JSCase 17. MAX RADIAL LOAD DURING N.O. occurring on PF7 , during LC#18

JSCase 18. MAX VERTICAL CENTERING LOAD DURING DISRUPTION occurring on PF7 , following LC#18

4.2.5 TF Coil Loading Cases

J.Schultz Cases 20 through 23 deal with TF coil loads. B&W has examined these cases down selected to the worst case condition and reported loading results to Westinghouse.

4.3 TPX COIL EM LOAD MAGNITUDES

The peak magnitude of the forces for each of the cases discussed above is summarized in Table 3.2 below. The table reports the net forces acting on each coil and for the CS coil reports the magnitude of the structural interactions thereby including the effects of loads on other coils and of the preload assembly. In the analysis performed to determine stresses in the coils, both the spatial and temporal variations of the force are taken into consideration. The analysis of the PF5, 6, 7 and the TFs includes the effects of the neighboring structure however the structural interactions are not shown below.

Table 4-2 Maximum values of the Worst Case Coil Loads[4]

	Max Radial Force (kN/turn)	Max Vertical Comp. (MN)	Surface Traction (Shear) (MN)	Surface Load (Normal) (MN)	L
CS Coils					
PF3U Load cases (60 Turns)					
Max. Radial Fault, LC#1	97.0	14.4	-4.36/-4.25	-14.29/14.40	
Max. Radial N.O., LC#1	45.6	22.5	-0.19 /-0.01	-19.18 / 22.5	
PF2 (96 turns)			Substitute		
Higher shear than PF3, LC#1	45.3	22.5	0.01 / -1.39	-19.18 / 22.5	
PF1 Load cases (120 turns)					
Max. compressive vertical, N.O., LC#16	28.5	31.3	-0.02 / -0.95	-17.95 / 31.33	
Max. compressive vertical, Fault , LC#16		Defaults to Normal Operation Load			
PF5 Load cases (128 turns)					
Max. radial , N.O., LC#1	27.4	6.4			
Max. Vertical, Disruption, LC#14	7.3	7.2			
PF6 Load cases (120 turns)					
Max. radial , Disruption, LC#9U	30.0	5.0			
Max. vertical, Disruption , LC#19L	22.5	8.2			
PF7 Load cases (84 turns)					
Max. radial , N.O., LC#18	14.9	-0.1			
Max. vert cent, Disruption , LC#18	12.6	3.6			
TF Load cases (xxx turns)					
Max. radial , N.O., LC#2?	(See B& W analysis of the TF Coil)				
Max. radial, Fault , LC#2?					

Of the five load cases sighted above for the CS coil three are individually analyzed using Finite Element Analysis. The worst case shear is substituted into the maximum radial normal operation case so that it provides a conservative worst case and the maximum compressive stresses during fault are taken to be a small multiple of stresses from LC#16 normal operation.

For the CS coils these forces with their spatial variation are applied to the detailed finite element models of the PF1 and PF3 coils along with the boundary loads in order to determine the coil stresses during the various loading situations[5]. The boundary loads on the CS coil are determined from the Westinghouse CS coil

[5] Hannan, W.F.,"PF 1-4 Coil Pack Structural Analysis",8/9/95, Document # 14-950809-WEC-WHannan-01

smeared properties models[6]. The analysis of the PF6 and 7 coils uses a slightly different method[7].

The approach used to determine test loads requires that the Finite Element Analysis load cases listed in Table 3.3 be run to assure that the stresses in the coils under load conditions are replicated as well as possible on test. Beyond the average values presented in Table 3.2 spatial and temporal variations exist in the EM force distributions. The spatial variations are included in the detailed finite element analysis and are presented in detail in documentation of the electromagnetics effort[8]. The temporal variations are discussed below and are considered in the determination of loads and boundary conditions for the analysis. The cases in Table 3.3 which have question marks in the various matrix locations will require multiple runs to determine the values of load which are sought for these locations.

4.4 FEA STRESS RESULTS FROM THE CS COIL PACK ANALYSIS

Table 3.4 shows the worst case stress results from the Finite Element Analysis for several of the load cases discussed above as well as contrasts for the effects of worst case external shear and cooldown from glass transition in place of cool down from room temperature as previously considered. Review of Table 3.4 shows that the worst case vertical compressive load during normal operation (FEA case 8) is the worst case condition for all components during normal operation. The maximum radial fault (FEA Case 5) causes some stresses to be significantly worse than for FEA case 8. However the latter will occur 30000 times while the former

---

[6] Corpuz, A.B., "CS Preload & Worst Case Loads", 8/1/95, Document # 14-950801-WEC-ACorpuz-01

[7] Schultheiss, T.? "PF 6/7 Coil Pack and Case Structural Analysis",8/10/95, Document # 14-950810-WEC-TShulthesis-03

[8] Krefta, M.P.,"Electromagnetic Analysis of TPX Poloidal Field Coils," TPX Document No. 14-950630-WEC-MKrefta-01, 6/30/95.

Table 4-3 FEA Analysis Load Case Table

Physical Load situations to Be Represented

FEA	PF3 Max Radial Force except Surfac traction from PF2 Load Case #1	Cool down T(g) -> RT	Mechanical Preload	Cool down RT -> 4K	EM Load Norm. Oper.	EM Load Disruption
Case 1	Load Offset during Cool Down	x	x			
Case 2	Cool Down Cycle	x	x	x		
Case 3	EM Load Offset	x	x	x	Real Close to Case	
Case 4	EM Alt. Ld., Normal Operation	x	x	x	x	
	EM Alt. Ld. only, Normal Operation	Case 6 - Case 5			x	
	EM Alternating Ld, Disruption	Degenerates to Case 3 & 4				x
Case 5	EM Alternating Ld, Fault	x	x	x		

	1/2 of PF1 Max Vertical Force Load Case #16	Cool down T(g) -> RT	Mechanical Preload	Cool down RT -> 4K	EM Load Norm. Oper.	EM Load Disruption
Case 6	Thermal Check PF1	x	x	x		
Case 7	EM Load Offset	x	x	x		
Case 8	EM Alt. Ld., Normal Operation	x	x	x	x	
	EM Alt. Ld., Normal Operation	Case 6 - Case 5			x	
	EM Alternating Ld, Disruption	Not a Seperate Run, Ratio Stresses From case 6				x
	EM Alternating Ld, Fault	Not a Seperate Run, Ratio Stresses From case 6				

FEA	PF6 or PF7 Max Radial Force Load Case #1	Cool down T(g) -> RT	Mechanical Preload	Cool down RT -> 4K	EM Load Norm. Oper.	EM Load Disruption
Case 9	Load Offset during Cool Down	x	x			
Case 10	Cool Down Cycle	x	x	x		
	EM Load Offset	x	x	x		
Case 11	EM Alt. Ld., Normal Operation	x	x	x	x	
	EM Alt. Ld. only, Normal Operation	Case 9 - Case 8			x	
	EM Alternating Ld, Disruption	Degenerates to Case 3 & 4				x
Case 12	EM Alternating Ld, Fault	x	x	x		

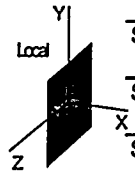
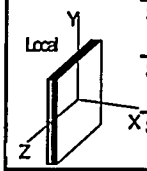
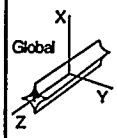
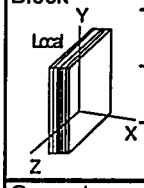
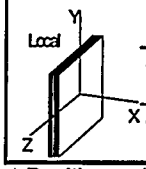
	5x5 Model Simulating Load Case #16	Cool down T(g) -> RT	Mechanical Preload	Cool down RT -> 77K	Simulating Norm. EM	Vertical Ld. Simulating Disruption	S
Case 13	Load Offset during Cool Down	x		x			
Case 14	Cool Down Cycle	x	?	x			
	Mech Ld. Offset	x	x	x			
Case 15	Mech Alt. Ld., Normal Operation	x	x	x	?		
	Mech Alt. Ld, Disruption	Not a Seperate Run, Ratio Stresses From case 11				?	
	Mech Alt. Ld, Fault	Not a Seperate Run, Ratio Stresses From case 11					

	3x2 Model Simulating Load Case #1	Cool down T(g) -> RT	Mechanical Preload	Cool down RT -> 77K	Simulating Norm. Oper.	Bending Simulating Disruption	S
Case 16	Load Offset during Cool Down	x	?				
Case 17	Cool Down Cycle	x	?	x			
	Mech. Load Offset(Same as case13)	x	x	x			
Case 18	Mech. Alt. Ld., Normal Operation	x	x	x	?		
	Mech. Alternating Ld, Disruption	Not a Seperate Run, Ratio Stresses From case 14				?	
	Mech. Alternating Ld, Fault	Not a Seperate Run, Ratio Stresses From case 14					

x Signifies that a load step for the finite element run is known.

? Signifies that the load is to be determined so as to match the critical stresses in the coil under similar load co

Table 4-4 FEA Maximum Stress Result Summary for the CS Coil Assembly*

		FEA Load Case #8 Max Vert Compression (MPa)	FEA Load Case #4 Max. Rad. Oper.W /shear (MPa)	Max Rad. Oper. W O /Shear (MPa)	FEA Load Case #5 Max Radial Fault (MPa)	Effects of Cooldown		FEA Load Case #7 11MNt Vert ld cldwn GT to 4K (MPa)
						Cooldown GT to4K (MPa)	Cooldown GT to RT (MPa)	
Conduit	SX	-583	-481	-463	-882	-382	-127	-311
		479	380	361	756	229	76.4	265
	SY	-749	-619	-609	-892	-291	-97.2	-398
		354	301	290	460	204	67.9	210
	SZ	-186	-112	-68.8	-51.3	-238	-79.3	-224
		215	226	251	520	-5.66	-1.89	-1.39
	SXY	-289	-184	-180	-378	-133	-44.2	-156
		216	241	228	402	122	40.5	168
	SINT	740	612	602	941	375	125	389
Kapton	SX	-94.1	-70.6	-73.9	-137	-45.2	-15.1	-43.7
		12.3	10.8	9.57	17.4	7.24	2.41	7.92
	SY	-40.7	-26.5	-26.9	-79	-14.4	-4.8	-16.1
		61.3	58	56.4	65.6	59.3	19.8	54.6
	SZ	-3.62	5.99	6.54	-25.7	10.8	3.61	5.36
		41.5	42.4	43.9	51.1	43	14.3	36.2
	SXY	-2.75	-1.99	-2.09	-3.38	-1.53	-0.51	-1.41
		2.71	2.19	2.18	4.48	1.56	0.52	1.31
Conduit Wrap	SX	-84.8	-71.1	-71.5	-123	-37.4	-12.5	-46.9
		19.5	21.8	22.2	29	28.1	9.36	25.8
	SY	-306	-232	-234	-483	-145	-48.4	-116
		307	293	272	366	241	80.4	260
	SZ	40.5	65	-69.4	-19.7	59.2	19.7	64.2
		184	190	189	203	166	55.3	163
	SXY	-76.3	-75.7	-76	-79.5	-60.7	-20.2	-63
		79.9	68.9	69.4	54.4	62.2	20.7	65.2
Roving	SX	-65.5	-53.5	-54	-88.7	-25.2	-8.41	-36.2
		131	149	149	135	216	71.8	168
	SY	-37.5	-32.7	-32.7	-51.8	-33.9	-11.3	-28.4
		229	214	211	226	173	57.5	186
	SZ	9.64	19.3	19.9	30.9	-10.8	-3.61	-7.25
		87.1	95.6	97	117	84.1	28	67.7
	SXY	-70.9	-61.7	-58.2	-74.8	-58.6	-19.5	-53.3
		61.8	69.8	70.3	84.1	74.7	24.9	63.6
Spacer Block	SX	-33.8	-27.7	-27.7	-55.9	-24.6	-8.21	-26.1
		298	265	276	223	225	74.9	244
	SY	-183	-132	-140	-286	-90.9	-30.3	-106
		49.2	37.2	31.2	58.5	94.1	31.4	40.8
	SZ	65.6	85.7	90.1	16.7	82.3	27.4	76.3
		236	228	238	201	192	64.1	199
	SXY	-91.8	-76.5	-77	-71.6	-67.7	-22.6	-76.7
		83	93.7	87.7	74.4	72.1	24	82.7
Ground Wrap	SX	-242	-183	-190	-279	-13.1	-4.38	-101
		95.2	56.1	55.1	42.7	49.1	16.4	52.4
	SY	-303	-236	-247	-308	-124	-41.5	-179
		145	109	116	118	80.1	26.7	97
	SZ	-130	-86.3	-88.6	-119	-36.5	-12.2	-77.1
		49.8	54.7	56.9	67	20.3	6.77	27.1
	SXY	-107	-99.8	-106	-152	-38.2	-12.7	-63.3
		134	87.3	82.8	109	26.8	8.93	52.4

* Positive values signify tension & negative numbers indicate compression.
Material properties reflect PDR baseline properties.
Results / Hannan PF 1-4 Coil Pack Structural Analysis, Document #14-950809-WEC-Whannan-01

only occurs once or twice. Many glass epoxy materials loaded to their limit at 30000 cycles can tolerate twice that level for a single cycle. Since none of the critical stresses for the fault loading appear to exceed twice the vertical load stresses, case 8 is taken as the worst case. Examining the stresses for FEA case 8, indications are that conduit wrap, roving and ground wrap all experience critically high loadings. The loadings are critical in that the resultant stresses are very near or over their limits. The conduit wrap will experience interlaminar shear stress which appear critical and the same is true of the roving and ground wrap. These loads while critical can still be interpreted as localized or are secondary provided the acceptance criteria of section 1 are met. The more significant feature of these stresses for this test program is the similarity of the coil loads to the loads that the test sample will be subject to during the 5x5 compressive testing.

4.5 DETERMINATION OF THE LOADS FROM FEA ANALYSIS OF THE 5X5 TEST SAMPLE

The stresses from the application of the coil loads to the models of the coils is used to set stress goals for the finite element models of the verification test samples. The test sample loads are set so as provide the same levels of critical stress as in the loaded coil. *Because the loadings proposed for the test samples match only certain simultaneous coil loading conditions the triaxial stress state expected in the coils will not completely match the triaxial stress state in the test samples during the testing. The stress goals will be set based on matching or exceeding the uniaxial values of stress which are deemed to be critical so far as other materials do not provide a structural limit*. Furthermore, it is intended that some margin be applied to the loads during the testing program in order to cover the variability in the analysis and the testing. In principle it is desirable to have on the order of 15% margin on critical stresses.

4.5.1 5x5 CS Coil Test Loads

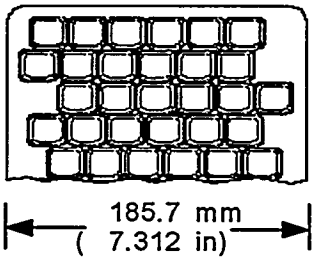
The test loads for the 5x5 test are fundamentally established by matching the alternating component of stresses inside the actual coil to the alternating stresses in the 5x5 test sample during compressive testing.

The results from the Finite Element Analysis and load cycle information indicate that the worst case vertical loading is the worst case loading condition for the CS coil and this is the condition that is nominally replicated by the 5x5 compressive test. The vertical load condition which will most closely replicate the actual loading can be determined by examination of the load that we expect on the actual coil. In the case of the worst compressive load examined as FEA case 8, (equilibria 16 + cooldown + preload), the externally applied force on PF1U represents almost all of the compressive force on the coil.[5] This places the average load on the coil at 31.33 MN according to Table 3. We know that the disruption force is 3.3% higher than the peak normal operating force[4] placing the peak load during disruption at 32.36 MN. This is the peak vertical load under any condition. The pressure on the coil can vary because the width of the coil can vary. For our purpose we will consider the pressure at the coil section that looks like the coil finite element model cross-section. In that configuration the coil is essentially seven conductors widths wide with an additional .31 inch of groundwall on each side. The resultant maximum compressive pressure averaged over the full diameter of the coil cross-section is:

Worst Case Verticle Compression = 32.36 MN
Coil Inside Radius = 28.237 in = 717.22 mm
Coil Outside Radius = 35.549 in = 902.94 mm
Coil cross-sectional area = Pi (35.549^2 - 28.273^2)
Coil c-sect. area = 1465.2 in^2 = 0.9453 m^2

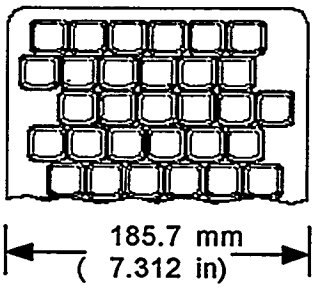
Average Vertical Compressive Stress:

$$\frac{32.36\ MN}{.9453\ m^2} = 34.23\ Mpa = (\ 4965\ psi\ )$$



The lower limit is used to establish the lower value of the alternating stress. The value is selected from the lowest point in the HC load scenario depicted in Figure 3.3 and shows to be 11.1 MN. The force is lower than the 15 MN preload because repulsive forces in other coils of the CS assembly act to reduce the clamping load on PF1 below the applied preload at this point in the temporal cycle . The associated compressive pressure can be calculated as was done above:

Minimum Verticle Compression = 11.1 MN
Coil Inside Radius = 28.237 in = 717.22 mm
Coil Outside Radius = 35.549 in = 902.94 mm
Coil cross-sectional area = Pi (35.549^2 - 28.273^2)
Coil c-sect. area = 1465.2 in^2 = 0.9453 m^2

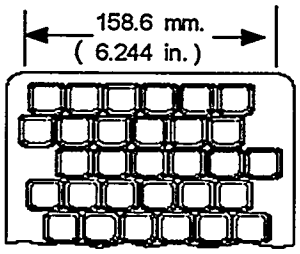


Average Vertical Compressive Stress:

$$\frac{11.1\ MN}{.9453\ m^2} = 11.74\ Mpa = (\ 1703\ psi\ )$$

While this pressure is the average across the nominal coil cross-section the pressure in the actual coil can be higher at the top and bottom because of the curvature of the corners. Furthermore all of the parts don't bear the load equally. For the purpose of consistency this discussion will adopt the same convention used in describing the boundary pressures for the finite element analysis which does not include the corner area. This results in a loading cross-section which is 1.068 inches more narrow than the full cross-section. Resulting pressure values are :

Worst Case Verticle Compression = 32.36 MN
Minimum Verticle Compression = 11.1 MN
Outside Radius of flat : 35.015 in = 889.38 mm
Inside Radius of flat = 28.771 in = 730.78 mm
Width of flat at surface = 6.244 in = 158.6 mm



Coil cross-sectional area = Pi (35.549^2 - 28.273^2)
Coil cross-sectional area = 1251 in^2 = 0.8072 m^2

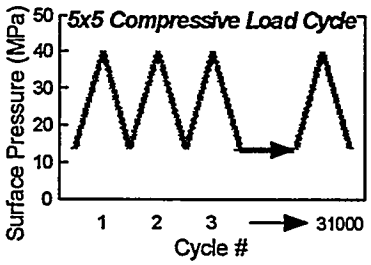
Avg. Max. Vert. Compressive Pressure at the Coil Surface:

$$\frac{32.36\ MN}{0.807\ m^2} = 40.09\ Mpa = 5814\ psi\ )$$

Avg. Min. Vert. Compressive Pressure at the Coil Surface:

$$\frac{11.1\ MN}{0.807\ m^2} = 13.75\ Mpa = 1994\ psi\ )$$

Sugested Compressive Test Loading:
27 +/- 13 Mpa



The external average pressure loads suggested for the test loading will be 41MPa and 14 MPa as the maximum and minimum stresses for the alternating portion of the test cycle provided that the finite element analysis confirms that the stresses meet the criteria discussed above.

4.5.2 FEA Stress Results for the 5x5 Test Sample

Table 3.5 shows the results from the finite element analysis of the 5x5 test sample cooled to 77°K and with purely compressive external loads applied. The 5x5

test samples appear to challenge the conduit wall insulation, roving and ground wrap stress at loads around 41 MPa of compression suggested by the previous analysis. Table 8 shows a comparison of the maximum compressive loads of FEA case 8 and the CS 5x5 test at 41 MPa. Typically the conduit wrap and cruciform filler material are the most critical materials. Failure in the conduit wall wrap can compromise the insulation and failure in the cruciform material can result in elevated conduit wall stress and provide short flash-over paths inside the coil. The conduit wrap stresses in the test sample are predicted to be generally comparable to the actual coil stresses. Cruciform filler material is over loaded slightly during test which adds margin for this component. The ground wall and spacer block do not come up to the level of stress that is expected in the coil. For the ground wall the worst type of failure would be a laminar tensile break because this would most likely compromise the coil electrically. A fairly good match is obtained for groundwall laminar tension. The spacer blocks provide support and transmits compressive loads. These compressive loads match reasonably to the test. Where the test loads are low in the ground wall and spacer blocks the failures which could occur would be delamination which are generally not primary load carrying mechanisms and don't compromise the insulation as significantly as other failures. Further review of the stresses are necessary to sort stresses which are highly localized or are artifacts of the modeling. Furthermore the alternating portion of the stress needs to be compared directly and will be included in the final version of this document.

The final test load consists of load to "failure". The failure is defined by observation of the load deflection plot and acoustic noise level. The load to failure tests consists of raising the load slowly to the point at which a noticeable offset or significant nonlinearity occurs in the load deflection curve and/or acoustic emission indicates catastrophic damage is occurring. Table 3.6 below shows a comparison of the loading applied to the 5x5 samples and the worse case loadings expected on the coils. Loading applied to each sample are indicated in a later table.

Table 4-5 FEA Stress Results Summary for the CS 5x5 Test

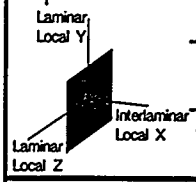
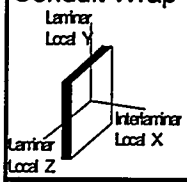
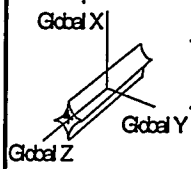
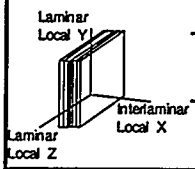
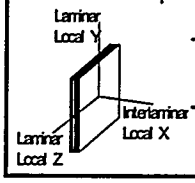
		41MPa Pressure Only (MPa)	Cooldown Only (MPa)	Cooldown and 41MPa Pressure (MPa)
Conduit	SX	-754	-189	-749
		700	120	686
	SY	-847	-141	-961
		439	106	472
	SXY	-335	-55	-339
		398	57.3	416
	SINT	946	194	988
Kapton 	SX	-136	-32.6	-150
		19.8	9.82	18.5
	SY	-50.6	-7.77	-36.6
		41.3	30.7	64.2
	SXY	-4.6	-1.18	-4.92
		4.7	1.1	4.86
Conduit Wrap 	SX	-117	-27.1	-127
		17.2	16.2	18.1
	SY	-263	-89.9	-253
		247	115	322
	SXY	-43	-54	-92.6
		40.1	30.5	53.4
Roving 	SX	-124	-19.6	-95.4
		-1.86	129	96
	SY	-36.4	-21.3	-33.3
		133	120	273
	SXY	-28.7	-40.9	-58.2
		29.6	44.8	77.7
Spacer Block 	SX	-27.8	-16.3	-32.4
		101	58.6	164
	SY	-177	-66.5	-234
		1.24	38.8	11.7
	SXY	-22.9	-24.5	-39.9
		26.2	23.6	39
Ground Wrap 	SX	-205	-11.2	-219
		14.2	21.3	35.2
	SY	-142	-50	-177
		107	23.4	135
	SXY	-54	-15.1	-58
		72.9	16.5	80.4

Table 4-6 Comparison of Worst Case CS Coil Stress and 5x5 Test Sample Stress

compare5.xls	A 5x5 Test Cooldown & 41MPa Press. Stress (MPa)	B 3x2 Test Cooldown & 90kN Force Stress (MPa)	C FEA Case 8 * Max Vert Comp & Cl Dn GT to 4K PF1 Lower, Eq16 Stress (MPa)	Comparison (A or B) / C
Conduit (Turn) Wrap				
Interlaminar Compression	-127	-	-84.8	150%
Interlaminar Tension	18.1	-	19.5	93%
Laminar Compression	-253		-306	83%
Laminar Tension	322		307	105%
Cir. Laminar Tension	-	220	184	120%
Interlaminar Shear	-92.6		-76.3	121%
Cruciform Filler Material				
Compression	-95.4		-65.5	146%
Tension	273		229	119%
Circumfrential Tension	-		87.1	
Shear	77.7		70.9	110%
Conduit				
SINT	988		740	134%
Spacer Block				
Interlaminar Compression	-32.4		-33.8	96%
Interlaminar Tension	164		298	55%
Laminar Compression	-234		-183	128%
Laminar Tension	11.7		236	5%
Interlaminar Shear	39.9		91.8	43%
Ground Wall				
Interlaminar Compression	-219		-242	90%
Interlaminar Tension	35.2		95.2	37%
Laminar Compression	-177		-303	58%
Laminar Tension	135		145	93%
Interlaminar Shear	80.4		134	60%

PDR Baseline material properties

4.6 3X2 TEST LOADS

The intent of the 3x2 tests is to simulate two stresses: laminar stress along the conduit length (z stress) and the interlaminar shear due to bending in the PF5, 6, 7 and TF coil systems. Final investigation of the CS, PF6, PF7 and TF coil systems has shown that the direct load and interlaminar shear is worse case in the CS coil system. These CS stresses are not associated characteristically with the coil bending between supports as in the PF5, 6, 7 or TF systems. They originate due to hoop extension of the coil or bending of the conduit. When originally planned the PF

6 and 7 did not have support structure to prevent bending between support points. The addition of the support has diminished the bending to the point where the CS stresses are the worst. PF5 has yet to be analyzed but it is anticipated that these stresses will prove to be lower than the CS system. As result the direct stress picked for the direct bending load in the system is 220 MPa based on margin above the 190 MPa tension along the length of the coil which occurs due to FEA load case #4.

The finite element results[9] indicate that the load verses deflection is relatively linear with load and at a load of 106N the peak stress is 285 MPa. At this load the deformation at the point of load application is 0.149".

4.7 5X5 TF CONDUCTOR PACK TEST LOADS

The TF coil configuration is designed and analyzed by B&W and the analysis is presented in their report on the TF coil Design. They have also analyzed the test setup for the TF coils and have arrived at loads and deflections that are used for test. The loads are based on the analysis reported in Tables 9 and 10. B&W has indicated that a compressive pressure load of 36 MPa or a deflection of .022 in (.55 mm) is considered to be the most appropriate loading[10].

The B&W coil is tested in the coil case as indicated in Figure 3.2. The analysis indicates that there is significant variability in the stiffness of the coil depending on the boundary condition between the coil and the coil case. B&W reports the peak radial compressive stresses varying by about 70% as a function of the boundary condition at the case. The actual condition that will exist during test is somewhat undetermined. The test coil will be fit into the testing fixture using epoxy resin as a filler to provide a tight fit. It is however uncertain whether or not the coil will be bonded consistent with the actual TF coil. As result the load of 36 MPa rather than the deflection will be used as the test limit. The minimum load for each cycle will be 0 and 6000 cycles will be applied consistent with the loading expected on the actual coil. Table 3.7 (Provided by B&W) shows a comparison between the expected stress in the coil and the test sample loaded at 36 Mpa.

---

[9] Hannan, W.F., 3x2 Verification Test Sample Finite Element Analysis
[10] Antaya, T.A., E-Mail to Sanger Et.al., TF 5x5 Mockup Compressive Strain,Date: 5 Jul 95

Table 4-7Comparison of Worst Case TF Coil Stress and 5x5 Test Sample

Stress Comparisons: Detailed Equatorial Model with Energized Coil to 5 x 5 Mockup Test Article under 36 MPa Pressure (Provided by B&W)					
	Sx (In Plane)	Sy (Thru-thick)	Sxy	Sz	Sint
Equatorial Model					
Conduit	-701 144	-85 20	<1	81 320	760
Kapton Layer	-198 66	-150 20	10	-167 5	
3D Overwrap	-301 254	-150 23	80	-51 167	
Corner Fill	-212 160	-260 60	75	1 100	
5X5 Model					
Conduit	-470 2.5	-66 1.3	<1	95 236	570
Kapton Layer	-106 42	-200 5	13	-122 10	
3D Overwrap	-160 208	-190 14	75	-150 160	
Corner Fill	-187 150	-169 73	74	-0.1 94	

* Stresses in MPa

4.8 DETERMINATION OF THE NUMBER OF TEST LOADING CYCLES

Beyond the peak magnitude of the stress the temporal character is also important. A sense for the variation can be determined by review of the temporal load data. M. Krefta has reported the temporal data for many of the load applications. Figures excerpted from M.Krefta's work[4] showing the temporal character of the Loadings are attached in Appendix A. Not all time histories are known so it is assumed that the ones that are known represent the worst case character.

Accounting for the complex load histories during the testing can be accomplished in one of two ways. 1) Test to the number of cycles required with a close facsimile of the desired load cycle or 2) analytically determine the number simple cycles necessary to accumulate the same damage and increase the number of simple cycles appropriately. The second method will be used (where required) in this phase of the program to conserve program resource as the more complex load cycle will slow testing. The magnitude of the load will be determined by matching components of the stress level in the insulation with the mechanical loadings proposed

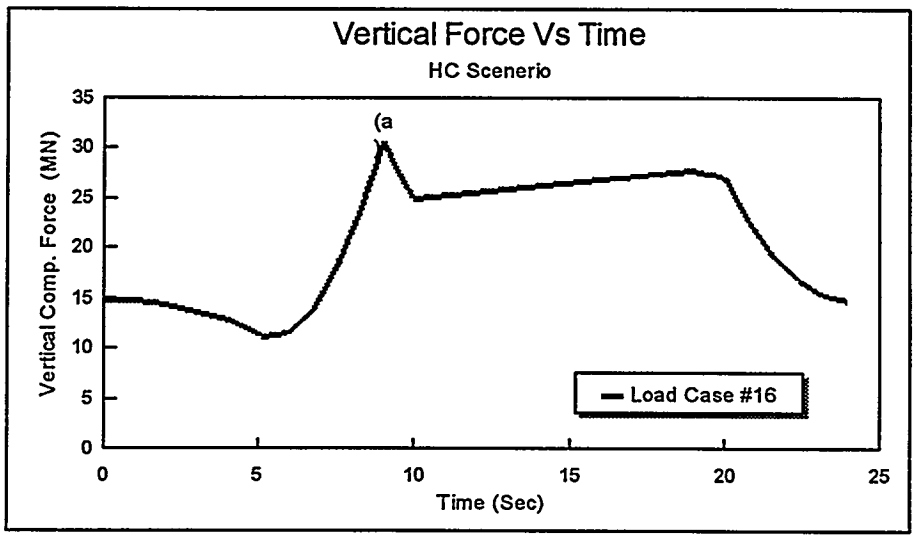
Methods for accessing the damage are available in the literature and the "TPX Structural and Cryogenic Design Criteria" document section I-4.2.1.5 deals with cumulative damage calculations. The Design Criteria document also discusses the methodology required for evaluation of aperiodicity in the load cycle in section I-4.2.3.1. and presents a method of accounting for a mean stress in the load when the fatigue data does not account for it in section I-4.2.1.4.

The 5x5 test loads and cycles will be driven by the vertical compressive force on the conductor pack. Worst case for this loading is #LC 16 Normal Operation and Disruption. (J.Schultz case 1) The temporal load cycle is shown in Figure 3 extracted from Appendix 1.

With rainflow counting method applied to the load cycle an equivalent set of simpler cycles can be applied. Figure 3.4 shows the components which can be considered to make up the more complex loading.

Damage calculations based on the load cycle shown in Figures 4.2 and 4.3 indicate that 300 additional cycles would compensate for the damage done in the secondary portion of the load cycle. Therefore with margin added for unknowns in the cycle one lifetime is taken to be 31000 cycles as opposed to 30000 cycles.

Figure 4-2 Compressive Force between CS 1U and 1L during LC #16.



5. TESTING CRITERIA AND TEST VOLTAGES FOR TPX 3X2 AND 5X5 INSULATION R&D MODELS

5.1 ASSUMPTIONS

Table 5.1 presents a summary of the peak operating voltages assumed for the TF and PF coil systems upon which we have based our acceptance criteria for 5x5 testing as developed below.

Table 5-1 Peak TF and PF Operating Voltages (V)

COIL	SCENARIO	TERMINAL VOLTAGE	PANCAKE-PANCAKE	TURN-TURN
TF, Line	Dump	7500	<312	<22
PF7	HC Normal	1327	197	17
PF5	12 V Startup	2645	355	23
PF1	12 V Startup	3059	347	30
PF7	20 V Startup	4067	628	55
PF5	20 V Startup	4437	595	39
	Peak Voltages	7500 TF 4437 PF	<312 TF 628 PF	<22 TF 55 PF

The maximum PF1-7 operating voltages in Table 1 are given in Memorandum 14-950214-MIT-ARadovinsky-01, February 14, 1995. Radovinsky calculated pancake-pancake peaking factors (local voltage/average voltage) less than or equal to 1.13 except for PF2 which had a large peaking factor of 1.43 during 12 V (inner) Initiation Sequence. Turn-turn peaking factors were less than 1.58 in all

cases, but since turn-turn voltages are less than or equal to 55 V they obviously do not drive the electrical insulation design and acceptance voltage criteria.

The maximum TF operating voltages presented in Table 1 are assumed to occur under energy dump leading to a peak terminal voltages of +/-7500 V, and that the 16 TF coils have a midpoint neutral. The actual voltage distribution within the coils under dump as well as other scenarios has not been calculated to our knowledge. Radovinsky has shown in the case of the PF coil system that peaking factors are less than 1.13 or 13% enhancements for all pancake-pancake voltage drops, except for PF2 under 12 V (inner) initiation sequence where a peaking factor of 1.43 is calculated, as discussed above. However, in the case of PF2 the peak pancake-pancake voltage is low (138 V) and therefore, doesn't drive the acceptance test voltage. Similar peaking factors for TF coils due to nonuniform voltage distribution under energy dump are expected to be slightly higher than in the case of PF, and a factor of 2.0 is assumed to be conservative. Since the average pancake-pancake TF stress for uniform voltage distribution is only 156 V and 312 V for peaking factor of 2.0, the TF coil system does not drive the selection of peak acceptance test voltage since even with this high peaking factor the pancake-pancake peak voltage for PF7 of 628 V is still higher by about a factor of 2.

5.2 DEVELOPMENT OF TESTING CRITERIA

5.2.1 Turn-Turn Peak Operating Voltage

The peak pancake-pancake voltage for all TF and PF coils is assumed to be 628 V, which occurs for PF7 under 20 V (outer) Initiation Sequence. Therefore we take 628 V as the peak operating voltage for pancake-pancake electrical stress to be verified in the 5x5 model program. This is also the assumed turn-turn voltage level since without barrier spacers in the design the pancake-pancake and turn-turn have exactly the same insulation configuration. Note that the peak turn-turn voltage for all coils under operating conditions is only 55 V and of no concern for selection of test voltage levels.

5.2.2 Turn-Ground Peak Operating Voltage

The groundwall insulation design is driven by the peak line lead voltage of 7500 V for the TF dump scenario. The peak line lead voltage for the PF system is 4437 V for the PF5 coil under 20 V (outer) Startup Sequence. Since the groundwall builds are nominally the same in both coil systems, we elect to test the groundwall insulation for acceptance at the 7500 V operating level for basic insulation. Since the number of energy dumps of the essentially steady state operating TF coils is small compared to the PF cyclic requirements, the PF5 peak voltage of 4437 V is assumed as the basis for determination of the life cycle testing voltage for ground wall. Since the groundwall is much thicker than the turn-turn insulation the 1.3 local peaking factor is ignored for ground insulation life cycle testing.

5.2.3 Peaking Factor for Local Stress Enhancements at Conduit in Kapton Wrap

Electric field analysis of winding pack configurations for PF cross sections has shown electric stress enhancement or peaking factors of 1.3 times average electric stress. This peaking occurs at the conduit corners within the Kapton wrap at the conduit Kapton interface. This local stress peaking factor is due to both the curvature of the conduit and the dielectric constant mismatch between Kapton (3.8) and glass/epoxy (5.3) insulation. We assume 1.3 as the local stress enhancement in the bulk insulation in the determination of the acceptance test voltage.

5.2.4 Peaking Factor for Vacuum/Helium Partial Discharge Simulation in Air Test

The acceptance testing for the 5x5 and 3x2 models will be performed in air for the models as received, after 20 thermal shocks in liquid nitrogen, and after at lease 30,000 mechanical load cycles. The issue of correlation of air testing results with actual operation under vacuum/helium conditions is handled by applying a peaking factor to simulate potential helium partial discharge damage to insulation over life cycle due to helium filled voids and cracks within the insulation. This peaking factor is estimated using Paschen breakdown curves for air and helium presented in Figures 1 and 2. Table 2 presents a summary of air and helium

Paschen breakdown voltage (kV), normalized breakdown stress (kV/bar-mm) and air/helium breakdown stress ratio derived from Figures 1 and 2.

Table 5-2Paschen Breakdown for Helium and Air

PRESSURE-GAP PD PRODUCT	HELIUM BREAKDOWN		AIR BREAKDOWN		RATIO AIR/HELIUM BREAKDOWN
bar-mm	kV	kV/bar-mm	kV	kV/bar-mm	
100	19	0.19	280	2.8	14.7
10	2	0.20	30	3.0	15
1	0.45	0.45	4.5	4.5	10.0
0.5	0.30	0.60	2.8	5.6	9.3
0.1	0.17	1.7	1.0	10.0	5.8
0.05	0.16	3.2	0.65	13.0	4.1
0.01	0.28	28.0	0.36	36.0	1.3
0.007	>2 Vacuum	>200 Vacuum	0.34	48.6	<0.002
0.005	Vacuum	Vacuum	0.35	70.0	NA

Note: Shaded areas are values for the Paschen minimum breakdown.

Based upon Paschen breakdown, helium voids have electric strength as good as or better than air for void pressure-gap product, pd less than about 0.01 bar-mm, that is just to the left of the Paschen minimum for helium at 0.05 bar-mm. Therefore, air voids with pd<0.01 operating under electric stress at room temperature (20 C°) and pressure (1 bar) conditions will simulate partial discharge activity which would occur under helium void discharges at the same pd product only for void sizes <0.01mm or about 1 mil, (ignoring the role of air chemistry in partial discharge damage to insulation). However, if the equivalent pd under operating condition in vacuum/helium states exceeds about 0.01 bar-mm then helium voids would breakdown at lower stress than the test stress in air, and therefore, some peaking factor to ensure turn on of air voids should be applied to acceptance testing. To first order we assume this peaking factor for partial discharge activity is just the ratio of air/helium breakdown stress (kV/bar-mm) as given in Table 2 at a given pd value. It is reasonable to assume that the voids and

cracks that we expect near end of insulation life will be in the 0.05 to 0.3 mm (2 to 12 mil) size range. In the case of a large crack like 12 mil, the crack size would represent 10/64 = 0.19 or 19% of the total through thickness turn to turn insulation build in the highest stress region. Such large cracks were observed in the 3x3 test program in the corner filler regions of 3x3 model at the end of 30,000 mechanical cycles. However, the electric stress in the corner fill regions is very low compared to the stress in the through thickness. Therefore, to account for simulated helium void discharge in the highest stressed regions of the insultion, i.e., the through thickness, we assume pd=0.1 bar-mm or a 4 mil void size at 1 bar. The air/helium stress ratio at pd=0.1 bar-mm is 10/1.7 = 5.8. We adopt 5.8 as the peaking factor to be applied during life cycle testing to simulate potential partial discharge damage due vacuum/helium void spaces under actual operating stress.

Application of a 5.8 peaking factor to simulate partial discharge equivalence between air and helium during AC life cycle testing must be weighed against the fact that the bulk insulation under air testing using a 5.8 peaking factor would also overstress the bulk insulation by the same factor. Since the bulk epoxy/glass insulation stress is to be less than of equal to 2.5 kV/mm based on the TPX design criteria, it may not be possible to apply the partial discharge peaking factor without exceeding this bulk insulation stress limit. However, since 3x3 testing of the Kapton baseline turn-turn insulation system under life cycle to 7 kVrms has been successfully demonstrated in air testing with an average stress in the epoxy/glass of >6 kV(peak)/mm, we believe that stressing the glass/epoxy to >2.5 kV/mm during life testing is acceptable because of the 4 mil Kapton conduit insulation. In any case, passing the life cycle test with high bulk insulation stress, applied to ensure simulated helium partial discharge activity, will demonstate that the insulation design is very conservative. In the case of the AC life cycle testing for the 5x5 and 3x2 models proposed below, we adopt to limit the peak bulk insulation stress to nominally 5 kV/mm for turn-turn and 2 kV/mm for turn-ground.

5.3 TEST VOLTAGE TO OERATING VOLTAGE CORRELATIONS

5.3.1 Turn-Turn Test Voltages

The estimated turn-turn voltage (pancake-pancake) with peaking factors for local stress enhancements (1.3) and partial discharge simulation (5.8) is

(1) V(T-T, peak) = 1.3x5.8x628 = 4735 V

The DC test voltage is defined as twice V(T-T, peak) plus 1000 V giving

(2) V(DC) = 2xV(T-T, peak) + 1000 = 2x4735 +1000 = 10,470 V

The equivalent AC test voltage is defined as V(DC)/1.7 according to standard testing practice in power apparatus giving

(3) V(AC) = 10,470/1.7 = 6159 Vrms

Therefore, based upon Equations 1-3, we propose to perform a 10 kV, 1 min DC Hipot test for turn-turn insulation and partial discharge testing up to 6 kVrms. The 15 min life cycle test will be performed at 6 kVrms.

It is noted that the V(DC) test level of 10 kV, based upon the assumed peaking factors, turns out to be nearly equivalent to the test voltage for a fault of the line voltage of 4437 V across the first pancake on the basis of twice fault voltage plus 1000 V without peaking factors, that is

(4) V(DC, fault) = 2x4437 +1000 = 9874 V

This voltage, V(DC,fault) = 10 kV is essentially the original test voltage proposed for acceptance of the 3x3 models and was used for the 3x3 Baseline Model #1. Eventually a 16 kV DC 1 min Hipot test was used to extend the determination of safety margin in the 3x3 testing program.

The proposed AC life test voltage of 6 kVrms is about a factor of two greater than usually employed to test life cycle. Normally the life cycle voltage in for turn-turn in this case would be given by

(5) $V(AC,T\text{-}T) = (V(T\text{-}T,peak) + 1000\ V)/1.7 = 5735/1.7 = 3374\ V$

so that a nominal 3.5 kVrms life test would be preferred. Using the 6 kVrms AC test voltage gives added margin against unaccounted for effects and stress risers giving a high degree of confidence to the critical winding pack insulation design.

5.3.2 Turn-Ground Test Voltages

The DC Hipot voltage for turn-ground is determined from the peak line lead voltage of 7500 V for the TF system. The test voltage is determined by

(6) $V(DC,T\text{-}G) = 2x7500 + 1000 = 16{,}000\ V$

The equivalent AC test voltage is given by

(7) $V(AC,T\text{-}G) = 16{,}000/1.7 = 9412\ Vrms$

Here we are justified in ignoring the peaking factors for electric stress enhancement and for partial discharge simulation since the DC Hipot is only required to determine basic insulation level at the 7500 V line lead level. With respect to AC life test voltage (same as the maximum AC partial discharge voltage level), the TF 7500 V line lead peak voltage is not the appropriate one to deterimine life cycle. We propose that the AC voltage level be based upon the 4437 V peak for the PF system which sees full life cycles, and not the 7500 V TF system voltage based on energy dumps which are required only TBD times during life cycle. Therefore, it is proposed to derive the turn-ground AC voltage level for life cycle testing and maximum partial discharge voltage level using Equation 2 without the factor of 2 multiplier on V(T-G, peak) as determined from Equation 1 without the 1.3 stress riser, that is

(8) V(AC, T-G) = V(T-G, peak) +1000 = (5.8x4437 + 1000)/1.7 = 15,726 Vrms

This voltage is too high for life testing for the groundwall since the peak average stress throughout the epoxy/glass ground insulation would be

(9) Eav(T-G,peak) = V(AC, T-G) x 1.414/(6.25 mm) = 3.56 kV/mm

exceeding the 2.5 kV/mm limit for epoxy/glass insulation. This assumes a minimum ground wrap insulation build of 6.35 mm or 0.25" allowed for PF coils. The equivalent minimum groundwall build for TF coils is 5.74 mm or 0.226" leading to even higher average stresses. Therefore, the test voltage predicted by Equation 8 should be reduced as a minimum by the ratio 2.5/3.56 = 0.7 for an estimated test voltage of 11 kVrms for AC life and maximum partial discharge testing. Based upon this estimate it is proposed to adopt an AC test level of 10 kVrms for the turn-ground life test which limits the peak bulk insulation stress to nominally 2.3 kV/mm. Since the actual average stress under peak line lead voltage is 4437 V/6.25 mm = 0.71 kV/mm, the proposed turn-ground AC test level voltage of 10 kVrms tests the insulation life to 3.2 times the average operating stress, which is considered adequate margin for TPX.

5.4 SELECTION OF TESTING VOLTAGES FOR 5X5 AND 3X2 MODELS

Table 5. 3 presents a summary of the recommended acceptance test voltages selected for the TPX insulation R&D 5x5 and 3x2 models. The voltage levels are the same as agreed upon at the May 2-3, 1995 TIM held at B&W in Lynchburg, VA.

Table 5-3 Recommended Test Voltages for 5x5 Model Acceptance Testing

INSULATION	OPERATING VOLTAGE kVpeak	DC TEST VOLTAGE kVdc	AC TEST VOLTAGE kVrms	AC LIFE TEST STRESS RATIO
Turn-Turn	628 PF	10	6	13.5
Turn-Ground	7500 TF	16	-	-
Turn-Ground	4437 PF	-	10	3.2

6. DESCRIPTION OF CONDUCTOR TEST SAMPLES AND FABRICATION PROCESS

The 3x2 CS bending models and 5x5 PF and TF models for the large scale verification test program were fabricated at the Everson Electric Company, Allentown, PA under factory environmental conditions. Everson personnel with experience in insulating and impregnating magnet coils performed the assembly and impregnation of the TPX winding pack models. The models were shipped to WEC-STC, Pittsburgh, PA where the mechanical and electrical test program was performed.

6.1 TEST SAMPLE CONFIGURATIONS

The sample configurations as designed are presented in Table 6.1. The 300 mm long A1 and B1 mechanical samples were dedicated to mechanical testing only. The 150 mm long A2 and B2 electrical samples were subjected to electrical testing throughout the mechanical test program, and had special extended end conductors for making electrical connections and preventing end breakdowns. The Incoloy 908 dummy conductors for all models were cut into nominally 150 mm and 300 mm lengths at Everson Electric and the ends rounded to prevent electrical stress enhancements. Ten of the nominally 150 mm conductors were cut longer to a 175 mm length for the extended conductors of the A2 and B2 insulation models. The TF conduits were rectangular with nominal dimensions of 22.6 x 27.2 mm; the PF conduits were square with nominal dimensions of 22.3 x 22.3 mm. The the conduit corner radius for both TF and PF conductors was 5.1 mm.

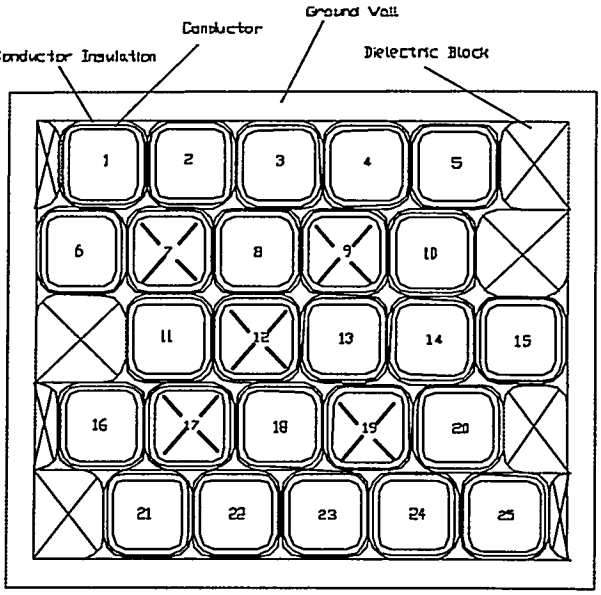
Table 6-1 Design Configurations of 3x2 and 5x5 Test Samples

SAMPLE TYPE	LENGTH mm	SAMPLE SIZE mm		INSULATION BUILDS mm	
		Height	Width	Turn-turn	Groundwall
PF 5x5 A1	300	135.4	159.3	1.626	7.87
PF 5x5 A2	150	135.4	159.3	1.626	7.87
TF 5x5 B1	300	135.4	158.2	1.626	7.11
TF 5x5 B2	150	135.4	158.2	1.626	7.11
CS 3x2 C1&2	300	71.78	47.85	1.626	None

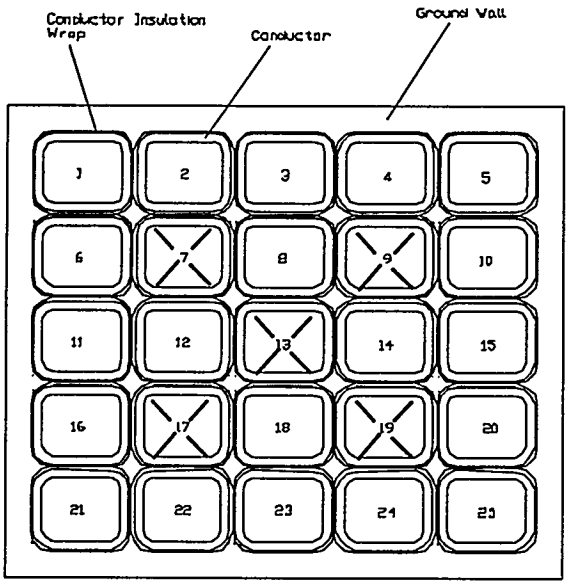
The conductors were shipped to WEC-STC in Pittsburgh. The dummy conductors were removed from the conduit jackets and the conduit surfaces throughly degreased and cleaned in acetone and methanol baths. All 112 conduits needed for the 3x2 and 5x5 construction were then simultaneously vacuum age hardened for 50 hours at 700°C. The conduits were placed in the vacuum oven in four bundles of 25, 25, 25, and 36 arrays using Ti strips for separators. The details of the age hardening process are found in TPX Memorandum 14-950622-WEC-JLowry-01. Following the age hardening by WEC-STC, the conduits were sent back to Everson Electric for fabrication of the 3x2 and 5x5 models.

The designed cross sections of the 5x5 PF A1, A2 models and TF B1, B2 models, and the 3x2 CS C1, C2 models are presented in Figure 6.1. The TF 5x5 cross section is a regimented array of 25 conduits with full groundwall insulation. The PF 5x5 cross section is an array of 5 offset layers designed to simulate key areas of a spiral winding section with full groundwall insulation. The CS 3x2 cross section for the bending models has no groundwall.

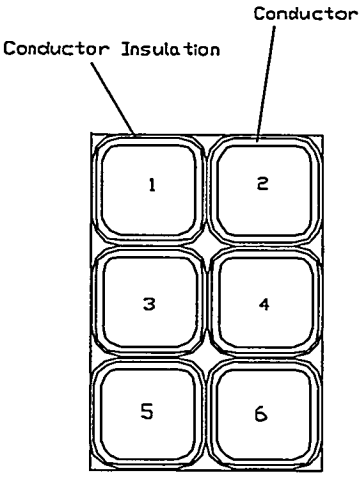
The conductor ends for the TF and PF 5x5 models which are marked with an "X" in Figure 6.1 are the extended conductor locations for the insulation samples. All center conductors of the 5x5 models had brass plug inserts placed inside conductor ends for the purpose of making electrical connections to the central conductors. Electrical connections to all turn exposed on the winding pack periphery were made on the outside surface of the models through the groundwall insulation.



5x5 PF Sample A2



5x5 TF Sample B2



3x2 CS Sample C2

Figure 6-1Cross sectional configurations of 3x2 and 5x5 samples showing extended conductors (marked with an "X") and identification of conductors for insulation testing.

6.2 FABRICATION AT EVERSON ELECTRIC COMPANY

6.2.1 Conductor Preparation Procedures

The conductors ends were sealed at Everson Electric to prevent resin from filling the hollow conduits. Round Buna-N rubbere O-ring material was cut and forced into the open ends of all conductors. RTV was then forced into the voids between the O-ring and conduit inside wall and extended over the ends of the O-ring and/or brass plug surfaces. Figure 6.2 shows the end preparation of typical conductors. The two conductors on the right have brass plugs.

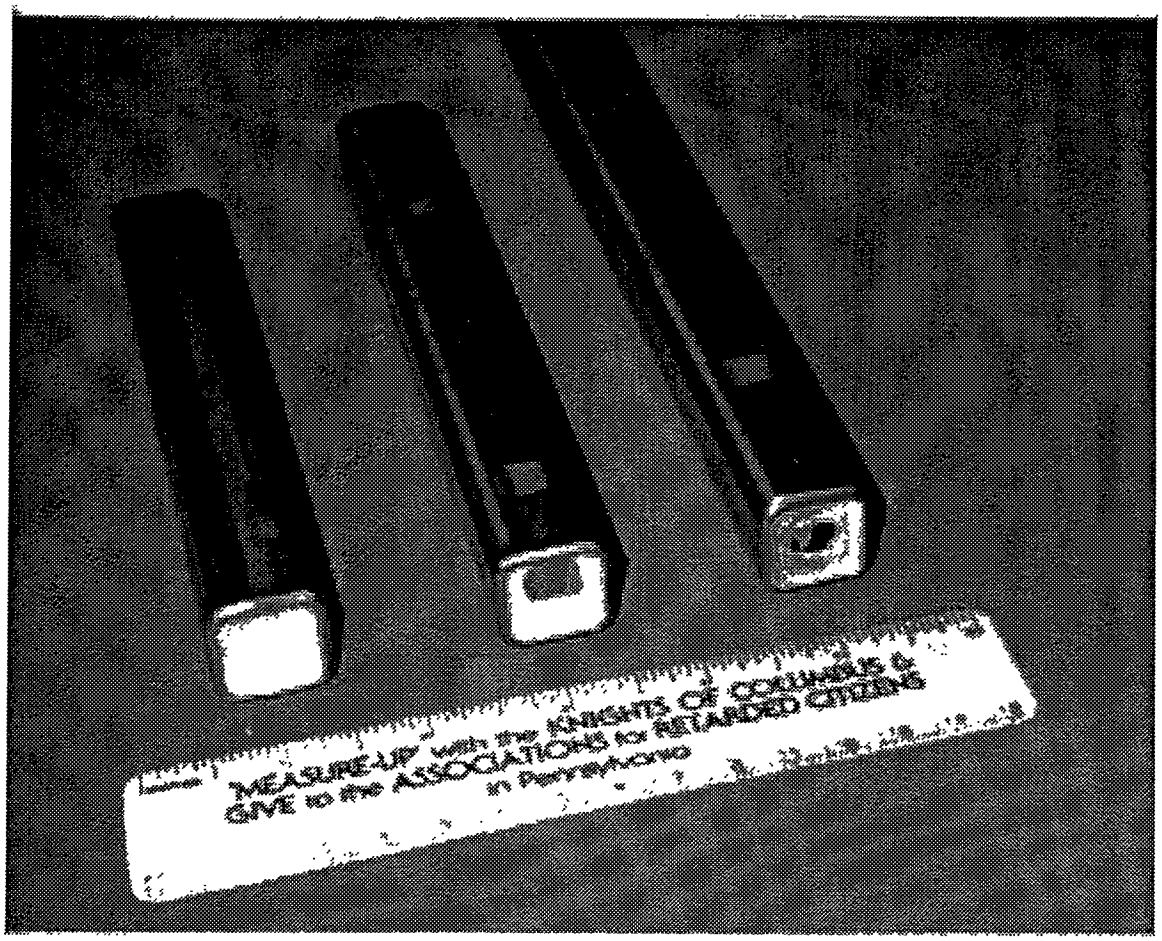


Figure 6-2 End preparation of Incoloy 908 conductors.

6.2.2 Insulation and Mold Assembly

The CPDR conductor insulation system was employed in the fabrication of all models. The conduits were first wrapped with 2-50% Kapton, Type H layers with Kapton extending over the ends of the conductors for about 5 mm. The Kapton was 25.4 mm wide and 0.025 mm thick. The Kapton wraps were then overwrapped with 1-50% 3-D weave S-2 glass tape, 25.4 mm wide and 0.356 mm thick, giving a nominal conductor turn-to-turn insulation build of 1.624 mm. The corner voids were filled with 3-D weave triangular shapes molded and tackified. The tacification process uses the Shell 826 resin system with acetone dilution which was developed at Techniweave for the TPX program. The block fillers for the 5x5 PF models A1 and A2 were molded and tackified from lamination stacks 3-D weave tapes. Three types of block fillers were required, two each with heights of one insulated conductor, 23.93 mm and 1/4, 3/4, and 1 insulated conductor widths, 5.98 mm, 17.95 mm, and 23.93 mm.

Figure 6.3 presents photographs of the assembly of the B1 an B2 TF models. The photograph on the right shows the models as insulated and groundwrapped, using nominally 0.18 mm thick S-2 dry glass tapes, 19 mm or 25 mm wide with either plane weave or 4-harness Satin finish weave purchase from Carolina Narrow Fabric or Textiles Industries Inc., respectively. Shown are the insulation tapes, tackified void fillers, and typical insulated conduits (for the A1 and A2 models). The photograph on the left shows the B2 and B1 models being assembled in the mold.

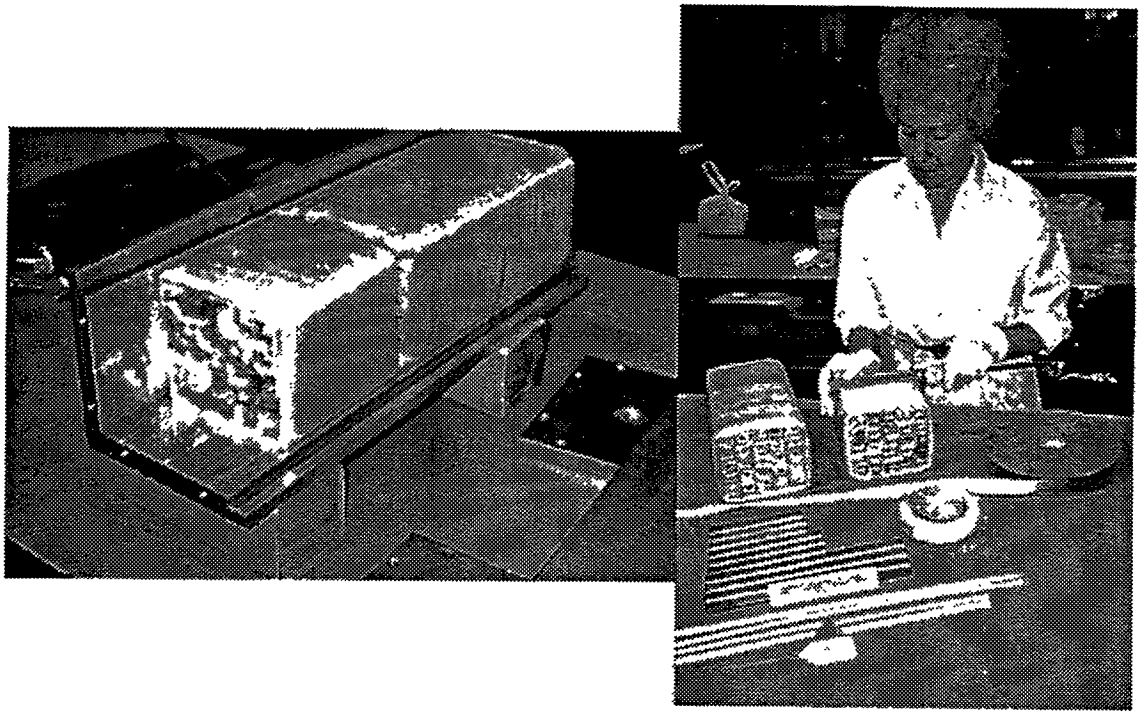


Figure 6-3 Insulated B1 and B2 5x5 samples and partial installation in mold.

The 5x5 mold was fabricated of aluminum. The mold closure process is depicted in Figure 6.4. The mold was sealed using RTV and then assembled with C-clamps to close the mold. The end flanges with RTV sealant were then bolted on. The mold was eventually held together with six pairs of steel bars, three sets on each of the sides, using all thread to tie the opposing bars together. One of the tie bars is shown on top of the mold in Figure 6.4.

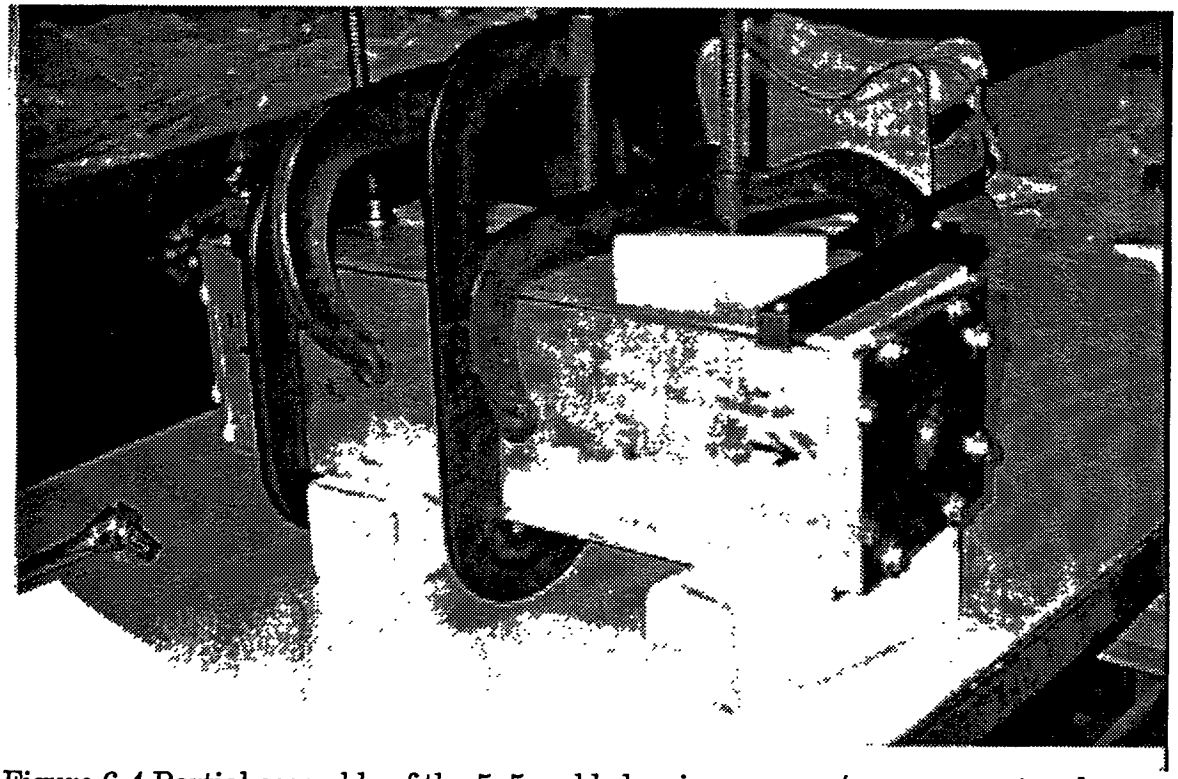


Figure 6-4 Partial assembly of the 5x5 mold showing vacuum/pressure port end flange, C-clamps, and clamping bar.

The 3x2 models were molded in the mold used for the TPX 3x3 R&D program. Shims were used to fill the voids left by in the mold by the smaller 3x2 array. The 3x2 and 5x5 mold cavities were sprayed with a mold release, and the models were wrapped in Tedlar tape mold release before assembly in the mold.

6.2.3 Impregnation Procedures

The mold assembly was allowed to sit for about 8 hours to allow the RTV sealant to fully cure. The mold was pressure tested to 25 psi before the vacuum-pressure-impregnation process was begun. The VPI process steps for the 3x2 and 5x5 program are briefly summarized in Table 6.2.

Table 6-2 VPI Impregnation Procedures for the 3x2 and 5x5 Models

STEP	DESCRIPTION
1	Install samples in mold and pressure test mold to 25 psi
2	Place mold in oven and conduct vacuum bake-out for 1 hour at 220 F and at least 8 hours at 130 F
3	Mix Shell 826 resin and Ciba-Geigy HY906 hardener at 110 F and degas mix for 1 hour at or below 700 microns
4	Add Ciba-Geigy DY062 Accelerator and degas again at 110 F for 15 mins
5	Fill mold under vacuum until bulb sight-glass is half full. Shut resin inlet valve
6	Let filled mold stay under vacuum for 2 hours and monitor resin level. Add resin as necessary to keep bulb sight-glass to half full level
7	Close vacuum line and pressurize mold with dry nitrogen to 20 psi and hold for 2 hours. Add resin if necessary through the vacuum line
8	While the mold is under pressure begin the curing cycle. First stage is to cure at 4 hours at 175 F. Then disconnect pressure from mold and continue curing for 10 hours at 260 F. At end of curing cycle let mold cool at room temperature and then remove samples from mold
9	A complete record of all events, ie. times, temperatures, vacuums and pressures are to be kept

6.3 AS RECEIVED SAMPLE CHARACTERISTICS

The completed models were shipped to WEC-STC for the mechanical and electrical testing program. The mechanical insulation A1 and B1 samples were cut as received and the average dimensions of the samples, including insulation spacings measured. Table 6.3 summarizes the as received sample dimensions.

The turn-to-turn insulation spacings for the C1 and C2 bending models were deduced from the overall outside dimensions by subtraction of the conduit dimensions. The 3x2 and 5x5 models had turn-to-turn insulation spacings within less than 2% of the design goal of 1.626 mm. The groundwall insulation was harder to control in manufacturing and depended upon the conductor stacking tolerances, the amount of groundwrap applied (using the estimated tape thickness to determine the number of laps required), and the mold compression during mold closure. PF A1 and A2 models had a groundwall thickness of 6.91 mm and the TF B1 and B2 models a groundwall thickness of 7.19 mm. These insulation builds are greater than the minimum requirement of 6.35 mm for the groundwall insulation design.

Table 6-3 Average Dimensions and Insulation Spacings of 3x2 CS and 5x5 PF and TF Models as Received

MODELS	HEIGHT mm	WIDTH mm	LENGTH mm		INSULATION BUILDS mm	
			1	2	Turn-Turn	Groundwall
3X2 CS						
C1, C2 CS	71.88	47.90	300	300	1.655	None
5X5 PF & TF						
A1, A2 PF	159.8	135.2	300	150	1.636	6.91
B1, B2 TP	159.0	135.2	300	150	1.626	7.19

7.

7. MECHANICAL TESTING PROGRAM

7.1 OVERVIEW OF TESTING

Figure 2.1 shows the general flow of the testing program. The program is set up so as to provide test specimens for verification of mechanical and electrical adequacy and assessment of remaining margin. All of the coil loading conditions were considered when developing the program and three types of mechanical loading were settled upon to provide representative mechanical damage to the coils. The three mechanical loading configurations were generally depicted in Figure 2.2. The three mechanical tests with one mechanical and one electrical sample each provide for six samples. Table 7.1 shows the detail plan for the testing of each sample. In the end two samples were not tested as planned. Samples B1 and C2 were removed from the program. Only sample A1 was sectioned as indicated in the table.

Table 7-1 Verification Testing Program & Sequence

5xtstseq.wk4	5x5 CS Coil Sample #A1 300mm	5x5 CS Coil Sample #A2 150mm	5x5 TF Coil Sample #B1 300mm	5x5 TF Coil Sample #B2 150mm	3x2 TF & PS Coil Sample #C1 300mm	3x2 TF & PS Coil Sample #C2 300mm
Sample Sectioned at Reciept(250 mm remains)	√	no	√	no	no	no
1 Initial Electrical Characterization ①	no	√	no	√	√	√
2 Thermal Cycles RT to 77K	20 Cycles	20 Cycles	20 Cycle	20 Cycles	20 Cycles	20 Cycle
3 *Sample Sectioned (200 mm remains)*	√	no	√	no	no	no
4 Mechanical Loading @ 77K One Full Lifetime	31000 Cycles 14 to 41 MPA Compression	31000 Cycles 14 to 41 MPA Compression	6000 Cyd 0 to 36 MI ◀ Comp with side restraint ▶	6000 Cycles 0 to 36 MPA	31000 Cycles 0 to 90 kN 3Pt. Bending	31000 Cy 0 to 90 3Pt. Bendin
5 Electrical Characterization @ R.T. ①	no	√	no	√	√	√
6 AC Voltage Life Test @ R.T. ②	no	√	no	√	√	no
7 *Sample Sectioned in Half (100mm remains)*	√	no	√	no	√ ③	no
POINT OF VERIFICATION	**Testing Done Beyond this point is for information not verification**					
8 Mechanical Loading @ 77K Four Additional Lifetimes	124000 Cycles 14 to 41 MPA Compression	124000 Cycles 14 to 41 MPA Compression	24000 Cycles 0 to 36 MPA ◀ Comp with side restraint ▶	24000 Cycles 0 to 36 MPA		124000 Cycle 60 ± 30 kN Bending
9 Electrical Characterization ①	no	√	no	√		√
10 AC Voltage Life Test	no	√	no	√		√ ③
11 *Sample Sectioned in Half*	*50 mm remains*	√	*50 mm remains*	√		√
12 Mechanical Failure	?? MPA		?? MPA			

Held In Reserve

Held In Reserve

① Turn to turn capacitance, partial discharge up to 10 KV, breakdown or 40 KV and Turn to ground capacitance, partial discharge up to 10 KV, breakdown

② 60 Cycle AC Voltage insulation life testing for 15 minutes at 10 KV.

③ Foil break down tests at 10 KV DC.

7.2 THERMAL LOAD CYCLING

The Large Scale Verification Test Program requires that the 3x2 and 5x5 samples be subjected to 20 thermal cycles. The tests consists of lowering each sample into liquid Nitrogen (LN_2) until it stabilizes at LN_2 temperature (77^0K), then removing it from the LN_2 and allowing it to return to room temperature. Since mechanical tests start during the twentieth cycle, the first 19 cycles are performed using the procedure described here.

Table 7-1 Verification Testing Program & Sequence

5xtsseq.wk4	5x5 CS Coil Sample #A1 300mm	5x5 CS Coil Sample #A2 150mm	5x5 TF Coil Sample #B1 300mm	5x5 TF Coil Sample #B2 150mm	3x2 TF & PS Coil Sample #C1 300mm	3x2 TF & PS Coil Sample #C2 300mm
Sample Sectioned at Reciept(250 mm remains)	√	no	√	no	no	no
1 Initial Electrical Characterization ①	no	√	no	√	√	√
2 Thermal Cycles RT to 77K	20 Cycles	20 Cycles	20 Cycle	20 Cycles	20 Cycles	20 Cycle
3 *Sample Sectioned (200 mm remains)*	√	no	√	no	no	no
4 Mechanical Loading @ 77K One Full Lifetime	31000 Cycles 14 to 41 MPA Compression	31000 Cycles 14 to 41 MPA Compression	6000 Cyd 0 to 36 MI ◀ Comp with side restraint	6000 Cycles 0 to 36 MPA ▶	31000 Cycles 0 to 90 kN 3Pt. Bending	31000 Cy 0 to 90 3Pt. Bendin
5 Electrical Characterization @ R.T. ①	no	√	no	√	√	√
6 AC Voltage Life Test @ R.T. ②	no	√	no	√	√	no
7 *Sample Sectioned in Half (100mm remains)*	√	no	√	no	√ ③	no
POINT OF VERIFICATION	**Testing Done Beyond this point is for information not verification**					
8 Mechanical Loading @ 77K Four Additional Lifetimes	124000 Cycles 14 to 41 MPA Compression	124000 Cycles 14 to 41 MPA Compression	24000 Cycles 0 to 36 MPA ◀ Comp with side restraint	24000 Cycles 0 to 36 MPA ▶		124000 Cycle 60 ± 30 kN Bending
9 Electrical Characterization ①	no	√	no	√		√
10 AC Voltage Life Test	no	√	no	√		√ ③
11 *Sample Sectioned in Half*	*50 mm remains*	√	*50 mm remains*	√		√
12 Mechanical Failure	?? MPA		?? MPA			

Held In Reserve

Held In Reserve

① Turn to turn capacitance, partial discharge up to 10 KV, breakdown or 40 KV and Turn to ground capacitance, partial discharge up to 10 KV, breakdown

② 60 Cycle AC Voltage insulation life testing for 15 minutes at 10 KV.

③ Foil break down tests at 10 KV DC.

7.2 THERMAL LOAD CYCLING

The Large Scale Verification Test Program requires that the 3x2 and 5x5 samples be subjected to 20 thermal cycles. The tests consists of lowering each sample into liquid Nitrogen (LN_2) until it stabilizes at LN_2 temperature (77^0K), then removing it from the LN_2 and allowing it to return to room temperature. Since mechanical tests start during the twentieth cycle, the first 19 cycles are performed using the procedure described here.

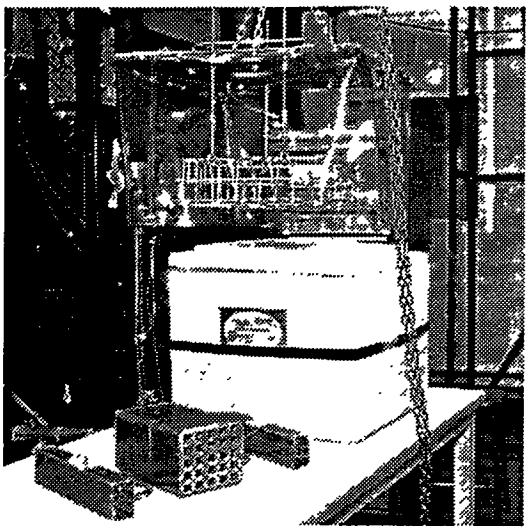


Figure 7-1 — Cooldown Test Rig

Figure 7.1 shows the equipment used to perform the thermal cycling. In the figure the equipment is accompanied by the TF coil sample B1 and the 3x2 bending test samples.

The equipment consists of a large Styrofoam container (16.5"x 16.5"x 13") used to hold the LN_2 and a wire basket assembly (14.5"x 14.5"x 4") used to hold the samples. The basket is suspended from a crane and chain hoist. A top and a plastic curtain surround the top and sides of the basket sealing the assembly when the sample is submerged in the Styrofoam container. A thermocouple is imbedded in each sample and a datalogger is used to read the thermocouple. Two small blowers and two heatguns are used to move air across the sample during the warm-up portion of the test cycle.

Different sample configurations were submerged for different time periods. Tests were conducted to determine how long each sample had to be submerged to reach liquid nitrogen temperature and how long they took to rewarm to room temperature.

Each different sample configuration was fitted with a thermocouple which was isolated so that when it was submerged it was not exposed directly to liquid nitrogen. For the electrical models the thermocouple was potted into a banana plug and then inserted into one of the test ports. For the 5x5 samples the thermocouple were placed at the center conductor since that will be the most difficult conductor to bring to temperature.

The samples are cooled by submerging them in the liquid nitrogen for 45 to 60 minutes. The thermocouples indicated that cooldown took 30 to 45 minutes with the 5x5 electrical samples having the sealed ends taking the longest. Fifteen minutes were added to the cool down times in order to assure that cooldown was complete.

After cooldown the samples were hoisted out of the LN_2 container and moved to the opposite end of the bench and the plastic curtain was moved out of the way to allow free air circulation around the sample. Blowers were placed around the basket and trained on the sample so that a steady volume of air was moved across the sample. The thermocouple in each sample was monitored used to determine when the sample had returned to room temperature.

The 5x5 sample having both ends open and the 2x3 models warm-up in 60 minutes using room temperature air only. The 5x5 electrical samples, with both ends sealed, needs heated air and take an hour and 45 minutes to warm to room temperature.

For the electrical samples no heat is applied for the first 20 minutes, just room temperature air. When the heat is turned on it is not applied directly to the sample but is used to warn the air directed across the sample by the blowers.

Each sample was cycled 19 times in the thermal test rig prior to being subjected to mechanical compressive testing. During subsequent mechanical compressive testing additional cycles are acquired when the sample was cooled for the tests. During these subsequent tests cool down and warm up occur at a slower rate.

7.2.1 Results of Thermal Testing of Sample A1

Prior to thermal cycling the A1 sample was sectioned to determine if any mechanical damage was present due to manufacturing. At this point the sample had been cooled from glass transition temperature to room temperature and could show evidence of the cool down and evidence of resin shrinkage during cure. Figure 7.2 shows a backlit section of the coil sample in the as "manufactured" condition.

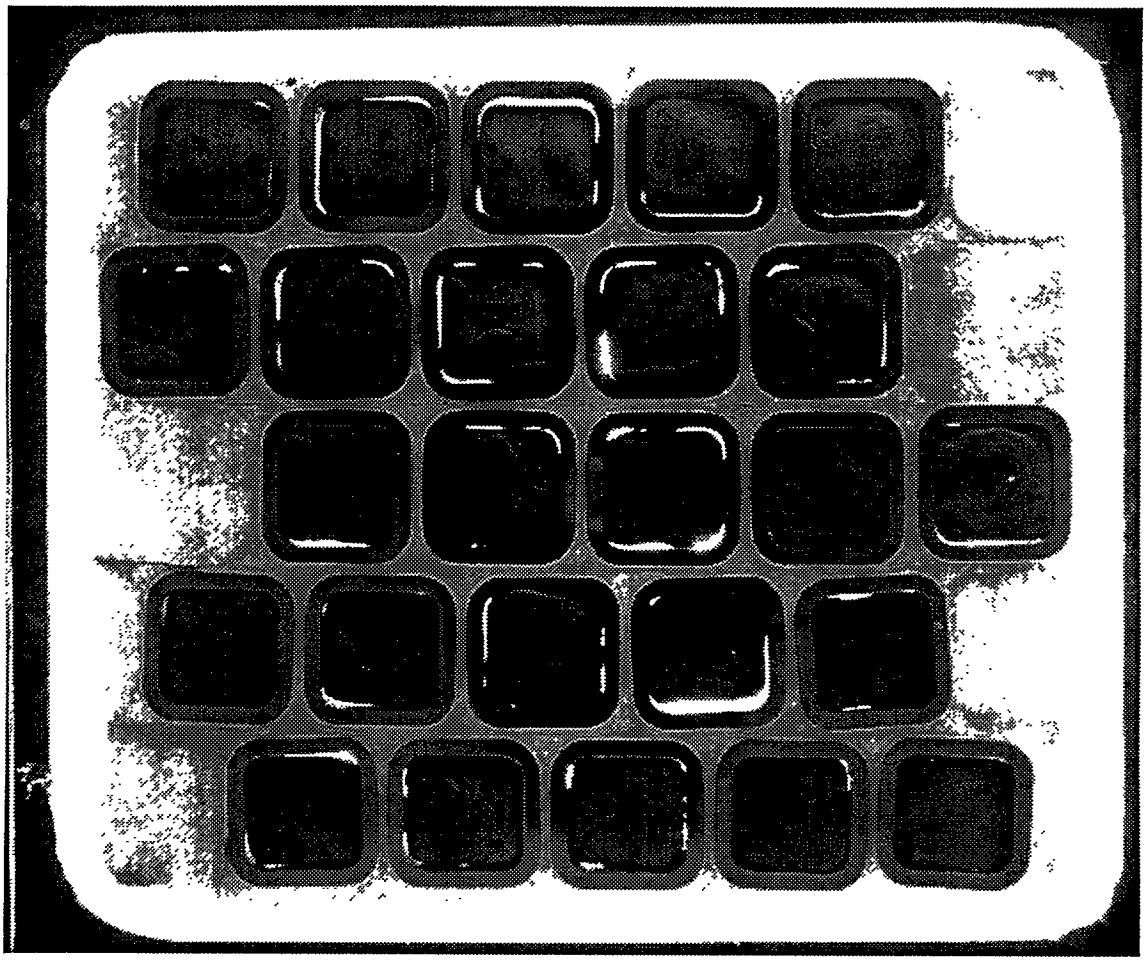


Figure 7-2 Sample A1 - Section 1 - As Manufactured

The sample appeared to be in good condition with very little cracking. Some minor cracking is present adjacent to filler blocks and some lateral cracks are present on the cruciform areas between rows 2 and 3. It is uncertain if any of the damage is caused by sectioning of the sample.

After completion of the 19 thermal cycles as described above, sample A1 was sectioned a second time. The difference between the as manufactured sample and the post thermal test sample provides an indication of the damage which occurs due to thermal shock. Figure 7.3 shows a backlit sample after 19 thermal cycles.

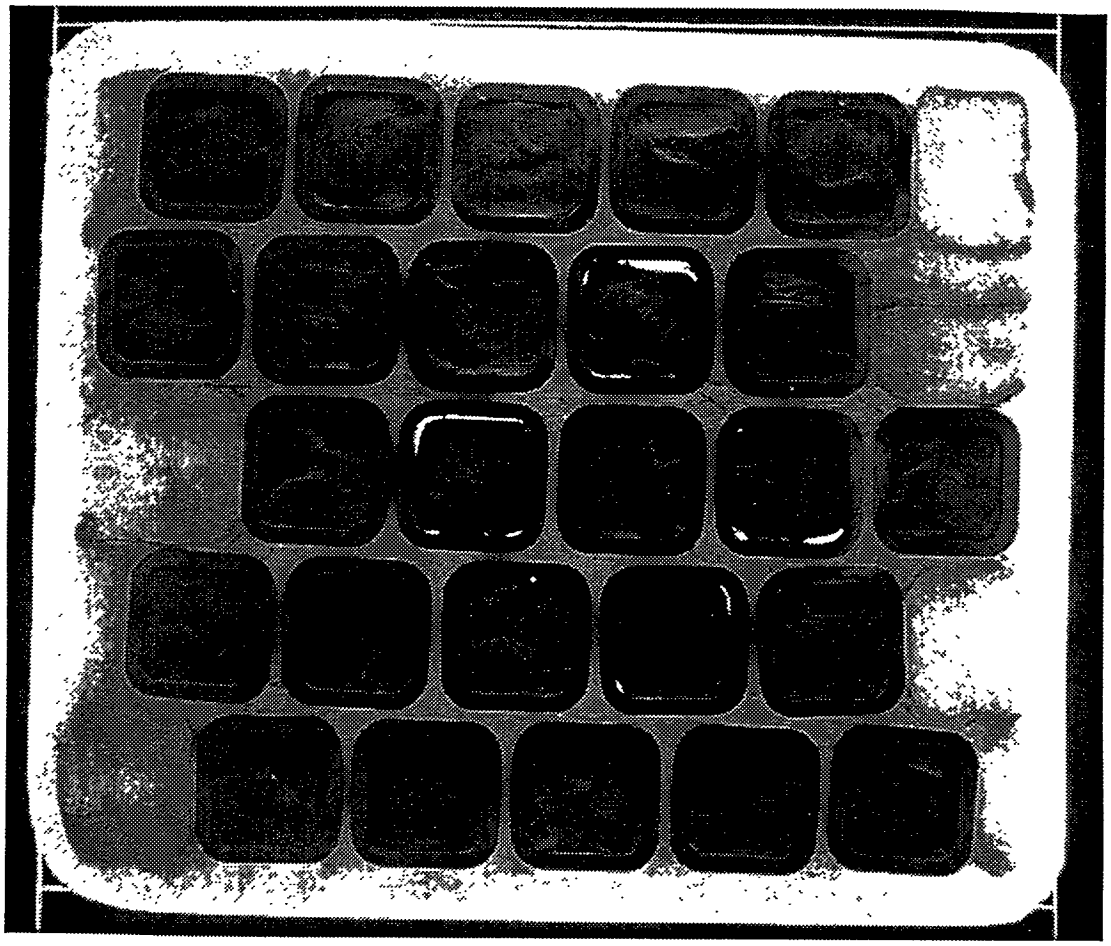


Figure 7-3 Sample A1 - Section 2 - After 19 Thermal Cycles.

Significant crack formation is evident after the thermal cycling. The sample shows that a good many of the crack patterns which show up in the mechanical tests are initiated during the thermal cyclic loading. However, none of the cracks come anywhere near violating the acceptance criteria set forth in section 3 and are difficult to detect without backlighting of the sample.

7.3 MECHANICAL COMPRESSION TESTS

7.3.1 CS 5x5 Compression Tests

7.3.1.1 Test Setup and Preparation

When received for mechanical testing the top of the sample has been identified and marked as indicated in section 6. Alignment is important because the sample must always have the same orientation during testing. Figure 7.4 shows the sample prepared for testing.

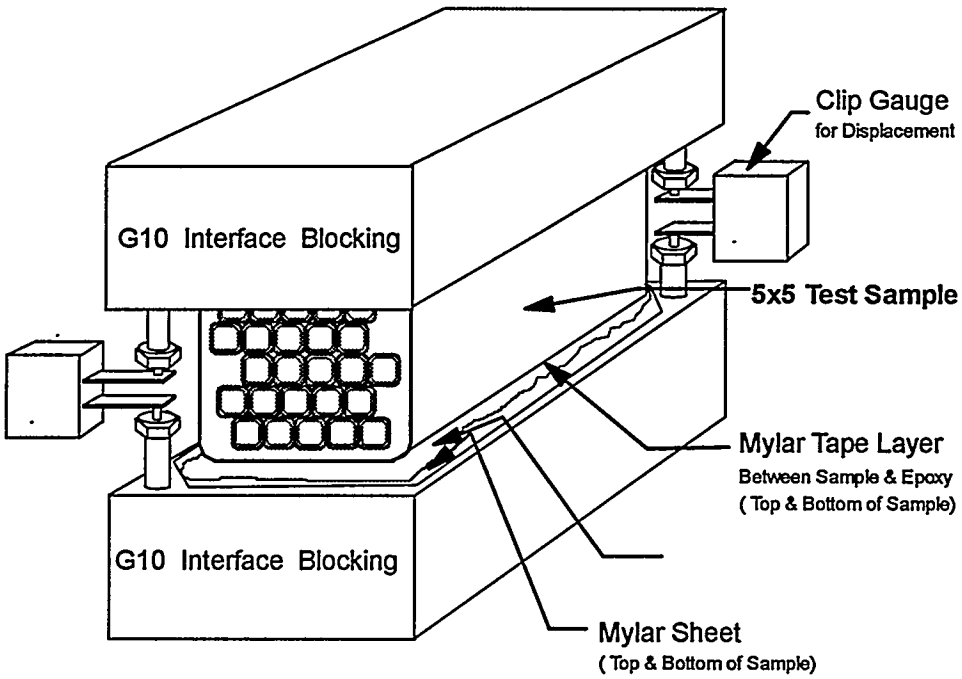


Figure 7-4 CS 5x5 Sample Prepared for Testing

The sample is prepared for compression testing by attaching 0.076m (3 inch) thick G11 test sample interface blocks to the top and bottom of the sample so as to provide proper alignment in the test machine and assure that the load is evenly distributed over the top and bottom surfaces. G11 material is selected as it will act as an elastic foundation against the sample. Before attaching the sample to the blocks any resin flashing or burrs on the top and bottom surface of the sample that interfere with proper parallel alignment of the blocks is removed using a fine file.

The test sample interface blocks are attached to the top and bottom of the sample using epoxy grout to level the surface and provide fine adjustment for paralleling the blocks. At the beginning of the process the top and bottom of the sample are covered with 0.05mm (0.002 inch) Mylar tape to provide for easy removal of the epoxy grout at the end of the test and to prevent the electrical test attachment holes from filling with epoxy. A two part epoxy kit is mixed so as to have a cure which provides a working time of about a half of an hour. This results in an interface which will have some plasticity when first placed in the test machine. The epoxy is troweled on to the sample, a sheet of Mylar is applied over the resin, and the blocks are pressed to the Mylar. The sample is centered on the blocks based on markings on both the sample and the blocks. The blocks are then adjusted using a metal gauge to assure that their faces are parallel to each other. The epoxy is then allowed to set for about an hour before the sample is placed in the test rig and cycled slowly up to the preload level. After the epoxy has initially set up to a plastic state, the test sample is placed in the test apparatus and aligned in the platens of the apparatus. Figure 7.5 shows the test setup. The loading apparatus consists of a large commercial MTS hydraulic load compression test machine capable of 1e06 Lb (4.4 MN) force. The nitrogen bath is located in such a fashion that that the load can be applied through the sample while it is submerged in liquid nitrogen as is indicated in the figure.

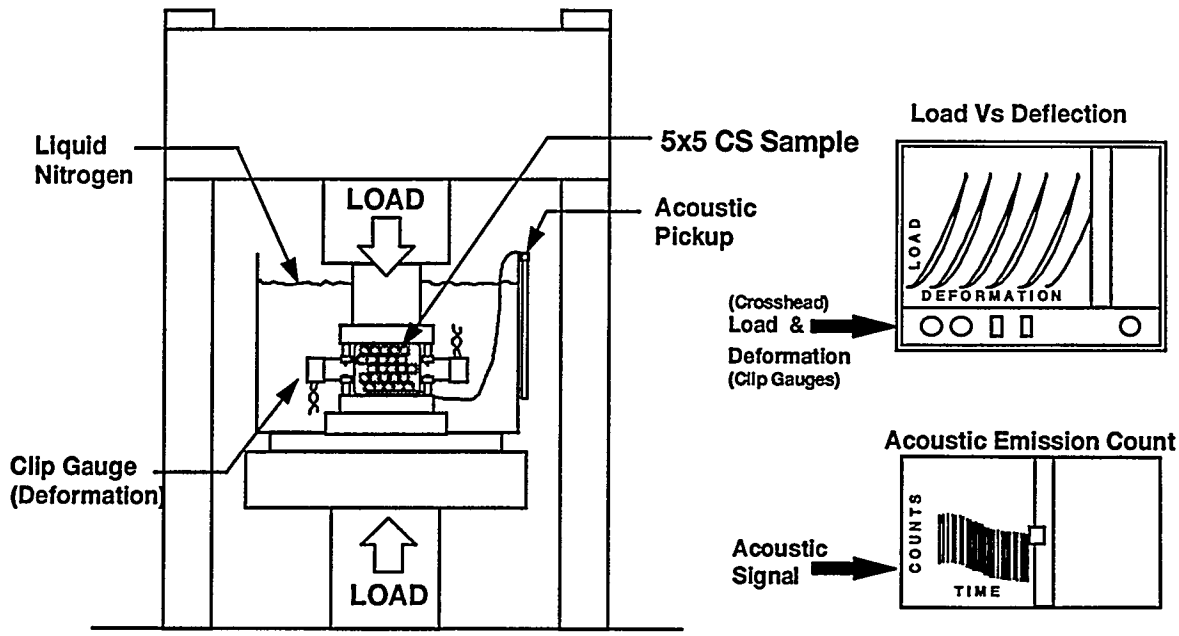


Figure 7-5 Test Setup Schematic

While still at room temperature a mild compressive load is applied to the sample to align the sample-interface blocks in the test machine. The epoxy still being plastic will adjust for misalignment. While the sample is held in place with the light load, two deflectometers are installed on the test sample as indicated in Figures 7.4 so that compressive deflection can be recorded along with load from the crosshead of the test machine.

The load is then successively increased over the course of several cycles at room temperature to a load of approximately 11 MPa. This is done to deform the epoxy grout one final time to "level" the sample in the test machine. The load of 11 MPa corresponds to the lowest load that the coil will be subjected to after it is built and in service. The mechanical preload of the actual coil is slightly higher. When the room temperature load deflection curves indicate that the permanent set is out of the assembly the sample is cooled to 4 degrees K. while the 11 MPa load is maintained.

7.3.1.2 Compressive Load Testing

Two samples of the CS 5x5 coil sample were tested and are reported on in the following section. Sample A1 is referred to as the mechanical sample. Testing and sectioning of this sample was optimized to allow an assessment of the mechanical performance. The A1 sample was sectioned as received, after cooldown, after one lifetime (31000 cycles), after five lifetimes (124000 cycles) and after the sample was taken to failure. Figure 7.6 shows the usage of that sample and Table 7.1 (from the introductory section) shows a summary of the test sequence. The "as manufactured" section and the post thermal test section previously presented are from this sample.

Sample A2 was used for electrical testing and was subjected to the same set of mechanical loads as A1 but instead of being sectioned was electrically tested as reported on in sections 7.2.

Table 7.2 lists the compressive loads that were applied to the CS 5x5 samples during test. They are consistent with the values discussed in section 4 which fundamentally reflects (cooldown + preload + equilibria 16 wherein the force follows an HC scenario). The load deflection results appeared to be fairly linear and between the steady load and the peak load. Maximum variation through a cycle was less than 10%.

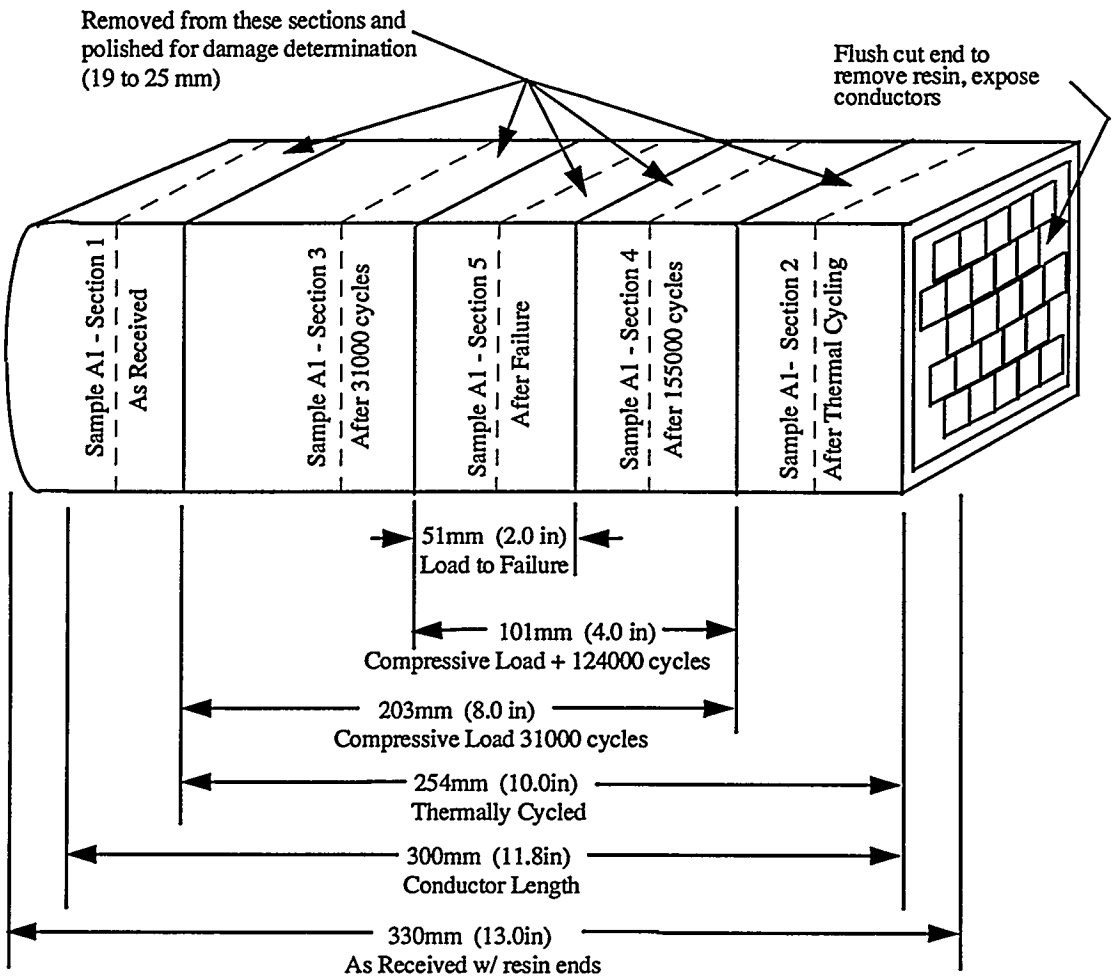


Figure 7-6 Usage of Sample A1

Table 7-2 Vertical Compressive Loads Applied During CS 5x5 Testing

	Test Loads					
	Steady Load bias		Alternating Ld.		Peak loads	
Sample length	Lbf	MN	Lbf	MN	Lbf	MN
8 inch = 203 mm	84600	0.376	163100	0.725	247700	1.101
6 inch = 150 mm	62400	0.277	120300	0.535	182700	0.812
4 inch = 102 mm	42300	0.188	81500	0.363	123800	0.551
2 inch = 51 mm	21100	0.094	40800	0.181	61900	0.275

Test Load = Pressure x Sample Length x Width of flat on top or bottom of sample

Steady Pressure =	2031	psi	=	14	MPa
AlternatingPressure =	3916	psi	=	27	MPa
Peak Pressure =	5947	psi	=	41	MPa
Coil Width (flat) =	5.206	inches	=	0.132	meters

7.3.1.3 Results of Mechanical Verification and Life Testing

Two mechanical measures are applied to the results of the tests to determine the adequacy of the coil. First the coil stiffness may not change by more than 10% over one lifetime of cyclic loading and second the cracking in the coil samples must comply with the acceptance criteria set forth in section 3 of this report.

7.3.1.4 Mechanical Compressive Stiffness of the CS Coil

Because the length of sample A1 changes over the course of the testing the compressive modulus rather than the compressive stiffness is reported. The modulus reflects the stiffness but is a more general term relating load and deflection. The formulation for the modulus is:

$$E = \frac{\text{Load} \times \text{Height}}{(\text{Length} \times \text{Width}) \times \text{Deflection}}$$

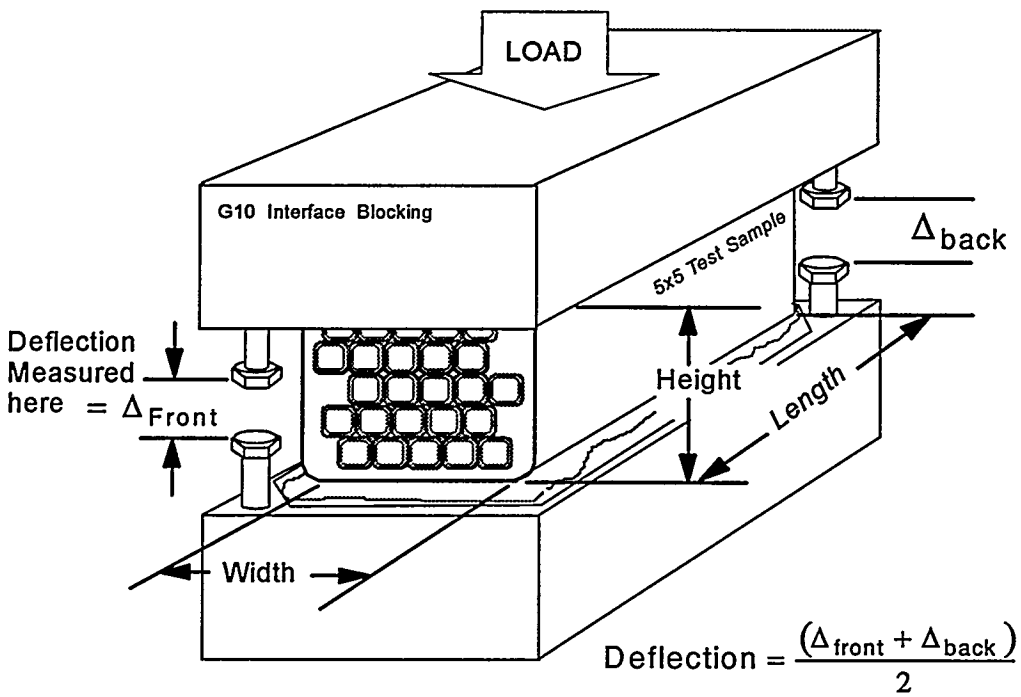


Figure 7-7 Schematic of the Parameters for Measuring the Modulus of the Sample

Table 7-3 Modulus and Chance in Modulus for the CS 5x5 Coil Sample

CS 5X5 Stiffness Tabulation

	SAMPLE A1				SAMPLE A2		
Number of Cycles	Sample Length	Elastic Modulus GPa	% Decrease in Elastic Modulus	Cumulative % Decrease in Elastic Modulus	Elastic Modulus GPa	% Decrease in Elastic Modulus	Cumulative % Decrease in Elastic Modulus
3 *	8	4.2					
5	8	7.5	-80.1%		6.9		
11000	8	7.5	0.0%	0.0%	6.9	0.6%	0.6%
31000	8	7.5	0.0%	0.0%	6.9	-1.2%	-0.6%
41000	4	7.2	3.6%	3.6%	6.4	7.1%	6.6%
124000	4	7.1	2.3%	5.9%	6.2	3.1%	9.7%
155000	4	6.9	2.0%	7.9%	6.3	-1.1%	8.6%

* Data at Room Temperature

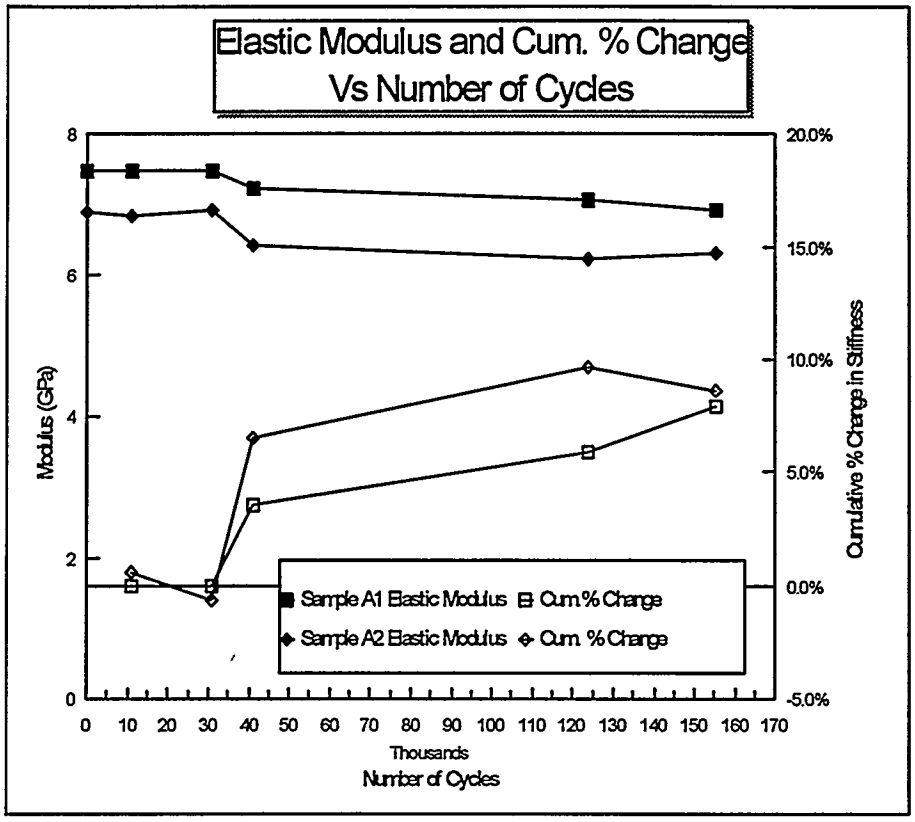


Figure 7-8 Modulus and Chance in Modulus for the CS 5x5 Coil Sample

Table 7.3 and Figure 7-8 shows the moduli derived from some of the stiffness measurements of the CS A1 and A2 coil samples. The results indicate that the stiffness decreases with the number of cycles. This result is similar to the result

seen for the 3x3 test. In those results the stiffness was seen to decrease by about 3 to 4 % over 15000 cycles. The per unit loading imposed on the 5x5 samples was about 18% lower than the 3x3 if the entire cross-section of the coil is considered. This results from the actual CS coil being almost eight conductors wide whereas the very conservative loading selected for the 3x3 samples had been based on the entire load being distributed over six conductor widths.

With the lower loading imposed on the 5x5 no deterioration in stiffness is evident during the first lifetime of 30000 cycles. Curiously a drop-off of several percent appears to occur shortly after one lifetime. For the A1 sample a decrease in modulus is immediately apparent after the sample is reloaded in to the test rig after sectioning (not included in the plotted data). For the A2 sample no such drop occurs, however, a decrease occurs within 15000 cycles. Several explanations can be presented for this behavior including: slow change in stiffness during crack initiation, scatter in the data, deterioration caused by thermal loading or other events in place of mechanical cycling. Insufficient data exists to determine which if any of these effects are responsible for the data trends. It does appear that *given the worst case loading as selected from various load cases, the decrease in modulus during the expected life time will be considerably less than the ten percent allowed by the acceptance criteria. The data further suggests that a reduction in modulus or stiffness on the order of 8% to 10 % can be expected over five lifetimes of loading at the worst case load conditions. Based on these tests it is concluded that the CS coil passes the stiffness based verification criteria.*

7.3.1.5 Verification Based on Crack Size

At the end of 30000 cycles the acceptance criteria specifies that crack length be within certain limits specified in section 3 of this report. At the end of the verification testing sample A1 was sectioned for a third time to verify that the physical crack growth is within allowable limits. Figure 7.9 shows the section after one lifetime of mechanical loading.

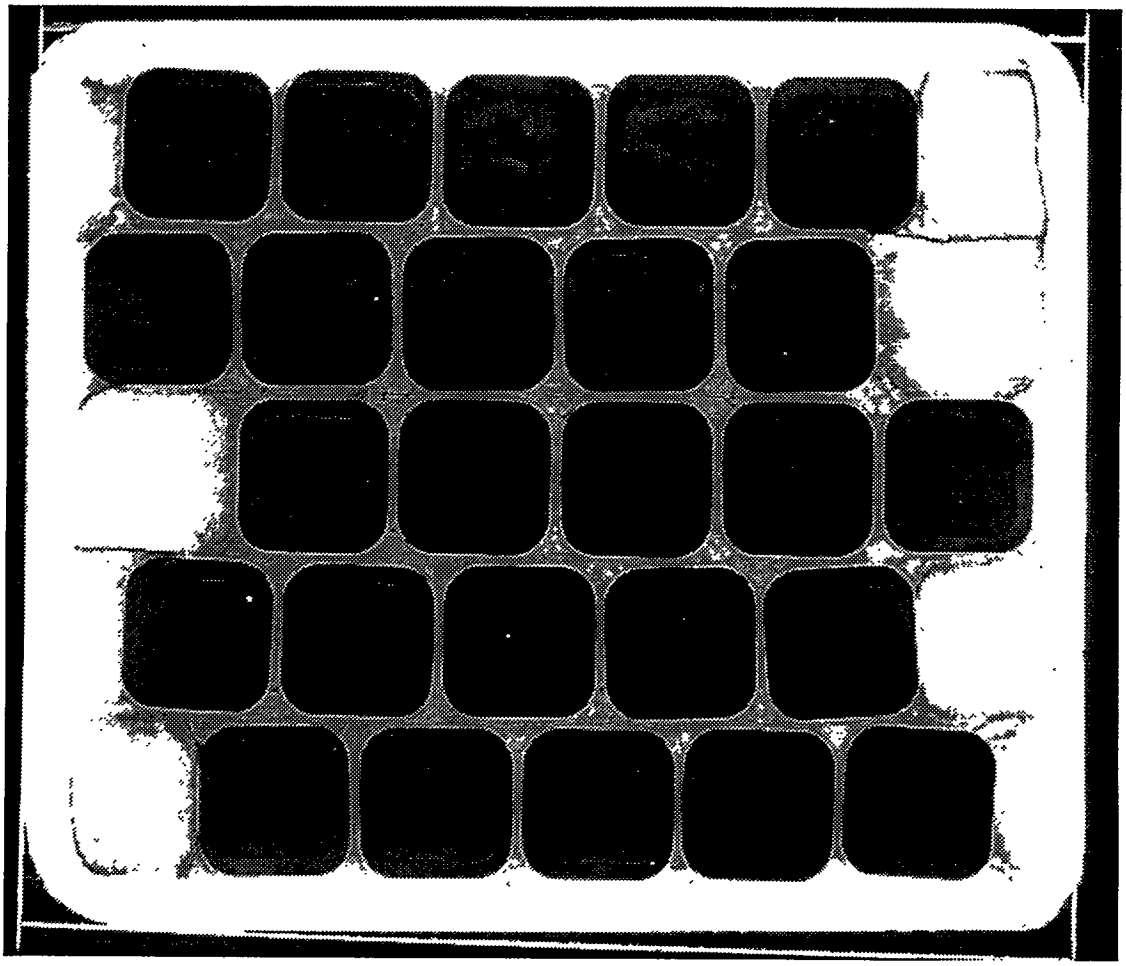


Figure 7-9 Sample A1 - Section 3 - After 31000 Compressive Load Cycles.

The cracking observed at the end of 31000 mechanical load cycles is worse than that which can be observed following the thermal cyclic testing although close observation is necessary to determine this from the back lit samples. Some of the areas that appear to be cracked show no surface indications. Surface indications tend to appear in areas where very crisp lines can be seen. This crisper look is more prevalent in the compressively loaded samples and observations of the surface indicate more cracks come appear at the surface. The nature of the composite with distinct boundaries tend to cause the appearance of cracks where none appear to exist under surface lit conditions. Observations that appear to disappear on subsequent figures may not be actual or they are cracks not extending very far along the length of the conductor. Areas that progressively deepen in color from section to section and become more distinct are likely important.

Observations of the samples indicate that the cracks do not appear to penetrate the conduit wrap or ground wrap. This suggests that the electrical integrity should not be compromised. The ground wrap and conduit wrap show very little distress. Some minor distress may be appearing in the conduit wrap on the lower right hand corner of the right most conduit in row 1. The ground wall wrap in the upper right corner is starting to show interlaminar distress. Neither of these effects show in the thermal section and both worsen in later sections. By contrast with the thermal samples a larger number of vertical cracks run through the filler (cruciform) area after the mechanical cycling and many cracks which appear on the thermal sample become crisper and grow vertically.

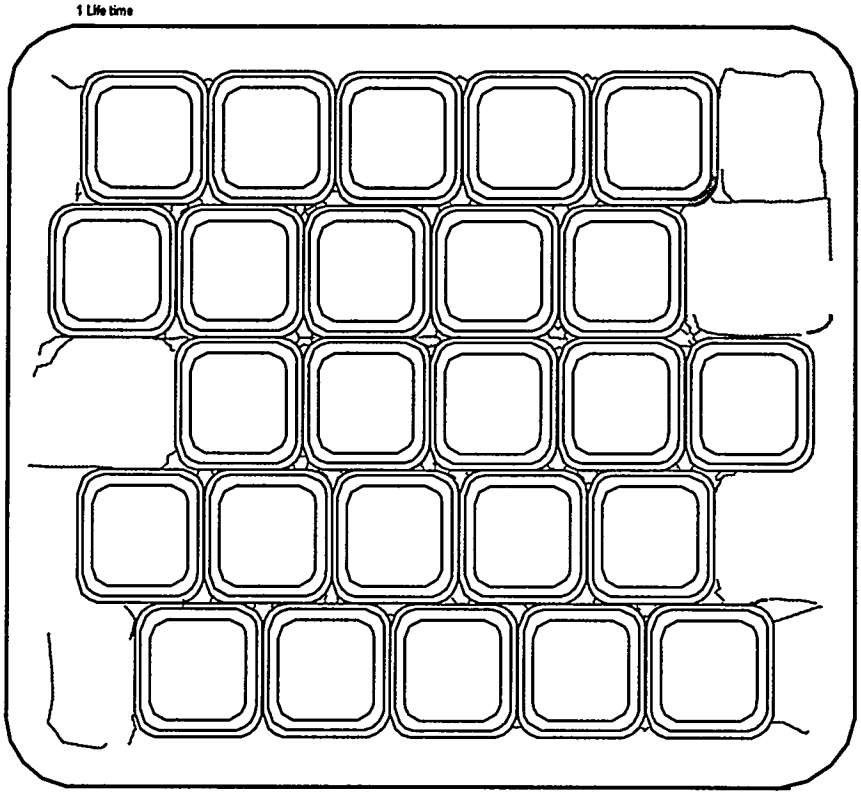


Figure 7-10 Characterization of cracking in - sample A1 - section 3 The cracking present does not violate the rules set forth in section 3 and the structure appear to remain mechanically robust. Figure 7.10 is intended to characterize the cracking observed from the section A1-3.

Figure 7.11 shows a back lit photo of sample A1, section 4, taken after 155000 cycles or 5 lifetimes. All of the effects observed in the previous sample section (after 31000 cycles) show up here and appear have become slightly worse. The characterization given for the previous sample applies to this sample also.

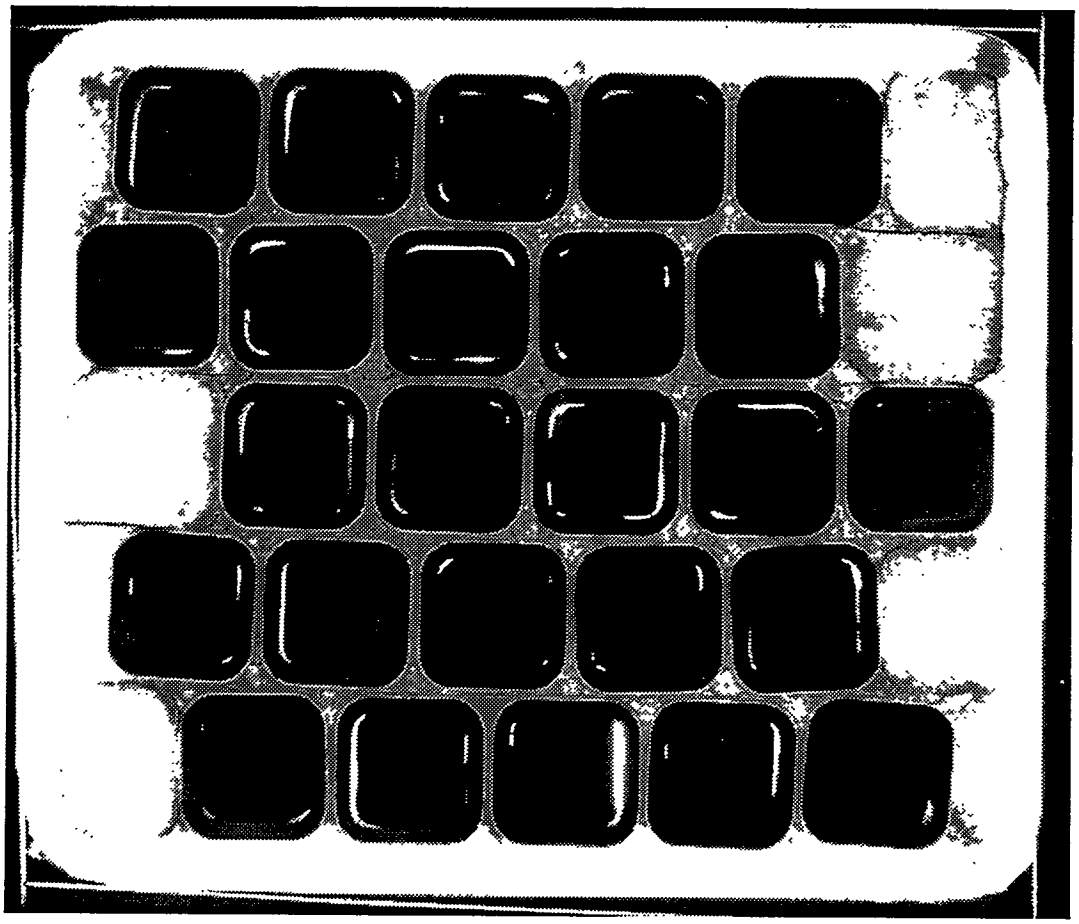


Figure 7-11 Sample A1 - Section 4 - After 155000 Compressive Load Cycles.

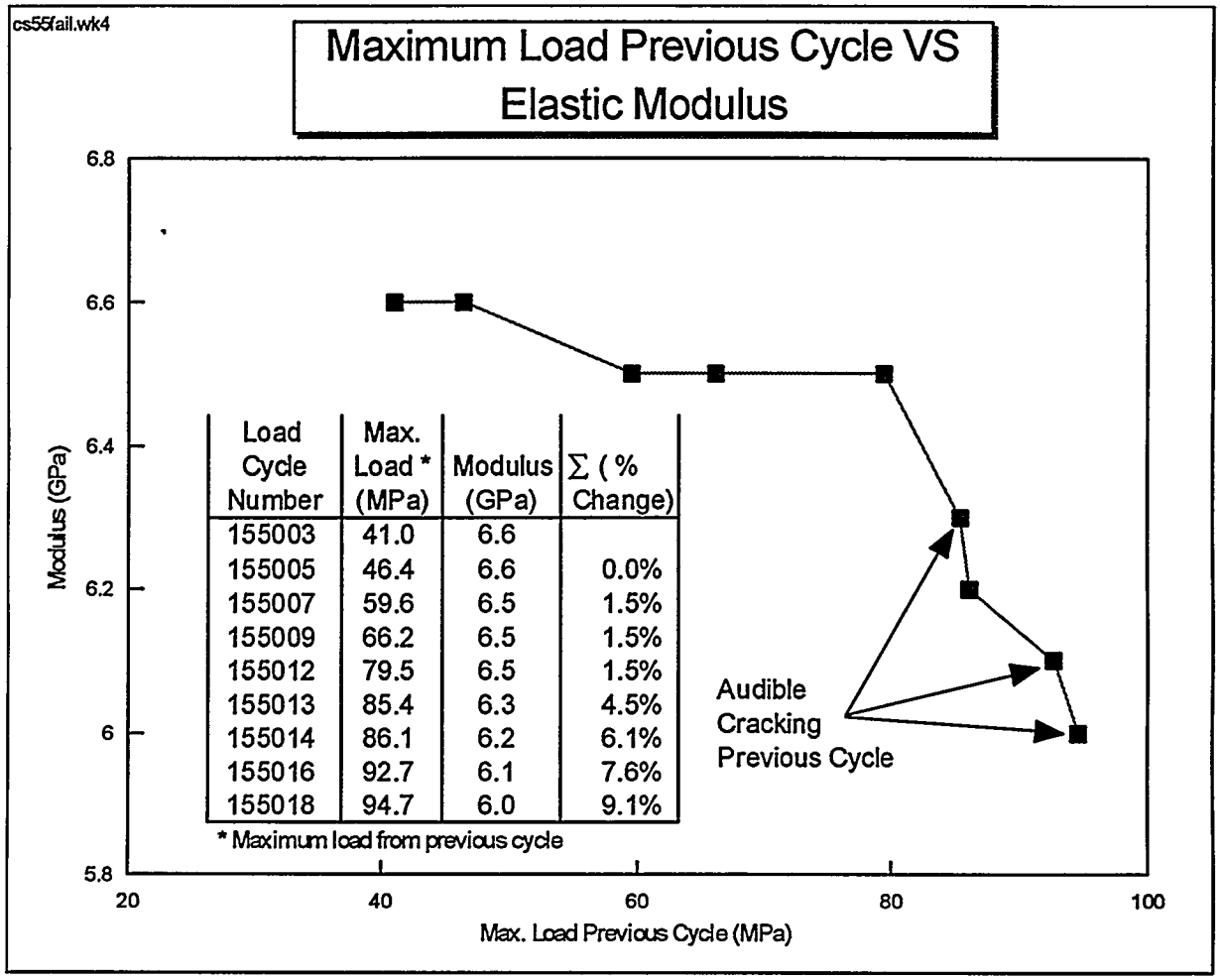
7.3.1.6 Results of Mechanical Load to Failure.

The results for the change in mechanical modulus as a function of mechanical compressive cycles is presented in the previous section. Over five lifetimes of cycling between 14 MPa and 41 MPa a slow drop in modulus of about 8 to 10% is observed.

As the load is increased the deterioration occurs more quickly. Figure 7.12 shows how the modulus is affected by the load during the previous load cycle.

These results were obtained from the last section of sample A1. This sample had been cycled for five life times prior to it being sectioned down to 51 mm which was its length throughout this test series. The data was obtained by increasing the load every one to two cycles while recording and visually monitoring the load deflection curves. The results indicated no change in performance until a level of approximately 60 MPa was reached. At that point a 2 % change in modulus was recorded dropping the modulus to approximately 6.5 GPa. The load deflection results remained fundamentally linear with no notable irregularities. No permanent set could be found with the deflection plot which appeared to return to the start point.

The modulus remained at the 6.5 GPa level until a load of 80 Mpa was imposed on the sample. At the 80 MPa loading level (cycle 155012) an audible cracking could be heard accompanied by a noticeable flat spot in the load deflection curve. The deflection associated with the cracking noise was about .09mm (.0035"). A permanent set of about half of this value was recorded at the end of the cycle. This same type of event occurred on the 155015th and 155017th cycles at 86 and 95 Mpa respectively. The deflection associated with the cracking noise at 86 Mpa was about .09mm (.0035") but at 95 Mpa the deflection went to .27 mm (.011") before being stopped by rapid removal of the load. About .09mm of permanent set was recorded. The sample is considered to have failed at this load as it appears incapable of carrying higher load and appears to reacts with large permanent sets to loads of 95 Mpa or above. Cycle 155018 was only taken to a little over 60 MPa for the purpose of recording a modulus.



Load Cycle Number	Max. Load * (MPa)	Modulus (GPa)	Σ (% Change)
155003	41.0	6.6	
155005	46.4	6.6	0.0%
155007	59.6	6.5	1.5%
155009	66.2	6.5	1.5%
155012	79.5	6.5	1.5%
155013	85.4	6.3	4.5%
155014	86.1	6.2	6.1%
155016	92.7	6.1	7.6%
155018	94.7	6.0	9.1%

Figure 7-12 Maximum Load Previous Cycle VS Elastic Modulus

After the testing was complete the sample was sectioned and polished. The section revealed that cracks which were closed but visible on the surface of previous samples were opened a discernible amount. Figure 7.13 shows the final section of sample A1 with backliting. Review of figure 7.13 and the sample show significant damage. Vertical cracking extends over several conduit heights, however, the cracking is interrupted. Furthermore, the sample is still structurally capable of bearing the design load as was evidenced by load cycle 155018 and based on the observation that cracks do not penetrate the conduit wall insulation load would probably operate electrically. Figure 7.14 shows a sketch of crack patterns from the failed sample.

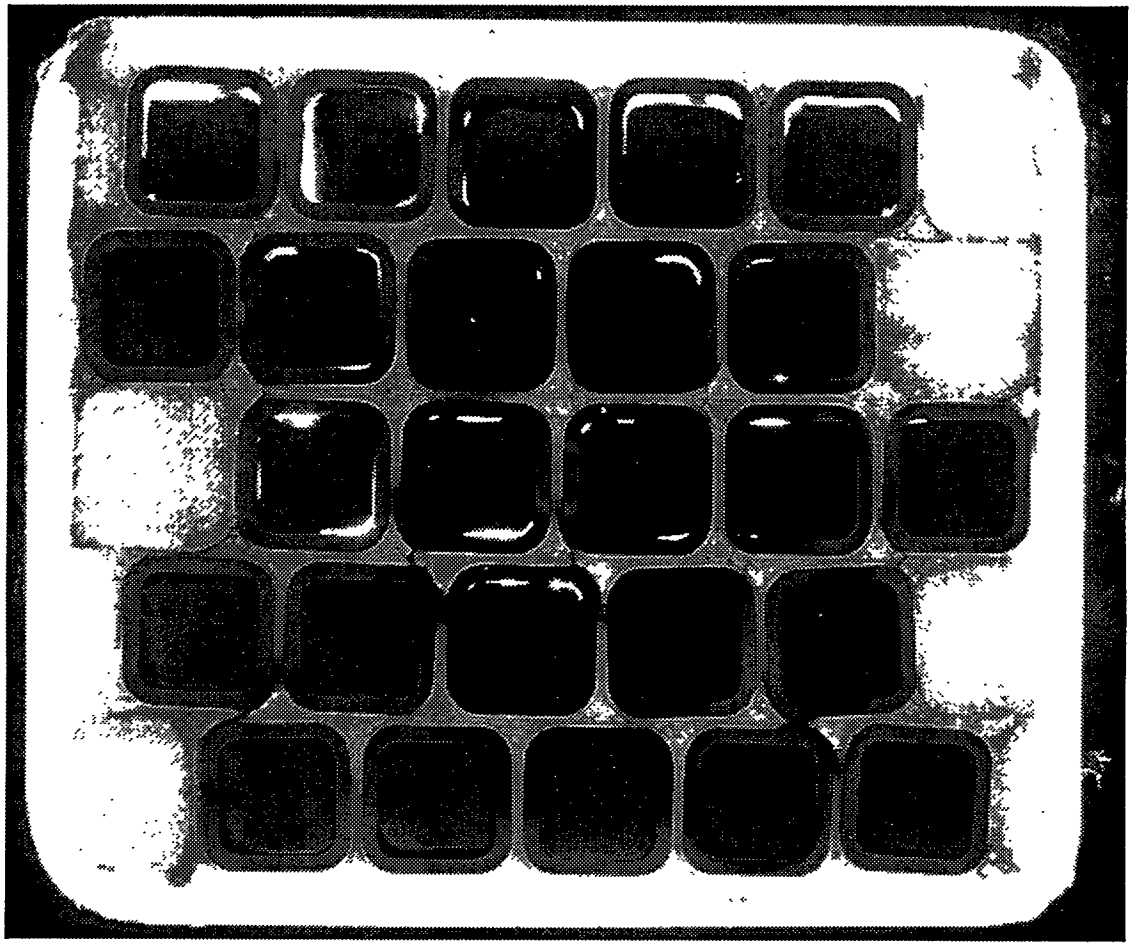


Figure 7-13 Sample A1 - Section 5 - After Compressive Failure

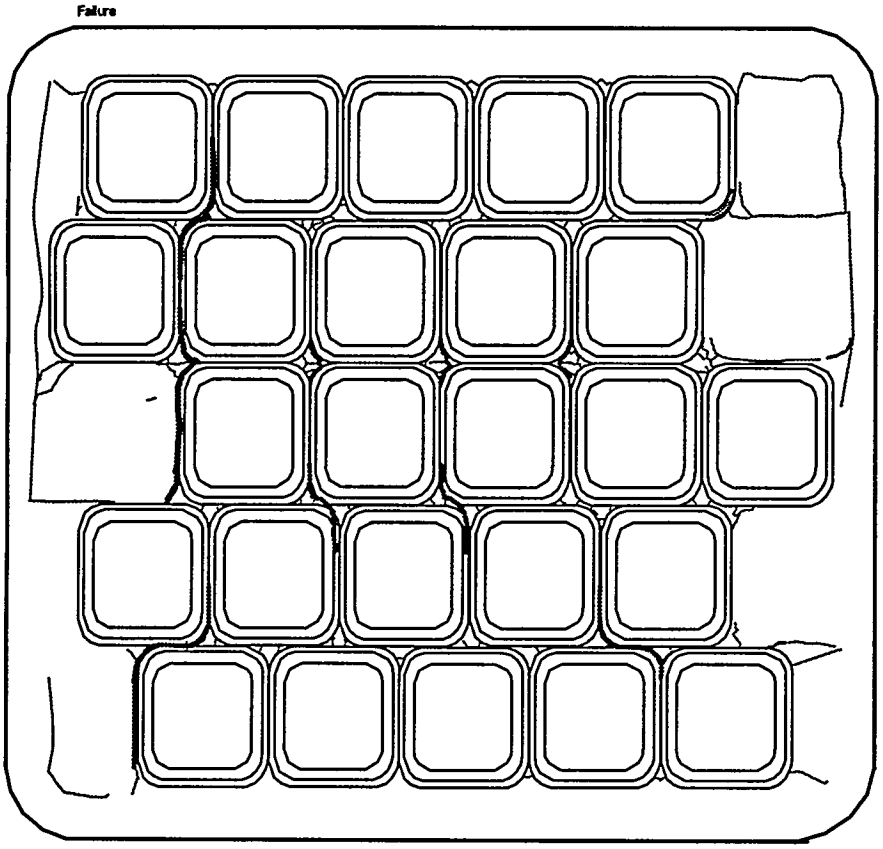


Figure 7-14 Characterization of cracking in - sample A1 - section 5

7.3.2 TF 5x5 Compression Tests

Two TF 5x5 samples were prepared for testing as described in Table 7.1. These were samples B1 and B2. Only the B2 sample was tested. This is the electrical TF coil sample which is has 150mm long conductor. The B1 sample was held in reserve in case an alternative test was decided upon based on results from the CS testing and TF electrical rests.

7.3.2.1 Testing setup and Preparation

When received for mechanical testing the top of the sample has been identified and marked as indicated in section 6. Alignment in the mechanical test fixture is possible only in one direction. Figure 7.14 shows the sample prepared for test.

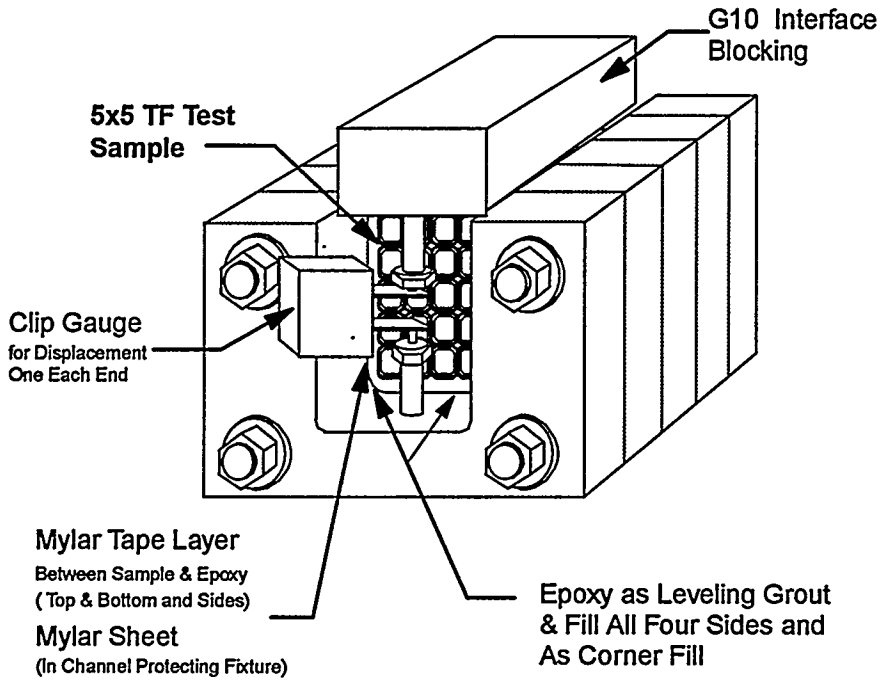


Figure 7-15 TF 5x5 Sample Prepared for Testing

The sample is prepared for compression testing by placing it in the test fixture and attaching 0.076m (3 inch) thick G11 test sample interface blocks to the top. G11 material is selected as it will act as an elastic foundation against the sample.

The test sample is grouted into the test fixture using epoxy as grout to level the surfaces and to provide fill between the sample and the fixture. The sample is a loose fit to the fixture without the grout. Mylar tape and Mylar sheet are used so that the sample can be removed from the fixture without damage to either. They also provide a known boundary condition during test. The same type of epoxy is used that is used in the CS 5x5 test. The blocks are then adjusted using a metal gauge to assure that their faces are parallel to each other. The epoxy is then allowed to set for about an hour before the sample is placed in the test rig and cycled

slowly up to the preload level. After the epoxy has initially set up to a plastic state, the test sample is placed in the test apparatus and aligned in the platens of the apparatus. Figure 7.5 from the CS write up shows the general test setup and the accompanying text describes the setup and information recorded. The information recorded, the method used for leveling the sample, and the general test procedure are identical to that discussed in section 7.3.1.

7.3.2.2 Compressive Load Testing

The testing reported on here was done on the B2 sample which was not sectioned but was used for electrical test. Two series of tests were performed one to 6000 cycles which is one lifetime then one to 24000 cycles which added four lifetimes for a total of five lifetimes of mechanical loads on this one sample.

B&W has conducted analysis which was discussed in section 4 of this report. Based on the result of the analysis B&W has recommended that a compressive pressure load of 36 MPa or a deflection of .022 in (.55 mm) be applied to the B2 sample.

Table 7.4 lists the compressive loads that were designated for the TF 5x5 samples. Only the 6 inch length was tested. The loads applied to the TF coil had effectively zero steady load with the entire loading being applied and released each cycle. In practice a load of a 4kN (1000 lb.) was maintained as a minimum.

Table 7-4 Vertical Compressive Loads Applied During TF 5x5 Testing

	Test Loads					
	Steady Load bias		Alternating Ld.		Peak loads	
Sample length	Lbf	MN	Lbf	MN	Lbf	MN
8 inch = 203 mm	1000	0.004	221900	0.987	222900	0.991
6 inch = 150 mm	700	0.003	163600	0.728	164300	0.731
4 inch = 102 mm	500	0.002	110900	0.493	111400	0.495
2 inch = 51 mm	200	0.001	55500	0.247	55700	0.248

Test Load = Pressure x Sample Length x Width of flat on top or bottom of sample

Steady Pressure =	23	psi	=	0.16	Mpa
AlternatingPressure	5198	psi	=	35.8	Mpa
Total Pressure =	5221	psi	=	36	Mpa
Coil Width (flat) =	5.335	inches	=	0.136	meters

Deflection results appeared to respond in a non linear fashion. Total measured deflection was slightly higher than predicted. Calculated deflection was .56mm(.022") and measured was .67mm (.026") typical.

7.3.2.3 Results of Mechanical Verification and Life Testing

Two mechanical measures are applied to the results of the tests to determine the adequacy of the coil results. First the coil stiffness is not to change by more than 10% over one lifetime of cyclic loading and second the cracking in the coil samples must comply with the acceptance criteria set forth in section 3 of this report. Because only the B2 sample was tested and no sectioning was performed only the change in stiffness criteria will be applied to the TF coil.

Mechanical Compressive Stiffness of the TF Coil

Because the modulus in place of the stiffness is reported for the CS coil it will likewise be reported for the TF coil. The definition for the modulus is discussed in section 7.3.2. The only difference will be that the entire width of the PF coil is used in the calculation.

The moduli determined from the test are recorded in table 7.5. While load and deflection were recorded down to .16 MPa the nonlinearity at the very low end of the cycle appear to introduce a good deal of variability into the results therefore the reproted stiffness is based on the data between 1.6 MPa to 36 Mpa. The modului reported reflect the slope of a line between these two points except for the final entry which reflects a line tangent to the curve at the 36 MPa level. The

results indicate an that an initial drop in stiffness occurs as the sample is cycled then an increase. The increase in stivffness between cycle 6000 and 6001 is likely due to variation in the test set up as this occurs after the sample is refit in the fixture after the electrical tests which occur between cycles 6000 and 6001. The increase over 30000 cycles could be drift in the test equipment or wearing out of some soft elastic components in the coil or test setup.

Table 7-5 Stiffness From Compressive Tests of TF 5x5 Coil

TF 5X5 Stiffness Tabulation

	Stiffness from 1.6 MPa			
Number of Cycles	Sample Length	Elastic Modulus GPa	% Decrease in Elastic Modulus	Total % Decrease in Elastic Modulus
20	6	7.7		
6000	6	7.1	8.7%	8.7%
6001	6	7.4	-5.0%	4.2%
31000	6	7.9	-6.7%	-2.2%
Tangent @ Max Load	6	10.0	-26.8%	

Based on the test results it is concluded that a decrease in stiffness of less than 10% takes place before 6000 cycles and little change takes place over the remaining five lifetimes. Based on this conclusion the TF coil passes the stiffness acceptance criteria.

7.3.3 3x2 Bending Tests. (Sample #C1&C2)

The finite element results[11] indicate that the load verses deflection is relatively linear with load and at a load of 106N the peak stress is 285 MPa. At this load the deformation at the point of load application is 3.78 mm (0.149 in.) The deformation predicted by subtracting the deformation at the support point from the deformation at the point of deformation is 2.2 mm (.088 in). This analysis assumes that the conduit will slip relative to the insulation. Based in the above performance the load and deflection that is desired during test is:

[11] Hannan, W.F., 3x2 Verification Test Sample Finite Element Analysis

7.3.4 3x2 Bending Tests

Two 3x2 samples were prepared for testing as described in Table 7.1. These were samples C1 and C2. Only the C2 sample was tested. This is the electrical TF coil sample which is has 150mm long conductor. The C1 sample was not tested because the results of the C2 tests indicated that the desired stresses in the insulation were not being achieved. The original purpose envisioned for this test was to develop the outer fiber bending stress and the interlaminar shear stress that are calculated for the worst case coil bending. Stress calculations indicated that these values were low and this test defaulted to attempting to match the worst case longitudinal (z) stress in the CS coil conduit wall insulation. Questionable results from strain gage data and reduced emphasis on this test caused the tests on the second sample to be placed on indefinite hold.

7.3.4.1 Testing setup and Preparation

The samples were prepared by attaching two pieces of instrumentation, a strain gage and a piece of foil for dielectric testing. Figure 7.16 shows the sample and infers the test loading.

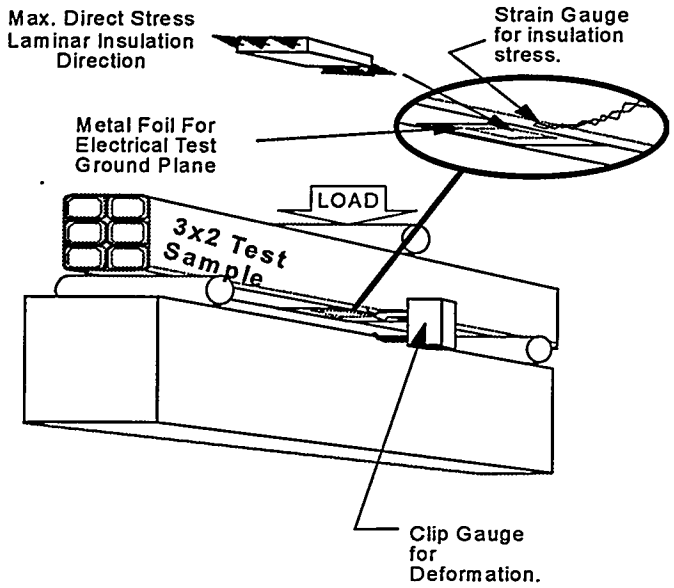


Figure 7-16 3x2 Sample Prepared for Testing

The sample is tested under liquid nitrogen in the same container as the 5x5 tests. A smaller load compression machine was used because of the smaller loads however the test setup is fundamentally the same as described for the CS 5x5 test. The sample is arranged as a three point bending specimen. A deflectometer is mounted beneath the sample at the center

in order to measure the maximum deflection.

7.3.4.2 3x2 Bending Tests.

The finite element results[12] indicate that the load verses deflection for the 3x2 is relatively linear with load, and at a load of 106N the peak stress bending stress is 285 MPa. The deformation is predicted by subtracting the deformation at the support point from the deformation at center of the span. This analysis assumes that the conduit will slip relative to the insulation. This indicates that the deformation at the load shown above should be is 2.2 mm (.088 in). Based in the above performance the load and deflection that is desired during test is can be calculator as shown below:

Target Direct Stress =	220 MPa :	31908 psi
FEA Calculated Dir. Str.=	285 MPa	41336 psi
FEA Calculated Load =	106 kN	23830 Lbs
FEA Calc. Deformation =	2.2 mm =	0.087 in.

Target Load:

$$\frac{220}{285} \times 106 = 81.82 \text{ Mpa} = (11868 \text{ psi})$$

=

Target Deformation:

$$\frac{220}{285} \times 2.2 = 1.698 \text{ mm} = (0.067 \text{ in})$$

Two sets of tests were run on the 3x2 sample both times 31000 cycles were run. The results are shown in table 7.6

[12] Hannan, W.F., 3x2 Verification Test Sample Finite Element Analysis

in order to measure the maximum deflection.

7.3.4.2 3x2 Bending Tests.

The finite element results[12] indicate that the load verses deflection for the 3x2 is relatively linear with load, and at a load of 106N the peak stress bending stress is 285 MPa. The deformation is predicted by subtracting the deformation at the support point from the deformation at center of the span. This analysis assumes that the conduit will slip relative to the insulation. This indicates that the deformation at the load shown above should be is 2.2 mm (.088 in). Based in the above performance the load and deflection that is desired during test is can be calculator as shown below:

Target Direct Stress =	220	MPa =	31908	psi
FEA Calculated Dir. Str.=	285	MPa	41336	psi
FEA Calculated Load =	106	kN	23830	Lbs
FEA Calc. Deformation =	2.2	mm =	0.087	in.

Target Load:

$$\frac{220}{285} \times 106 = 81.82 \text{ Mpa} = (11868 \text{ psi})$$

Target Deformation:

$$\frac{220}{285} \times 2.2 = 1.698 \text{ mm} = (0.067 \text{ in})$$

Two sets of tests were run on the 3x2 sample both times 31000 cycles were run. The results are shown in table 7.6

[12] Hannan, W.F., 3x2 Verification Test Sample Finite Element Analysis

Table 7-6 3x2 Test Results

	Load kN	Deflection mm	Stiffness kN / mm	Conduit Wrap Laminar (Z) Ins Stress ①
Calculations:				MPA
FEA Analysis (Non Bonded)	106	2.2	47.6	285
FEA Analysis (Bonded)	369	1.9	196	362
Hand Calc. (Non Bonded)	79	1.6	49.4	220
Hand Calc. (Bonded)	270	1.3	215	220
Actual LN2 Tests	Applied Load	Measured Deflection		Per Strain Gauge E = 25e9 Pa
Test Series 1	89	1.0	91.0	52.6
Test Series 2	127	1.5	83.9	76.8

① Target stress is 220 MPa. based on 120% of 183 MPa PDR Baseline Max Vert Compression

The results from the bending tests indicate that the sample is behaving in a manner which is stiffer than would be expected for a sample where the conduit wall insulation is not bonded to the conduit wall, but more flexibly than a bonded sample. This is not surprising. However the results from the strain gauges are unexpected and there are several possible explanations. The gauges could be in error, the gauges could be affecting the insulation strain locally, the insulation could be behaving poorly locally or friction between the conduit wall and the insulation may be inhibiting insulation strain in areas where the amount of insulation strain relative to the conduit is small such as at the center of the sample.

The cause of the problem was not determined when it became clear that a thorough investigation of this test exceeded the time and funding available. No detrimental effects were revealed by this test and the sample was tested electrically after the cyclic loading reported here.

8. ELECTRICAL TEST RESULTS

This section summarizes the electrical testing results for the 3x2 and 5x5 models. The electrical acceptance testing was discussed in Section 5, and the voltage test levels presented in Table 5.3. After receipt of the models from Everson Electric electrical connection holes were drilled in the central end conductors with the brass plug inserts and throught the conductor walls for all turns on the periphery of the test samples. Banana plug leads were used to make connections to adjacent turns and turn arrays during the electrical testing.

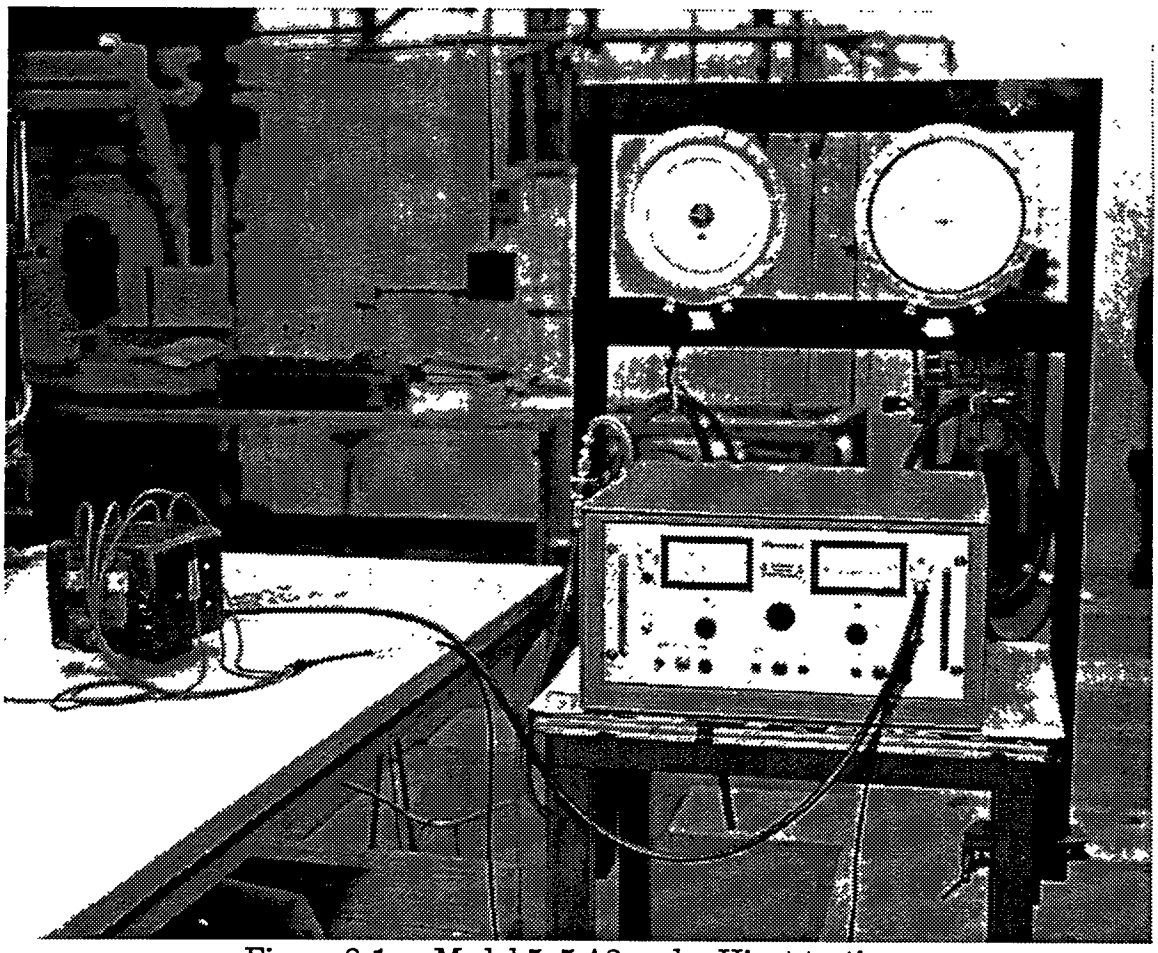


Figure 8-1 — Model 5x5 A2 under Hipot testing.

Figure 8.1 shows a photograph of the PF A2 sample under Hipot testing.

Figure 8.2 shows a photograph of the B2 sample with the copper foil electrode

installed for testing the groundwall insulation acceptance. The foil is made using a strip of copper foil, folded on the edges, and then taped down with adhesive Kapton. A lead is soldered to the foil strip for application of HV during groundwall insulation testing; the foil/groundwall insulation interface is filled with an insulating coating to reduce partial discharge activity.

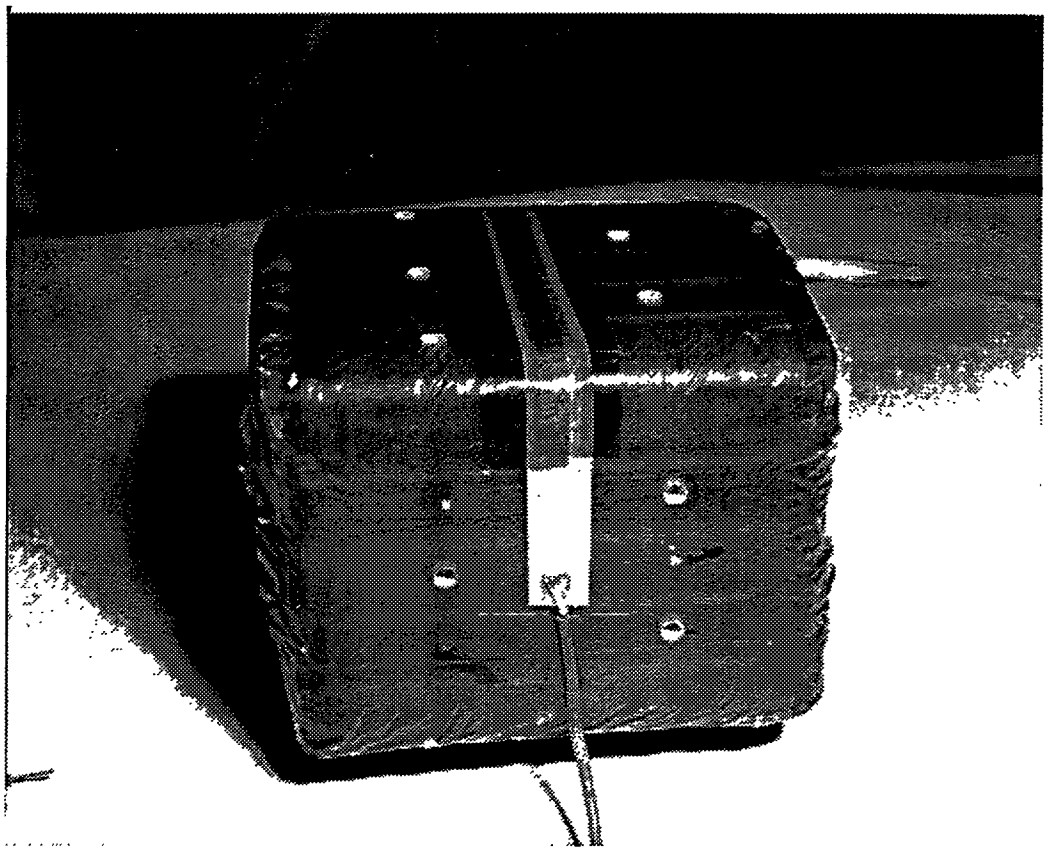


Figure 8-2 Groundplane foil electrode on 5x5 sample B2.

The dielectric characteristics were measured for all samples in the as received (AR) and at the end of all mechanical testing (EMT). The capacitance (pF) and percent (%) dielectric loss were measured at 0.1, 0.4, 1, and 20 kHz for selected turn pairs and turn pair arrays. The dielectric characteristics remained essentially unchanged from as received through all thermal and mechanical cycling loads. A summary of the EMT dielectric characteristics is presented in Table 8.1 for selected electrical connections.

The normalized capacitance per turn per mm (pF/mm) was estimated from the total measured capacitance by dividing by the number of full adjacent turn-to-

turn spaces represented by the electrical connections and by the conductor length. The A2 PF model has slightly lower capacitance as expected due to the offset of adjacent turns within layers which leads to a reduction in capacitance. The dielectric loss was less than 0.5 % in all cases and tended to be highest for the A2 PF models due to the slightly higher stress expected in a larger fraction of the corner void filler region.

Table 8-1Measured Dielectric Characteristics at 20 kHz

SAMPLE	ELECTRICAL CONNECTIONS		CAPACITANCE		DIELECTRIC LOSS
	HV	GD	pF	pF/mm	%
A2	8	2,3,4,7,9, 11,12,13	220.3	0.37	0.49
	18	12,13,17, 19,22,23	201.2	0.34	0.48
B2	13	7,8,9,12,14 17,18,19	240.4	0.40	0.39
	7	2,6,8,12	235.8	0.39	0.40
C2	3,4	1,2,5,6	522.9	0.46	0.37
	1,3,5	2,4,6	389.1	0.43	0.37

The electrical connections used in Hipot testing of the A2 and B2 to ensure testing of every turn pair are presented in Table 8.2 with the conductor numbering correlated to Figure 6.1. For the CS C2 bending model all 7 turn pairs represented by the 3x3 array were tested. For groundwall testing the foil electrode was placed at HV and all adjacect conductors on the periphery of the model were grounded.

Table 8.3 summarized the acceptance testing for the 3x2 and 5x5 electrical models for selected connections, which were chosen because they had the highest partial discharge activity. The 5x5 and 3x2 models passed all Hipot, partial discharge, and AC life acceptance testing as required, both in the as received condition (AR) and at the end of all thermal and mechancial cyclic load testing (EMT). No failures of any kind were recorded, including any external lead faults

and/or end turn creep faults. In fact, Hipot testing was performed for all turn pair and turn array connections shown in Table 8.2 without failure of any kind. As can be seen from Table 8.3 the partial discharge activity at 6 kVrms at 60 Hz did increase generally after mechanical testing was complete. The Foil test in the case of the bending models was performed at reduced voltage levels, that is 4 kV for Hipot and 3 kVrms for AC life testing, since the 3x2 models have no groundwall and the foil is separated from the adjacent conductors by only the thickness of the conductor insulation wrap, that is nominally 0.81 mm. The AC life testing for the groundwall foils for the 5x5 models was tested at 10 kVrms as per the acceptance criteria.

Table 8-2 Electrical Connections for Hipot Testing A2 and B2 Samples

SAMPLE A2		SAMPLE B2	
HV	GD	HV	GD
12	8,11,18,13	13	8,14,18,12
7	2,8,11,6	7	2,8,12,6
9	4,13,8	9	4,10,14,8
17	11,18,22,21	17	12,18,22,16
19	13,23,24,18	19	14,20,24,18
2	1,3	4	3,5
4	3,5	2	1,3
22	21,23	6	1,11
24	23,25	16	11,21
18	23,22	22	21,23
8	3	24	23,25
1	6	20	25,15
FOIL	ALL ADJACENT	10	15,5
		8	3
		18	23
		12	11
		14	15
		FOIL	ALL ADJACENT

Following final mechanical testing and the successful completion of the electrical acceptance testing, the Hipot residual or margin capability of the turn-to-turn and groundwall insulation for the 5x5 models was measured by taking the insulation to failure up to 40 kV withstand. As in all Hipot testing, the leakage current trip on the power supply was set at the 50 μA level. Table 8.4 summarizes the Hipot failure results. The A2 PF model had turn failures from 21-33 kV with 40

kV withstand for the groundwall insulation foil test. The B2 model had turn failures from 24-33 kV with external failure at the ground foil edge of 32 kV. In all failure cases the failure mode was due to external lead-to-lead or lead-to-foil electrode faults or due to internal faults at the ends of the model which were clearly observed by visible discharges within the end insulation turns. No internal failures were recorded which did not envolve the end turns. Therefore, the insulation turn-to-turn is better than 20 kV and the ground insulation better than 30 kV after all thermal and mechanical load cycles.

Table 8-3 Summary of High Voltage Test Results for Selected Connections
(Where: AR=As received; EMT=End of Mechanical Testing)

SAMPLE	CONNECTIONS		HIPOT 10 kV, 50 µA		PEAK PARTIAL DISCHARGE, pC 6 kVrms		AC LIFE 6 kVrms, 15 min	GROUNDWALL HIPOT 16 kV	
	HV	GD	AR	EMT	AR	EMT	EMT	AR	EMT
A2	18	ALL	P	P	3200	4000	P	-	-
	8	ALL	P	P	3000	3000	P	-	-
	FOIL	ALL	-	-	125	800	P 10kVrms	P	P
B2	13	8,12, 14,18	P	P	1200	2000	P	-	-
	7	2,6,8, 12	P	P	800	1000	P	-	-
	FOIL	ALL	-	-	NT	2600	P 10kVrms	P	P
C2	1	2 or	P	P	-	-	-	NA	NA
	4	3	P	P	-	-	-		
	6 or	2, 3, or 6	P	P	-	-	-		
	3	5	P4kV	P4kV	-	-			
	FOIL	1,2	-	-	120	2500	P 3kV		
	FOIL	5,6	-	-	200	700	-		
	1,3,5	2,4,6	-	-	-	-	-		
	3,4	1,2, 5,6					P		

Table 8-4Hipot Failure of A2 and B2 Samples after all Mechanical Testing

SAMPLE	CONNECTIONS		HIPOT FAILURE (50 μA)	FAILURE MODE
	HV	GD	kV	
A2	7	2,11,16	21	EXTERNAL LEAD
	9	4,13,8	25	EXTERNAL END
	2	1,3	32	INTERNAL END
	4	3,5	31	INTERNAL END
	8	3,12	28	EXTERNAL END
	1	6	33	INTERNAL END
	FOIL	ALL	40	WITHSTAND
B2	13	8,14,12	27	EXTERNAL LEAD
	7	2,8,6,12	24	EXTERNAL LEAD
	9	4,10,14,8	27	INTERNAL END
	4	3,5	33	INTERNAL END
	2	1,3	26	INTERNAL END
	6	1,11	30	INTERNAL END
	10	15,5	26	EXTERNAL END
	8	3	26	INTERNAL END
	12	11	27	INTERNAL END
	14	15	24	INTERNAL END
	FOIL	ALL	32	EXTERNAL FOIL EDGE

9. CONCLUSIONS

The following conclusions are reached based upon the results of the Large Scale mechanical and electrical verification test program of the CPDR electrical insulation system for the TPX magnet coils.

Mechanical Cracking Criteria

Sample A1, 5x5 CS model had very little visible cracking in the as received condition. After 19 thermal cycles in liquid nitrogen significant crack formation was visible. Many of the crack patterns seen throughout the tests appear to initiate during the thermal cyclic loading and grow significantly during subsequent compressive loading. The acceptance criteria set forth in Section 3 provides limits on crack length and location at the end of 30,000 cycles.

Observations of cracking in the CS 5x5 coil sample A1 after 31,000 mechanical cycles indicates that:

1) No cracks appear to penetrate into the glass epoxy coil over wrap (outer ground wall) or extend into the glass epoxy conduit over wrap (conduit wall insulation). This satisfies mechanical acceptance criteria 2.

2) Most of the cracks appear to be localized in the filler or cruciform area and they do not extend between the conduits beyond the filler area and none approach the unit cell limit as described in section 3 and figure 3.1. As result the sample passes mechanical acceptance criteria 3.

All of the observed cracking is well inside that allowed by the acceptance criteria. *Therefore, the CS models pass all of the mechanical acceptance criteria regarding crack size and location. Beyond acceptance at 31000 cycles the samples pass the crack criteria after five lifetimes of mechanical compressive loading although the coil acceptance criteria does not require this.*

Mechanical Stiffness Criteria

From mechanical compressive stiffness measurements of the A1 and A2 5x5 CS models it appears that given the worst case loading the decrease in modulus during the expected lifetime will be significantly less than the ten percent after 31000 cycles allowed by the acceptance criteria. The data suggests that a reduction in modulus or stiffness on the order of 8% to 10% can be expected over five lifetimes of loading under worst case load conditions. Actual measurements indicate about 8% loss of stiffness at 155000 cycles. *Therefore, based on the test data the CS coil model passes the verification criteria for stiffness.*

From the mechanical compressive stiffness measurements of the B2 5x5 TF model it appears that this coil like the CS coil experiences a small decrease in stiffness of about 8%. The reduction appears to take place over the first 6000 cycles with little no reduction indicated in the following 24,000 mechanical load cycles. *This coil like the CS passes the acceptance criteria at both 1 lifetime and after 5 lifetimes although by the goals of the criteria it needed to pass only at 1 lifetime.*

Therefore, the CS and TF models pass all of the mechanical stiffness acceptance criteria for which they were tested. Furthermore, they not only pass at one life tine as required but also after five lifetimes.

Mechanical Strength

No criteria has been established for mechanical strength, however, tests were conducted on the CS 5x5 coil samples which evaluate that behavior. The results of those tests indicate that at the end of five liletimes the coil can withstand approximately two times the peak operating load before significant damage begins to occur and can withstand 225% of operating load before limits are reached.

Electrical Acceptance Criteria

The 3x2 C2 and 5x5 A2 and B2 samples passed all Hipot, partial discharge, and AC life cycle electrical acceptance criteria as set forth in Section 5 in the as received condition and after completion of all thermal and mechanical cyclic loading tests. *The CS and TF 5x5 samples and CS 3x2 bending samples met all electrical acceptance criteria without electrical failure of any kind, including electrical lead and/or model end conductor faults. The 5x5 models had residual Hipot capability of >20 kV for all turn pairs and >32 kV for the groundwall insulation as determined in Hipot failure testing following completion of all mechanical testing at the end of the program.*

Based on the mechanical and electrical testing criteria the mechanical and electrical integrity of the coils for the TPX magnet system is adequate to meet the rigors of the worst case loading conditions for the lifetime of the coil and indications are that the CS coil which is thought to have the worst case loading has a margin in excess of 5 on life and 2 on mechanical load.

Therefore it is concluded that the coil system will perform adequately both structurally and electrically at the prescribed loads for its intended life.

?

TDS Page

Distribution List

Science & Technology Center

*A. Melissaratos, 801-3C54
Library (3)

* TDS Page Only

TPX Magnet Helium Stub Manufacturing R&D

R. J. Hillenbrand, P.A. Sanger, G. Swartzback, and W. Urban
STC Advanced Electromechanical Systems Department

August 18, 1995

TPX 14-950818-WEC-JHillenbrand-02

APPROVED:

P.A. Sanger
Westinghouse TPX Chief Scientist

APPROVED:

D. R. Potter
Westinghouse TPX Engineering Manager

Westinghouse Electric Corporation
Electronic Systems Group

401 East Hendy Avenue, Sunnyvale, California 94088-3499

CONTENTS

Page

LIST OF FIGURES ii

LIST OF TABLES ii

ABSTRACT ii

1. INTRODUCTION 1-1

2. REQUIREMENTS 2-1

3. SELECTED CONFIGURATION 3-1

4. PENETRATION OF THE CONDUIT WALL 4-1

4.1 INTRODUCTION 4-1
4.2 OPTIONS CONSIDERED 4-1
4.3 DESCRIPTION OF THE SELECTED PROCESS 4-3
4.4 TEST RESULTS & CONCLUSIONS 4-4

5. PENETRATION OF THE CONDUCTOR FOIL WRAP 5-1

5.1 INTRODUCTION 5-1
5.2 ALTERNATIVES CONSIDERED 5-1
5.3 DESCRIPTION OF THE SELECTED PROCESS 5-2

6. TPX COOLING STUB ATTACHMENT PROCESS 6-1

6.1 INTRODUCTION 6-1
6.2 ALTERNATIVES 6-3
6.3 EXPERIMENTAL PROGRAM 6-4
6.3.1 Initial Test Results *6-4*
6.3.2 Welding Trials at Arc Applications, Inc. *6-6*
6.3.3 Welding Trials at Westinghouse *6-10*
6.3.4 Demonstration Sample Welding at Arc Applications *6-18*

7. VERIFICATION TESTING 7-1

7.1 PROCESS DEMONSTRATION 7-1
7.2 CRITICAL CURRENT SAMPLES 7-2
7.3 HYDRAULIC TESTING 7-5
7.4 LEAK CHECKING 7-5

8. CONCLUSIONS 8-1

9. RECOMMENDATIONS 9-1

APPENDIX A 9-2

LIST OF FIGURES

FIGURE 1-1 HELIUM COOLING STUB 1-1
FIGURE 3-1 SELECTED APPROACH 3-2
FIGURE 3-2 DIMENSIONS OF HELIUM COOLING STUB AND HEADER USED FOR TEST. 3-4
FIGURE 4-1 CONDUIT PENETRATION WITH A ROTO BROACH TOOL. 4-3
FIGURE 4-2 BURR FORMING ON THE INSIDE OF CONDUIT 4-4
FIGURE 4-3 PICTURE OF A ROTO-BROACH USED FOR PIERCING THE SHEATH. 4-5
FIGURE 4-4 MICROGRAPH OF A CONDUIT PIERCED WITH A NEW ROTO BROACH 4-6
FIGURE 4-5 THE RESIDUAL BURR LEFT BY A ROTO-BROACH AFTER PIERCING AN INCOLOY 908 SHEATH 4-6
FIGURE 5-1 SCHEMATIC OF THE PREPARATION OF THE CONDUIT FOR WELDING 5-1
FIGURE 6-1 DEGRADATION BEHAVIOR OF NBTI. 6-2
FIGURE 6-2 CONFIGURATION OF INTERNAL WATER COOLED CHILL BLOCK 6-5
FIGURE 6-3 CONFIGURATIONS ATTEMPTED FOR MINIMIZATION OF CABLE TEMPERATURE 6-7
FIGURE 6-4 "T" CONFIGURATION FOR INITIAL TESTING AT ARC APPLICATION 6-8
FIGURE 6-5 WESTINGHOUSE PLACED THERMOCOUPLES 6-9
FIGURE 6-6 TYPICAL TIME TEMPERATURE HISTORY FOR T WELDING SERIES. 6-10
FIGURE 6-7 THERMOCOUPLE PLACEMENT INTERMITTENT WELDING DEVELOPMENT TESTS. 6-12
FIGURE 6-8 WELD TEMPERATURE PLOT 6-12
FIGURE 6-9 TYPICAL WELD BEAD PROFILE OF A HELIUM COOLING STUB ASSEMBLY (16X). 6-14
FIGURE 6-10 HELIUM COOLING STUB WELDMENT EXHIBITING LACK OF FULL PENETRATION, 32X 6-14
FIGURE 6-11 RECORDING OF THE CABLE TEMPERATURE AS A FUNCTION OF TIME DURING WELDING 6-16
FIGURE 6-12 SCHEMATIC OF THE LOCATION OF THE THERMOCOUPLES OF THE DEMONSTRATION COOLING STUB 6-16
FIGURE 6-13 TEMPERATURE RECORDING OF THE CABLE DURING THE WELDING OF THE 316LN HELIUM COOLING STUB WITH INTERMITTENT WELDING. 6-17
FIGURE 6-14 SKETCH OF THE INTERNAL CHILL USED DURING THE WELDING OF THE HELIUM STUB. 6-19
FIGURE 7-1 THE LOCATION AND LAYOUT OF THE STRAND FOR WHICH THE CRITICAL CURRENT WAS MEASURED. THE STRAND IDENTIFIERS REFER TO THE LOCATION IN THE CABLE STARTING WITH THE LARGEST SUBCABLE INDICATED BY A LETTER. THE VIEW IS FROM THE TOP OF THE HELIUM STUB UNDERNEATH THE SHEATH. 7-2

LIST OF TABLES

TABLE 4-1 ASSESSMENT OF PIERCING APPROACHES 4-2
TABLE 6-1 JOINING APPROACHES CONSIDERED FOR THE HELIUM STUB TO CONDUIT. 6-3
TABLE 6-2 WELDING PROCESS TEMPERATURES AT THE CONDUCTOR 6-5
TABLE 7-1 MEASUREMENT OF THE CRITICAL CURRENT OF STRAND UNDERNEATH THE STUB WELD 7-4

ABSTRACT

A TPX development program was initiated to select the techniques to attach the helium cooling stub to the CIC conductor of the TPX coils, to demonstrate these techniques on two samples and to verify its performance. The techniques that were developed are as follows:

- The shape of the helium cooling stub is circular and mated to a header piece.
- The height of the stub is short enough to allow for inside inspection of the weld using a borescope.
- The conduit is pieced with a Roto Broach tool leaving a very small burr (<0.1 mm).
- The foil which is wrapped around the cable is removed by a manual process using tweezers.
- The weld is intermittent TIG welding using internal and external water cooled chills.
- The weld stub is inspected visually using a borescope.
- The ID of the stub is machined to remove 1.5 mm off the inside surface and eliminating any remaining areas of lack of penetration.
- The stub weld is leak checked with a helium mass spectrometer leak detector.
- The leak detection is speeded up using a plug with an O-ring seal in the pierced hole to isolate the cooling stub from the CIC conductor.
- The stub assembly is completed by a TIG weld between the header and the stub.

This process was demonstrated on two samples, one each of 316LN and Incoloy 908 and found to be leak tight after five thermal cycles to 77K and hydraulic pressure testing to 100 atmospheres.

1. INTRODUCTION

Helium coolant must be introduced into the CICC conductor at numerous locations in the all of the TPX coils. The He cooling stub is the junction between the helium coolant tubing and the conductor. This joint is made during the coil manufacturing process and is insulated with the coil. The location of the stub is determined by global dimensions on the coil and is attached to individual conductors as they are wound in place. When the exact location is located, the conduit wall must be breached, the conductor stainless steel foil must be pealed open and a stub assembly must be attached. Figure 1.1 shows the general appearance of the Helium Stub as it is configured at the end of the Phase I design effort.

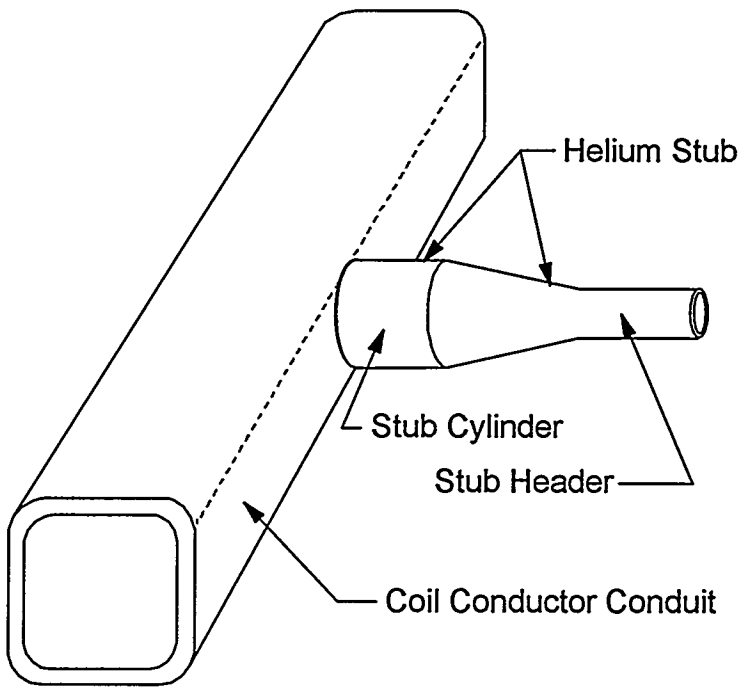


Figure 1-1 Helium Cooling Stub

The stub configuration, the method of conduit penetration, the method of removing the foil wrapper on the conductor at the penetration and the method of Stub attachment are the subject of this report. The selected methods are:

Conduit Penetration - Using a Roto Broach tool and an automated drilling rig to directly machine a hole in the coil conduit.

Foil Removal - Manually lift the foil and tear the foil against the conduit opening using tweezers or small pliers.

Cooling Stub Attachment - TIG Welding using an intermittent process

Finishing Operation- For the Incoloy 908 conduits, bore the ID of the stub to remove crack initiators on the inside of the stub

2. REQUIREMENTS

The helium cooling stub is a critical feature of the TPX coil. While providing entrance and exit for the helium coolant the configuration must also meet the following requirements:

Withstand cyclic operation operating pressure of 0-4 atm.
Withstand over pressure up to 20.0 Atmospheres.
Withstand normal load induced conduit strains.
Minimize the dead flow zone in the conductor.
Remain leak free for the ten year life of the coil.
Be inspectable.
Be compatible with the winding operation.
Be compatible with Incoloy 908 reaction heat treatment.
Not create insulation stress risers.
Be compatible with the insulation wrapping process.
Be compatible with the VPI process.
Be compatible with subsequent connections.

In addition, the process of putting the cooling stub in place must not damage the superconductor mechanically or thermally. The superconductor strands must be protected from over temperature and from physical damage during the penetration process.

In arriving at the approach to conduit penetration, stub configuration and stub attachment method, criteria were established to evaluate alternatives. The

criteria was applied to each of the aspects of the design and process. The criteria in order are:

- **Reliability** of the overall design.
- **Minimization of superconductor strand time temperature** history.
- **Leak Free** mechanical performance of the stub.
- **Inspectability** of the penetration and joining.
- **Automation Possible.**
- **Cost Effectiveness.**

3. SELECTED CONFIGURATION

The helium cooling stub assembly consists of two pieces. The first piece, the stub itself, is welded directly to the conductor conduit. The second piece, the stub header, welds to the stub. The first weld is a full penetration intermittent Tungsten Inert Gas weld. The second weld is a "full penetration" continuous TIG weld with integral backup.

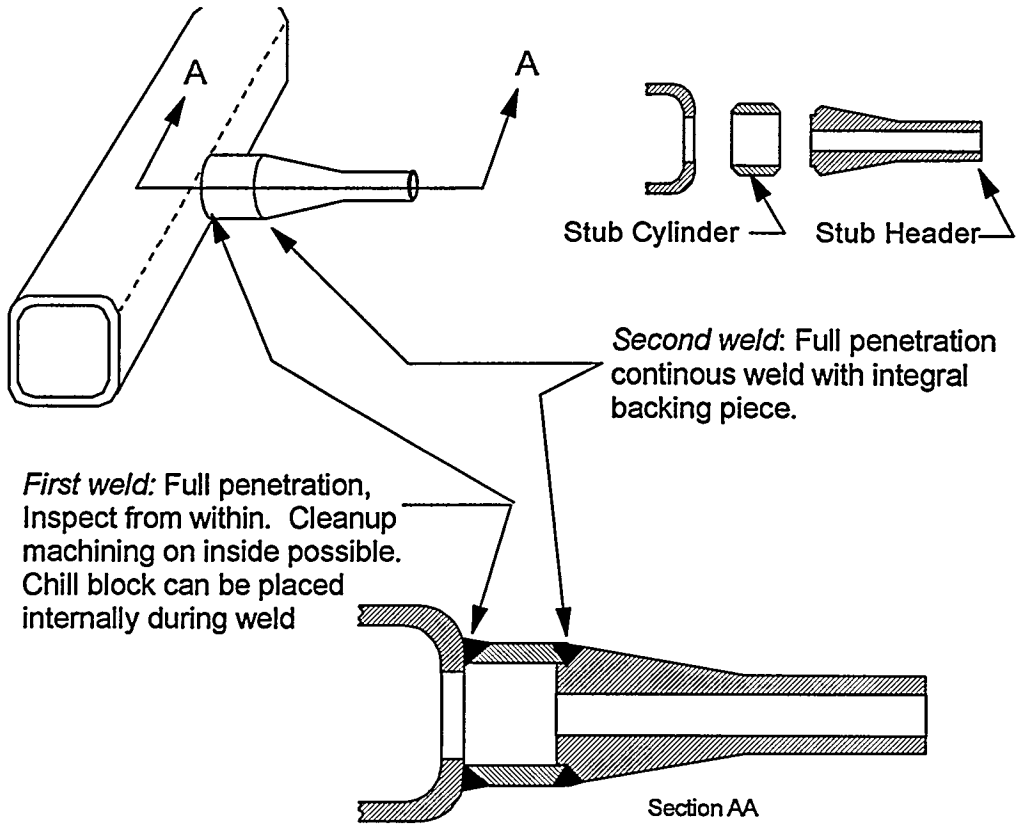


Figure 3-1 Selected Approach

Two Piece construction to allow access to the back of the weld. This allows for the use of a chill block during welding which provides direct cooling of stub cylinder and the conductor during the welding process. After completion of the welding operation, the back of the weld is inspected to determine if penetration is complete. For the Incoloy 908 conduit, this also allows the boring of the ID to remove crack initiators. After inspection, a leak check is performed. A plug is inserted through the open end of the stub cylinder to isolate the stub weld for quick and sensitive leak checking.

Smooth External Shape to facilitate insulation and eliminate external corners thereby to minimizing dielectric stress.

Tapered strain relieving header configuration relieving high cantilever root stresses which would exist at the end of the tube typically at a weld location.

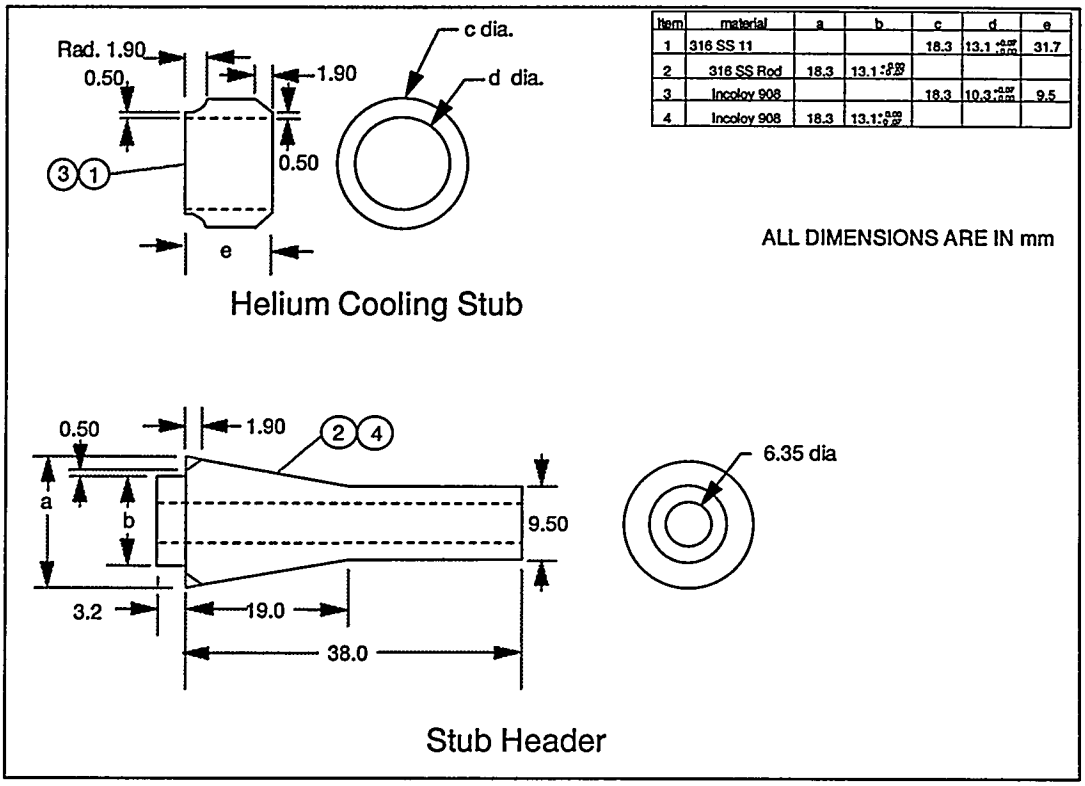
Circular geometry allowing automation of the stub header weld and tube weld using a conventional automated tube welder.

The dimensions selected for the penetration opening, the cylinder and header were varied somewhat over the course of the program. Several opening shapes were considered and multiple openings were considered. These variations were based on concerns for sufficient flow cross-section when entering the wire from the side and dead flow areas across the conductor from the entry. Review indicated that a single 9.5 mm (0.375 inch) hole was sufficient for the flow area. The issue of the dead flow area was judged to not be a problem but it should be reviewed in phase II. The diameter of the opening which was selected was the largest that accommodated a stub which set squarely on the flat portion of the conduit side. Larger diameter cylinders extended over the corner radius and required additional filler material during welding. This is undesirable because of the temperature sensitivity of the superconductor strands.

The wall thickness of the cooling stub was picked to be similar to the thickness of the conduit wall 2.41 mm (.095 in.) to provide heating balance in the parts during welding. The length of the cylinder was varied during the course of the welding experimentation and is determined by the overall piping layout work. From the standpoint of the helium stub a longer stub allows more access for cooling during header attachment but restricts access to the back of the cylinder for weld inspection. Lengths between 9.5 mm (0.375 in.) and 31.7 mm (1.25 in.) are acceptable. Figure 3.2 shows the dimensions used for manufacture of the welding test pieces. These general dimensions within the range shown will be used on the TPX coils.

The material for the stub header matches the material of the conduit, i.e. 316LN for the PF6 and 7 and Incoloy 908 for all the others. Phase transformation

in the stainless steel and stresses caused by the thermal mismatch magnified by the 650C change would be detrimental consequences of subjecting the stainless steel to the 650-700C heat treatment. Since tubing will be required for the heat treatment, it could be made of a material suited to the high temperature of the heat treat without regard for the cryogenic or magnetic properties, and welded to the stub and replaced after the reaction heat treatment.



Item	material	a	b	c	d	e
1	316 SS 11			18.3	13.1	31.7
2	316 SS Rod	18.3	13.1			
3	Incoloy 908			18.3	10.3	9.5
4	Incoloy 908	18.3	13.1			

Figure 3-2 Dimensions of helium cooling stub and header used for test.

4. PENETRATION OF THE CONDUIT WALL

4.1 INTRODUCTION

In order to introduce and vent helium from the conductor, it is necessary to place an opening in the wall of the coil conduit. Numerous methods were considered and are discussed below. In establishing the penetration method the primary consideration was minimization of the damage done to the underlying superconductor from both a thermal and a mechanical prospective.

For the selected method the coil conductor conduit wall is pierced by means of a 9.525mm (0.375 in) four fluted Roto Broach tool, with the chip breaker removed, chucked into a portable depth controlled horizontal drill. This tool is a trepan type boring tool. This boring operation takes place after forming of the conductor into the coil (but before the conduit is reacted for the Nb_3Sn coils). The drill head is attached to a drill fixture which secures the conduit to the drill assembly and both are supported so that the drill can be positioned to align with the conduit. The conductor will be protected from the boring tool in three ways. First, the depth of the drill will be digitally controlled and the operator will stop it at a certain depth. Second, a bushing in the drilling fixture will prevent the drill from going beyond a certain depth and third the tool will be configured so that it will push the plug being removed so as to depress the conductor away from the cutter. The spring pressure can be optimized to minimize the burr and maximize the separation of the cable from the back of the sheath.

4.2 OPTIONS CONSIDERED

During the development of the conduit wall penetration process, numerous methods were considered. Many were the outgrowth of suggestions offered at

technical interchange meetings. Table 4.1 contains an evaluation of the various processes. In summary numerous methods are available to effect the penetration. It is believed that the Roto Bore approach offers a simple cost effective method of penetrating the conduit and is compatible with minimal welding at the conduit and offers the best overall solution.

Table 4-1Assessment of Piercing Approaches

Approach	Advantages	Disadvantages
Roto Bore/Broach	Pushes conductor away from cut (minimum risk to conductor) Final cut made dry (no cutting fluid)	Cutting fluid should be used for first part of cut, allowing for a cleanup procedure before completing the cut
Pressure Sensitive Drill		Requires feedback system
Hole Saw		Similar to Roto Bore but higher risk since conductor not displaced
Direct Machining		Removes more metal Requires cutting fluid
Weld to Plug and Withdraw		Difficult with high strength material
Chemical Etching		Hazardous chemicals in proximity to conductor

4.3 DESCRIPTION OF THE SELECTED PROCESS

Penetration of the 316 stainless steel or 908 Incoloy conduit is made in one operation using a Hougan Roto-Broach, part number 11108 along with an arbor, part number 11088. The four flutes on the Roto-broach were reground to exclude the chamfer that blunts the point where the outside diameter and the lead cutting edge meet (it is approximately a 0.25 mm chamfer). While depth control is primarily a operator function, the drill fixture is configured to prevent the tool from going too deep and damaging the conductor.

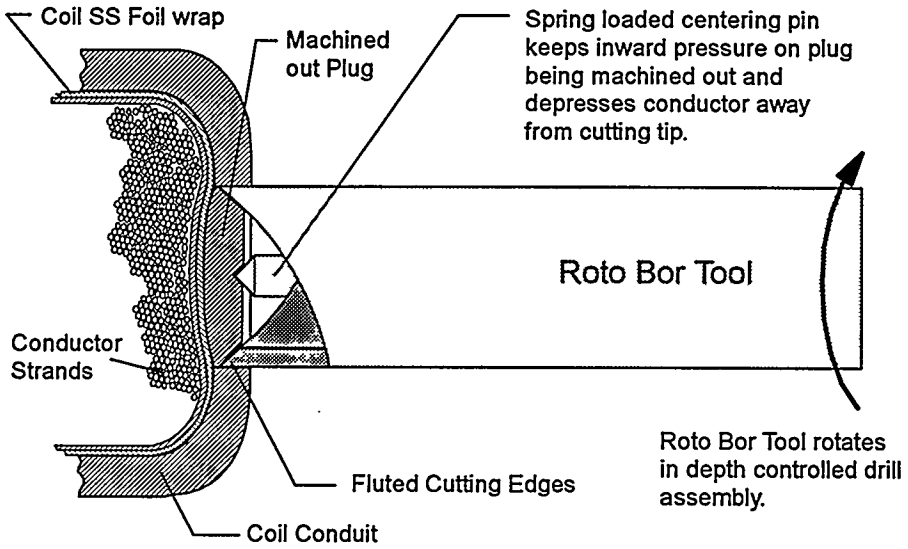


Figure 4-1 Conduit Penetration with a Roto Broach Tool.

Figure 4.1 depicts how a Roto Broach tool pierces the conduit wall. The fluted tips (4) cut away material while the spring loaded centering pin pushes the plug of material being removed down, which in turn pushes the conductor and protective foil wrap down away from the cutting tips. The center pin can be set so as to allow no more depth than the nominal wall thickness minus the bend in the plug, thereby assuring that the cutting flutes cannot touch the conductor. The spring load can also be adjusted to provide differing amounts of pressure on the plug allowing for variation in the amount of pressure on the plug and conductor controlling the

amount of depression of the plug and the underlying conductor as the tool penetrates the conduit.

Any of the operations evaluated leave some amount of burr on the inside of the conduit wall when the tool penetrates the wall. The burr is minimized by using a new sharp tool for each operation and using the correct pressure or feed rate as the conduit is penetrated. Many of the weld samples were bored using old tools which can leave a substantial burr. These samples are not representative of a well machined part. Figure 4.2 illustrates how the burr could be formed on the piece.

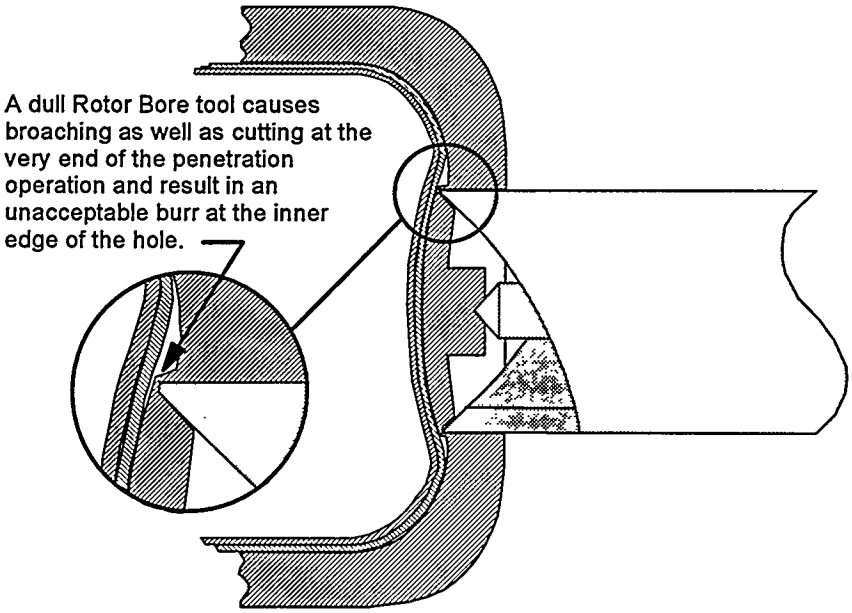


Figure 4-2 Burr forming on the inside of conduit.

4.4 TEST RESULTS & CONCLUSIONS

Several trials were made with both the Roto-Bore and the Roto Broach. It appears that either one can perform adequately. However smaller burrs were obtained recently with the Roto-Broach tool using no spring pressure and thus at

this time the selection is the Roto-Broach tool shown in Figure 4.3. Figure 6.9 shows an unacceptable burr made with a dull tool. For comparison, Figures 4.4 and 4.5 are micrographs of an extremely sharp cut with almost no burr but done without any tool pressure. Without pressure on the cable, there is only the thickness of the foil (0.05mm) as cushion for avoiding nicking the cable. Further optimization of the spring pressure will allow a tradeoff of these two competing factors. The trials indicate that a properly machined opening will have a burr of no more than 0.1 mm.

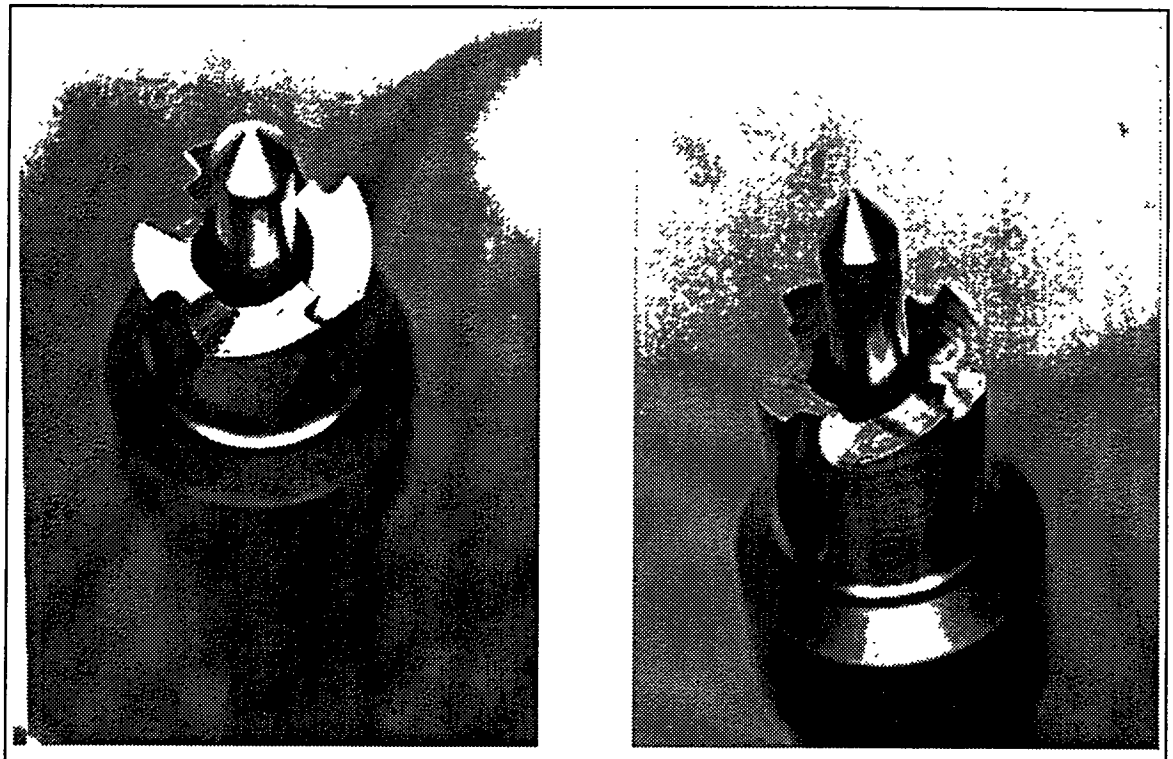


Figure 4-3 Picture of a Roto-Broach used for piercing the sheath.

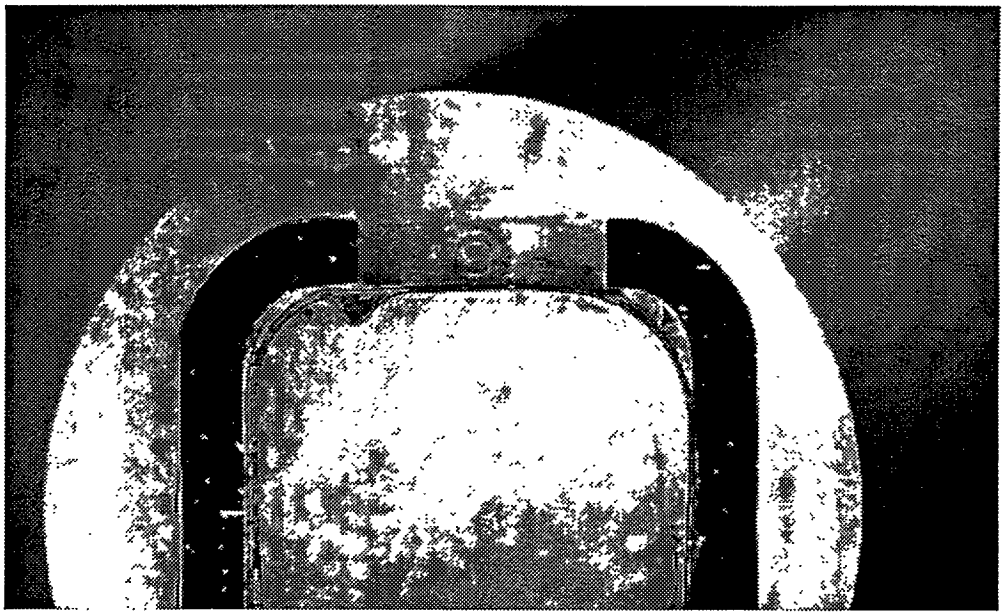


Figure 4-4 Micrograph of a conduit pierced with a new Roto Broach

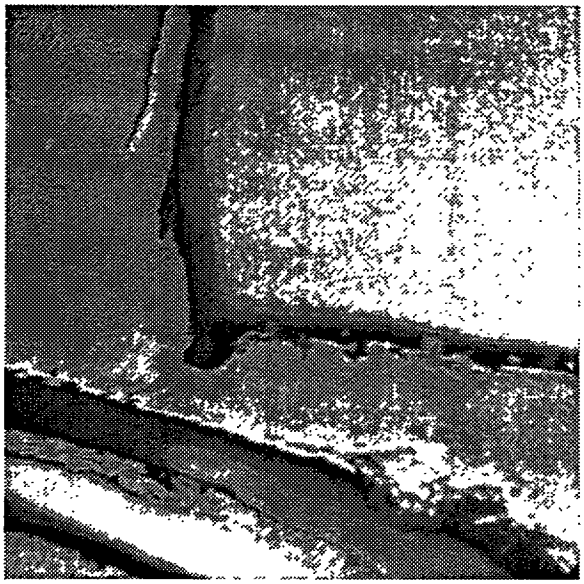


Figure 4-5 The residual burr left by a Roto-Broach after piercing an Incoloy 908 sheath

5. PENETRATION OF THE CONDUCTOR FOIL WRAP

5.1 INTRODUCTION

Inside the conduit, surrounding the superconducting strands, is a half-lapped 0.002 in (0.05 mm) stainless steel foil. This results in two layers of foil at any location.

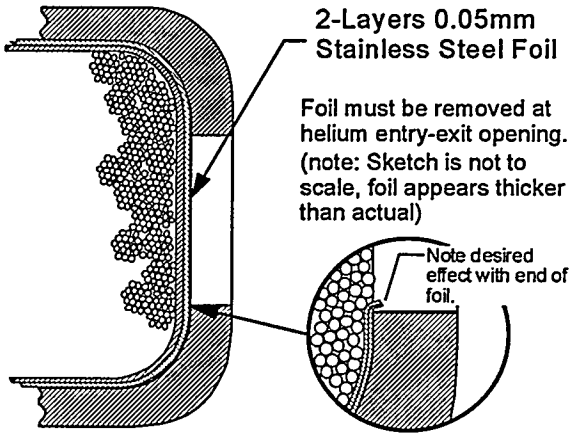


Figure 5-1 Schematic of the Preparation of the Conduit for Welding

The foil must be removed at the helium stub entry to allow the helium to pass into the superconducting strands without very large pressure drops. In addition to removal of the foil it is the objective of this procedure to leave a relatively clean foil edge and to leave enough foil at the edge of the opening to cushion the strands from the edge of the opening.

5.2 ALTERNATIVES CONSIDERED

Alternatives considered are listed below roughly in the order of preference.

1. Tweezers (manual operation)

2. Single point tool serving also as a deburring tool
3. Die with serrated razor edge or needle points with internal gas pressure
4. Diaphragm piece and blowout
5. Vacuum pulse and shock tear
6. Roughen foil to lift and grab
7. Super glue to pull foil out
8. Cold weld
9. Tweezer weld
10. Combination of glue and serrated edge.

5.3 DESCRIPTION OF THE SELECTED PROCESS

The process discussed here meets the stated requirements. The approach used during the stub attachment development process was to take a sharp scribe and carefully puncture the foil and lift an edge of the material. Then grab the edge with a gripping device such as a small pliers or tweezers and tear the material out using the edge of the hole as a shear edge. The material is easily torn roughly at the opening edge. This operation appears to be the least critical of the penetration and attachment processes. Many of the alternatives listed above could add refinement to this procedure. One of the more promising refinements would be the use of a circular array of pins which could be used to perforate the foils such that the removal process becomes a "tear on the dotted line" procedure.

6. TPX COOLING STUB ATTACHMENT PROCESS

6.1 INTRODUCTION

The helium cooling stub is attached to the coil conduit by welding. Alternative methods were considered; however, welding offers the highest reliability considering strength and leak tight performance and can be very cost effective. Tungsten Inert Gas welding (TIG) was selected because it is a highly developed process which can easily achieve most of the objectives of the joining process. The concern is the temperature of the superconductor during the welding process because of the degradation that takes place in the superconducting critical current from exposure to temperatures above 300 C. Mindful of this temperature limitation, a welding development program was undertaken with the following objectives:

1. To product gas tight, single pass, full penetration welds free of excessive concavity, cracks and porosity, etc.
2. To avoid degradation of the NbTi conductor lying directly under the weld due to excessive heating.

Concerns for superconductor damage during welding are focused primarily on the NbTi superconductor used in PF6 and PF7. However, it is known that temperature degradation can occur for the Nb_3Sn but this superconductor is much more tolerant of temperature exposure principally because it requires a long exposure to 650C to form the Nb_3Sn. By using the limits established for the NbTi to develop the helium cooling stub welding process for both types of conductor, no problems should result from the process.

Two sources exist for the data describing the damage overtemperature does to the superconductor. The first is by Schneider and Turowski[1] and reports temperature degradation vs. time at temperature. Figure 6.1 shows a plot of their data at 7 Tesla. This data suggests that it is advisable to keep strand temperatures below 300C. The second source is compliance data from Supercon Inc. for TPX superconductor and is documented in 1141-950724-LLNL. The results are significantly better indicating that the superconductor tested for TPX is less susceptible to the thermal degradation than indicated by the Schneider data. Supercon, Inc. data indicate no significant degradation at 500 C at 30 seconds and minimal degradation at 600 C for 10 seconds.

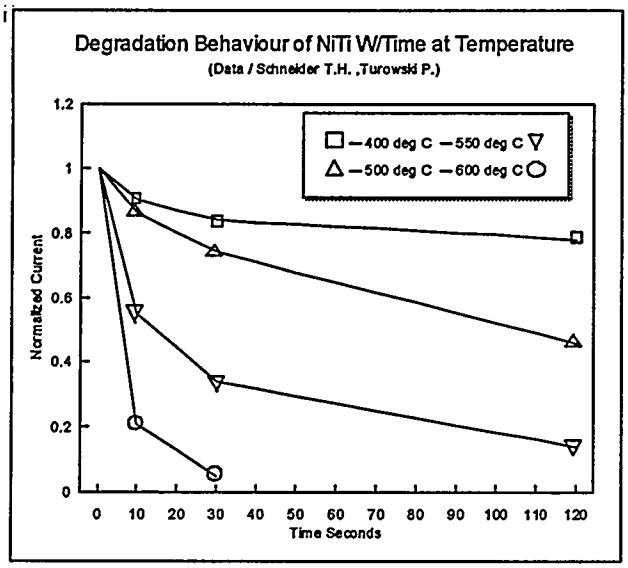


Figure 6-1 Degradation behavior of NbTi.

As a result of the above information relating to degradation of the superconductor, effort was directed toward maintaining low temperatures in the superconductor during the welding operations. The process where the cooling stub is joined to the conductor conduit received the most emphasis because of the proximity of the weld to the conductor. The second weld can be isolated from the conduit by an external chill around the cooling stub between the conduit and the second weld.

[1] Schneider, T.H., Turowski, P., Critical Current Degradation of a NbTi-Multifilament Conductor Due to Heat Treatment, Kernforschungszentrum Karlswruhe, Institut for Technische Physisik, Kurlsruhe, Germany, 9-20-93.

6.2 ALTERNATIVES

A number of joining processes were considered for joining the cooling stub cylinder to the coil conduit. Most were variations on welding. Brazing, soldering, and bonding were also considered. A list of methods is shown in Table 6.1.

Table 6-1 Joining approaches considered for the helium stub to conduit.

Approaches	Advantages	Disadvantages
Automatic TIG Weld (Pulsed)	Equipment commercially available Continuous process Moderate heat input	Orbital weld head design/development required Weld process development required
Manual TIG Weld (Pulsed)	Equipment commercially available No weld head required Intermittent process - can stop and let cool	Weld process development required Intermittent welding could introduce porosity, leaks
Laser Weld (Pulsed)	Small heat-affected zone Equipment commercially available	Orbital weld head design/development required Precise joint fit-up and beam delivery required Process development required Very expensive equipment
Ultrasonic Welding	Equipment commercially available	Material next to ultrasonic tip must be thin Butt joints are a problem Temp. at interface may reach 0.35 to 0.5 of melt point of alloy
Friction Welding a) Inertia Welding b) Spin Welding	High temperatures but fairly localized	Large amount of upset Upset on inside of weld High equipment cost Probably requires post-machining
Flash Welding Upset Welding Percussion Welding		Interface reaches melting point/heat provided by electrical arc and/or resistance heating Wider heat pattern
Cold Welding		Only works with very ductile materials
EB Welding	Equipment commercially available Small heat-affected zone	Extensive development required High cost Non-vacuum EB requires head to be within 3-5 cm of weld
Soldering		Flux required Low temperature solders have low strength
Brazing		Not recommended for 908 alloy (could be used with 316 alloys)
Epoxy		Poor strength, poor reliability

6.3 EXPERIMENTAL PROGRAM

6.3.1 Initial Test Results

Programs were undertaken at Westinghouse STC and at Arc Applications, Inc. in York, Pa. Westinghouse STC focused on welding of the 316 stainless steel which is the conduit material for the PF6 and PF7 and Arc Applications focused on welding of the Incoloy 908 used for the other coils. Three test series were undertaken. The initial tests were conducted at Arc Applications, Inc. to establish the conductor temperatures that would result from continuous welding of the cooling stub to the conduit and the temperature which would result from building up material prior to joining the stub to the conduit. Based on high temperatures from these initial tests a second series of tests were conducted at WSTC to develop an intermittent process. The intermittent process appears to work well with both alloys but better with the stainless steel with its lower viscosity weld puddle. These first two test series used conduit containing "dummy" copper conductor. A third series of tests was run to demonstrate a process for both the Incoloy 908 and the 316 LN materials and to expose NbTi superconductor to welding temperatures for evaluation of loss of Ic. This was run at both WSTC and Arc Applications, Inc.

Table 6.2 shows the temperatures from the first two test programs. Figures 6.4, 6.1and 6.8 show the locations of the thermocouples during the various tests. The early tests indicated no way to make a continuous full penetration weld while maintaining the desired low temperature. This was true of both the Incoloy 908 and the 316 SS. Example 1 and 2 in the table are indicative of the best results from the 908 tests. The first set of experiments at Arc Applications indicated that water chilling, represented in Figure 6.4, made a significant difference in the time that the conductor is exposed to the maximum temperature. However, the peak temperature was not affected significantly. During these tests performed at Arc Applications some additional chill blocks were placed on the sides of the conduit and some argon gas was passed through the conductor. Additional detail appears below.

Table 6-2 Welding Process Temperatures at the Conductor

Examples ↓ Process		Peak Temp. deg C.	Time ab 350 deg
1 Continuous TIG butt weld.	①	580	252
2 Cont.TIG w/chill blocks @ conduit, header and cond.	①	518	11
3 Low heat input weld buildup.(just buildup)	①	486	70
4 Intermittent welding process w/ center block.	②	186	0

① Tests performed at Arc. Applications York Pa.
② Tests performed at WSTC

After confirming the results obtained by Arc Applications using stainless steel, two things were tried to reduce the temperature. The first was to use a pulsed power supply and the second was to use a intermittent welding technique. The pulsed power supply did not have a significant effect but the intermittent welding did. The intermittent welding gives the chill more time to pull out the heat allowing the sample to cool between heat applications. These experiments were the most successful in maintaining low temperatures in the conductor. These tests utilized a

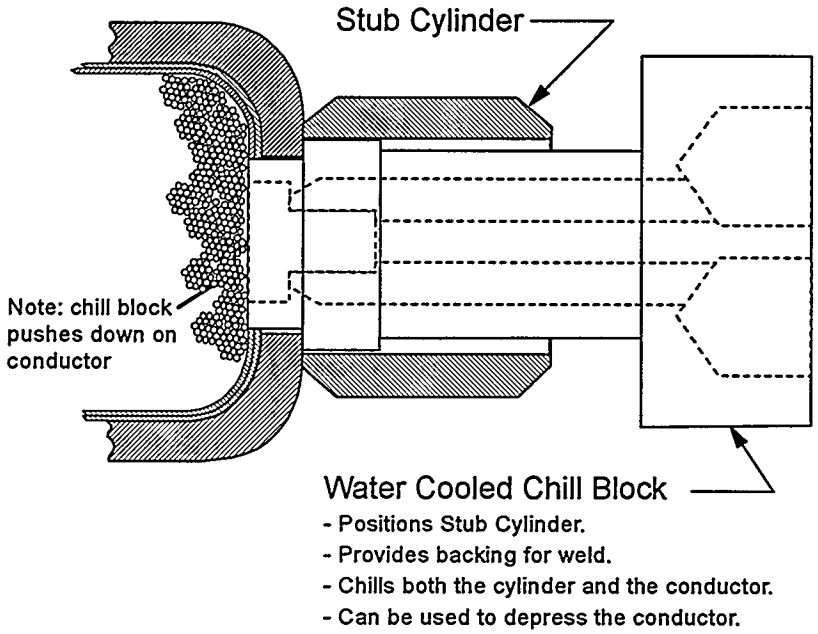


Figure 6-2 Configuration of Internal Water Cooled Chill Block

chill as pictured in Figure 6.2 but did not utilize external chill blocks.

In terms of the temperature measurements, the third series of tests using the superconductor did not appear as successful as the second series because of the location of the thermocouple.

6.3.2 Welding Trials at Arc Applications, Inc.

The first experiments were conducted on Incoloy 908. Their purpose was to gain an understanding of the temperatures which the conductor might see during the welding of the stub to the conduit.

None of the efforts were highly successful. One characteristic of Incoloy 908 is an extremely viscous weld puddle. As a result the weld does not flow well and penetration becomes a problem. In addition the thermal conductivity of this alloy is poor and thus concentration of the heat in the puddle becomes a problem. Manual welds were made on coupon tests but they lacked fusion in some areas and showed some drawbacks. Automation of the process was attempted but no set of parameters could be found that would perform the weld. Based on these tests a strategy was developed to obtain a more sophisticated process which would result in a better weld while limiting the temperature of the superconductor. In addition the stub configuration shape was changed to a round cylinder to better facilitate eventual automation of the process. Prior to this a rectangular shape had been considered. The weld configurations shown in Figure 6.3 depict the methods recommended.

The process which had been developed, while less than completely satisfactory, was felt to create representative temperatures and was used to develop characteristic conductor temperature information. The configuration of the sample used for these tests is referred to as the "T" configuration and is shown in figure 6.4. The configuration involved attaching a L shaped Incoloy part to a 4" long section of

Incoloy 908 conduit filled with "dummy conductor" and instrumented with thermocouples. "Dummy conductor" is soft copper which is used to simulate the superconductor during early tests. These tests were run to establish data showing the actual thermal cycle that the cable experiences during attachment welding.

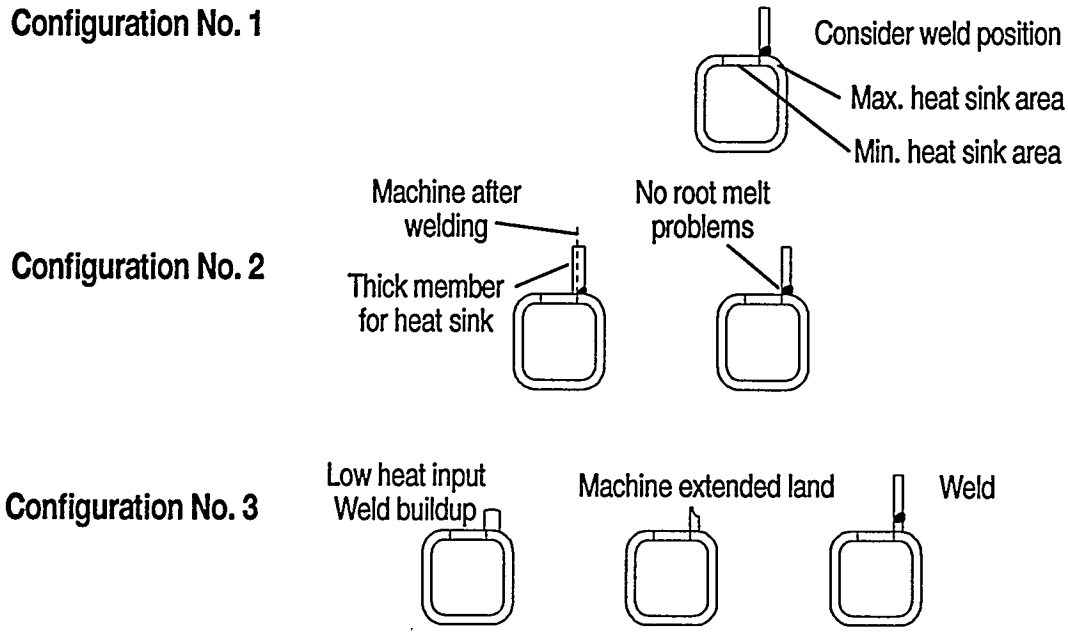


Figure 6-3 Configurations attempted for minimization of cable temperature

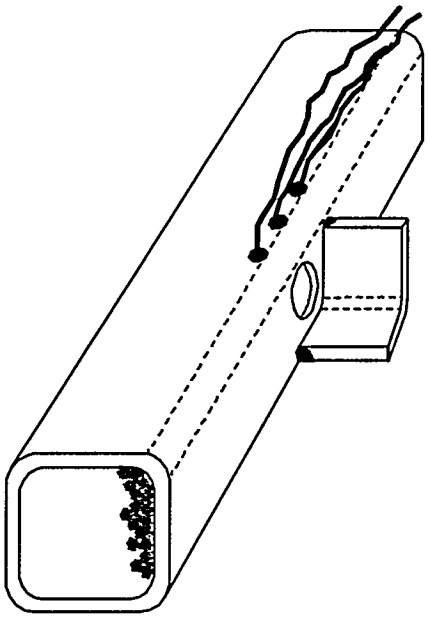


Figure 6-4 "T" configuration for initial testing at arc application

A series of welds were made to model a direct square "T" stub to sheathing attachment. A weld build-up deposit was also run for comparative purposes. Considered to be conservative test models, the thermal cycles experienced by the cable during welding showed the following average peak temperatures:

Average Peak Temperature ºC	Weld Type	External Cooling
578	"T" Attachment	No Cooling
510	"T" Attachment	With Cooling
486	Weld Build-up	No Cooling

Cooling rates varied but were, in general, shown to be slowed by increased ambient temperatures. External cooling blocks did not promote significant reductions in time at temperature, but tests suggested that improved cooling could be effective by increasing cooling rates. Figure 6.5 shows the location of the

thermocouples during this test series. Their location are very important in interpretation of the results.

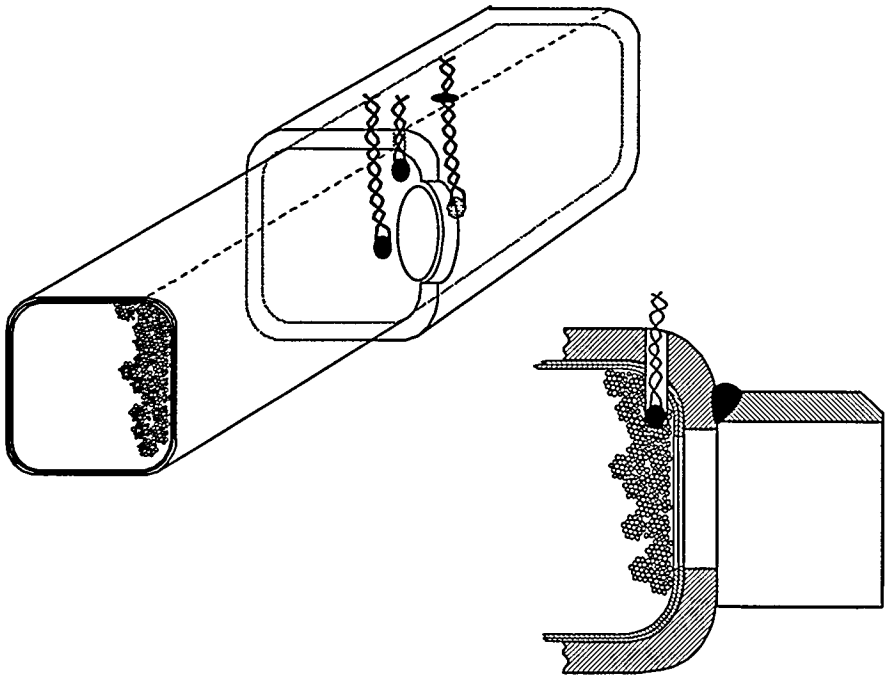


Figure 6-5 Westinghouse placed thermocouples.

Figure 6.6 shows the temperature during the first welding trial. The thermocouple was not embedded into the cable but simply placed on the conductor from the opening. The sketch on the plot shows the location of thermocouple. This was the worst time/temperature history recorded during this test series and is presented as a typical behavior. No cooling was used during this particular trial and it did not represent the best settings for the process. Additional detail is available in the report from Arc Applications attached as Appendix 1.

The test series showed that thermal cycles were fairly consistent and that the "T" attachment averaged higher peak temperatures than build-up deposits. While peak temperatures did not seem to be affected by external cooling, additional work is required to determine the best methods for reducing peak and time at temperature profiles.

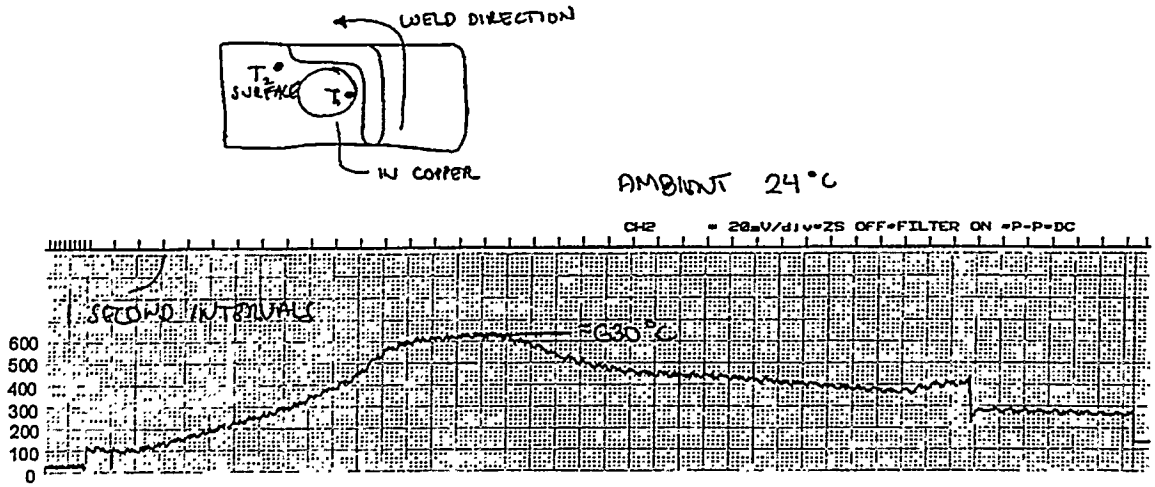


Figure 6-6 Typical time temperature history for T welding series.

6.3.3 Welding Trials at Westinghouse

The initial tests performed on the 908 Incoloy samples indicated that a lower temperature process had to be developed particularly for the stainless steel conduit which contains NbTi superconductor. Ultimately an intermittent process was developed which had a significant effect on time/temperatures histories. These welds are considered to meet the requirements of the process

Weld procedure specification, GWS950726 (attached in Appendix 2) describes the weld process. Briefly, the gas tungsten arc welding process is used to place overlapping, intermittent weld beads around the cooling stub. The assembly is allowed to cool for one minute between successive weldments. Low heat inputs are used to minimize heating of the underlying NbTi conductor. A water-cooled copper chill is used to quench the conductor and to provide backing for the weld. The conductor is also cooled by the flow of argon through the conductor during welding. The gas is free to flow up the stub between the copper chill and stub wall to provide shielding

for the underbead. During test runs, thermocouples were placed in mock-up conductors with copper filaments. The final parameters are shown below.

INTERMITTENT WELD PREPARATION & PROCESS

Weld Preparation

Initial Cleaning - Scotch Bright Pad, Alcohol Wipe
Interweld Cleaning - Wire Brush
Groove Design - J-Prep w/.0508mm land

Weld Process

Gas Tungsten Arc Weld, 70 Amps, 11.5 Volts
Single pass, intermittent, full penetration, overlapping weld
H2O Cooled Copper Chill 1.9 l / min 0°C
Filler - 0.9mm dia ER308L
Inert Gas - Argon 570 l / min.
Electrode - 1.6mm Dia., 2% Thoriated
Time delay between welds @ 1miniute
Weld Length @ .4.76mm (15 sec)
Internal Purge Gas - 280 l / hr. Argon

Figure 6.7 shows the location of the thermocouples during this test. These thermocouples, placed 2.8, 6.0 and 9.0 mm below the conductor sheath and directly under the weld line, recorded maximum temperatures of 155°C, 165°C and 190°C,

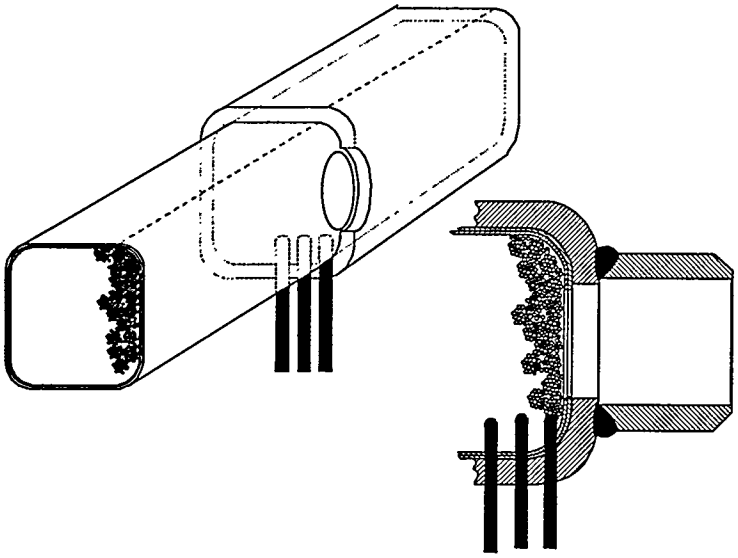


Figure 6-7 Thermocouple placement intermittent welding development tests.

Chart Speed - 2 min. / major div., Max.Temp. - 186 deg. C

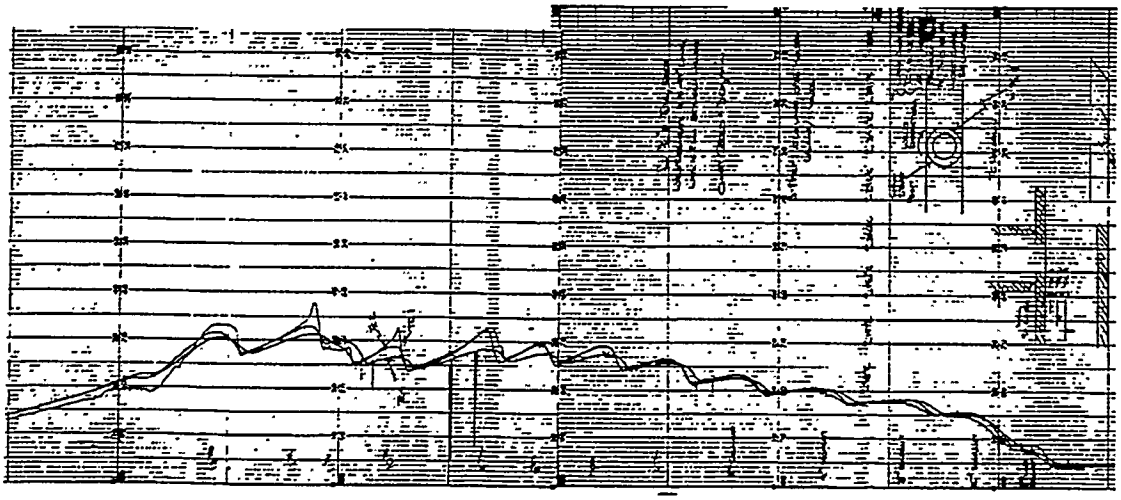


Figure 6-8 Weld temperature plot.

respectively. Extrapolating to the foil surface under the sheath indicates temperatures of the top layer of fibers may not exceed 300°C. However, electrical testing of actual NbTi components is required to verify that degradation has not occurred. Figure 6.8 above shows the time/temperature history for the thermocouples for a typical weld.

While this procedure was successful at limiting the temperature, there are other issues to be resolved. In order to achieve full penetration welds at these low heat inputs, the weld prep had to be opened up to give access for the proper torch angle for penetration. The larger openings requires more weld metal to fill the weld and difficult to achieve in one pass. This can result in weld bead profiles as shown in Figure 9. The concavity of the bead in this figure is borderline acceptable per most weld codes. Less than optimum torch angle or excessive wire feed can result in isolated areas of incomplete weld penetration as shown in Figure 6.10.

The usual solutions to this problem generally are detrimental to the integrity of the conductor. Welding current can be increased to assure complete penetration, but that will expose the conductor to higher temperatures. The joint preparation can be opened to allow the welding arc to be directed at the root. This will require a second weld pass to fill the joint and further degrade the conductor since the heat damage is accumulative. As will be discussed in the following section, it was necessary for the welding of the Incoloy 908 to add an additional machining step to remove the unwelded backing section of the cooling stub and thereby removing any areas of lack of penetration. The ID of the helium cooling stub is initially machined to a smaller diameter which would allow for a final boring of the back of the weld removing any lack of penetration. This extra step was not deemed necessary for the 316LN welds but could be added to improve the reliability of the cooling stub attachment process.

Two helium cooling stub mock-ups with actual NbTi conductor have been welded with thermocouples imbedded into the cable. The first mock-up was welded

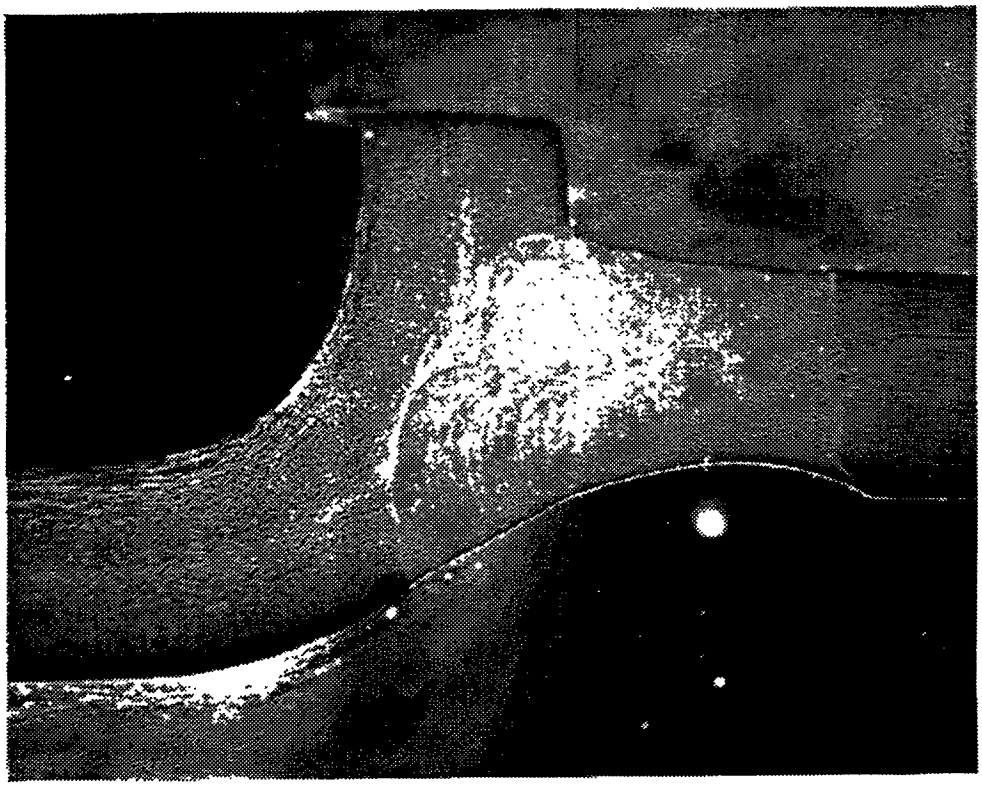


Figure 6-9 Typical weld bead profile of a helium cooling stub assembly (16X).

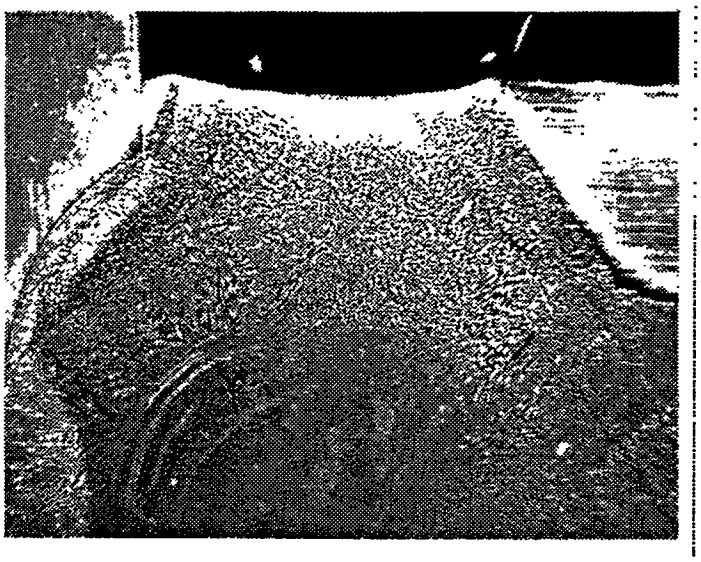


Figure 6-10 Helium cooling stub weldment exhibiting lack of full penetration, 32X

per procedure specification GWS950726. The time temperature history is shown in Figure 6.11. The thermocouple placement is shown in Figure 6.12. Extra filler wire was added to assure acceptable external weld bead profile. Visual inspection via a borescope indicated possible isolated areas of incomplete penetration. This procedure minimized heat input to the conductors.

The joint preparation on the second mock-up was widened to allow better access to the root and welding currents were increased by 10 to 15% to increase penetration. Two weld passes were required to produce an acceptable bead profile. No other changes were made. Post weld inspection indicated all visual acceptance criteria was met.

After reviewing Figures 6.11 and 6.13, the high temperature spike from one of the thermocouples in each graph is striking in its size. In these welding tests, it should be recognized that tremendous temperature gradients exist with molten nickel alloy (greater than 2000C) separated by only a few millimeters from the cable measured to be at a few hundred C. The specific location and exactly what the thermocouples contact controls the temperature recorded. These samples contained thermocouples inside the conduit installed by passing the fabric insulated thermocouple pairs on the outside of the foil wrap and inserting them under the foil at the location desired After removal of the sheath to recover strands for Ic measurement, we inspected the location of the thermocouples and discovered that, while the tip of the thermocouple was underneath the foil, the uninsulated wires came directly in contact with the back of the sheath. Therefore the temperatures recorded in these two cases can be measuring the temperature of the sheath.

Aside from these two thermocouple reading, the thermocouple readings did not show large difference from the previous mock-up. In any case, measurements of the superconducting critical current supports higher than expected temperature and suggest that further improvement in the process is indicated.

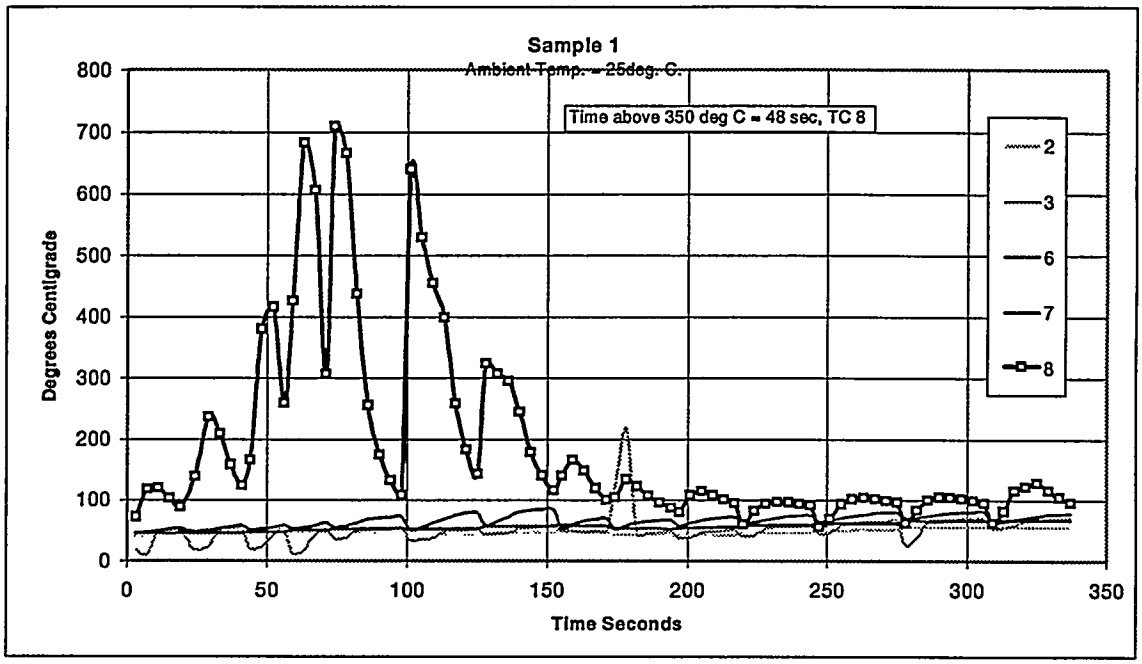


Figure 6-11 Recording of the cable temperature as a function of time during welding

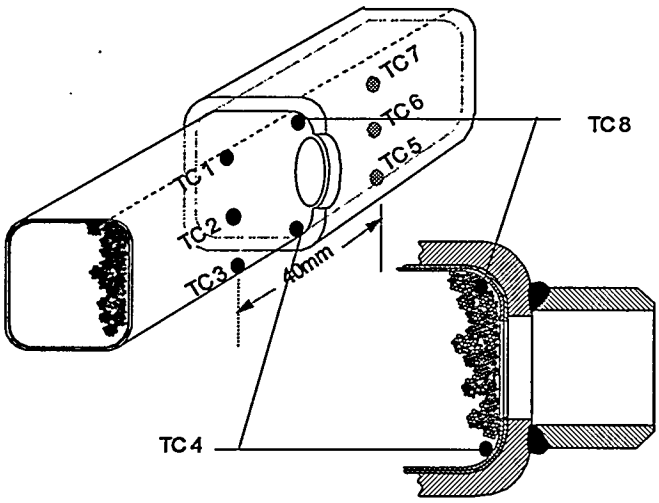


Figure 6-12 Schematic of the location of the thermocouples of the demonstration cooling stub.

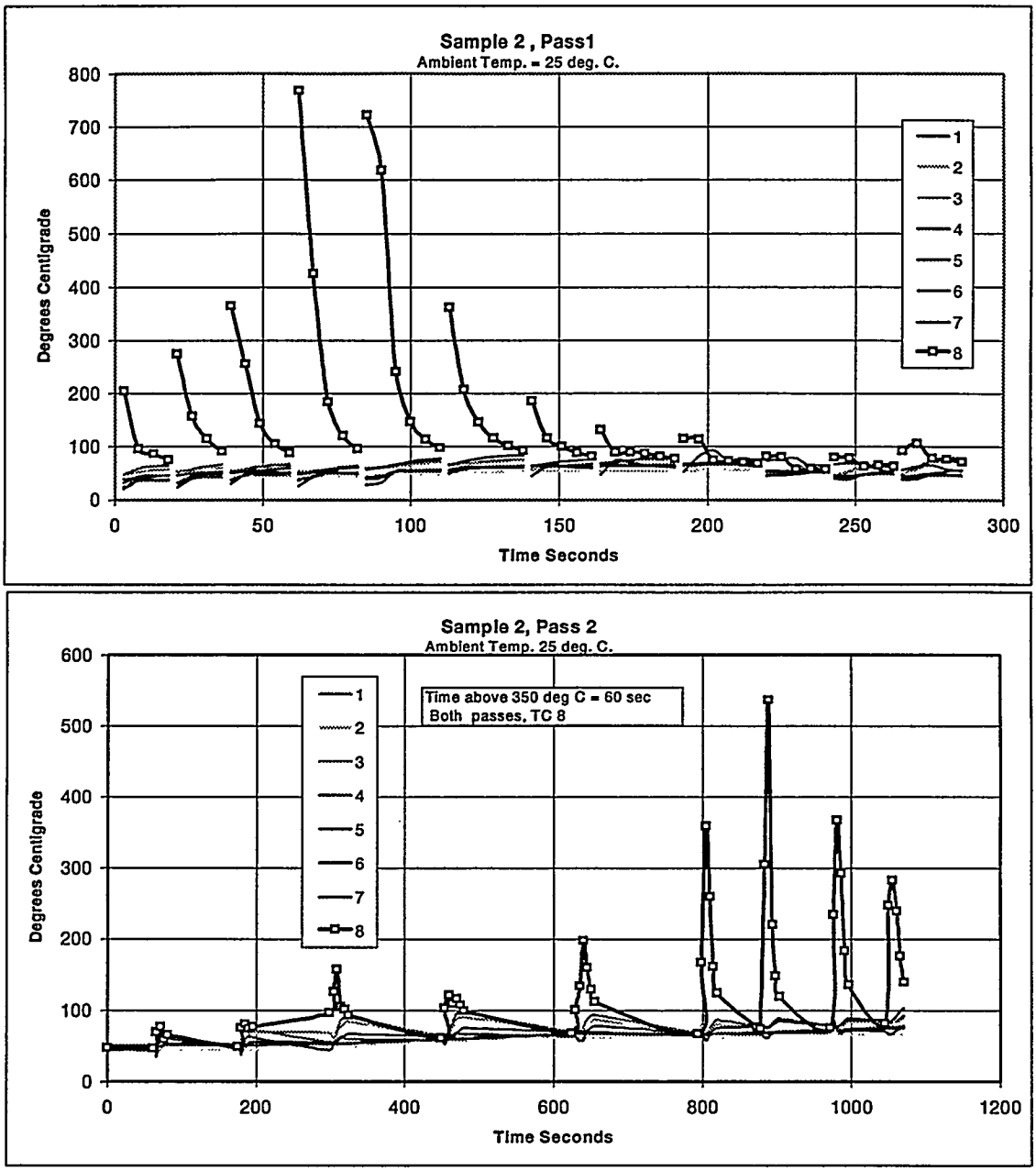


Figure 6-13 Temperature recording of the cable during the welding of the 316LN helium cooling stub with intermittent welding.

6.3.4 Demonstration Sample Welding at Arc Applications

Based on the successful results of the WSTC, AAI attempted unsuccessfully to implement the same procedure for the Incoloy 908 welds. The intermittent welding process worked fine but full penetration could not be achieved. As noted before, this has been attributed to the extremely viscous weld puddle of Incoloy 908. To compensate for this characteristic, the weld procedure was modified in the following way:

1. A 0.5mm thick and 0.5mm long land area was machined on the end of the helium cooling stub. This land is removed after welding to remove any lack of penetration.
2. The ID of the helium cooling stub was reduced to 10.3 mm to allow for machining of the bore of the stub to the final ID of 13.1 mm.
3. The machining of the stub bore after welding includes machining of the sheath to a maximum depth of 0.5mm.
4. A copper disk was placed at the bottom of the conduit hole to support the stub and conduct heat away from the weld. This disk is in pressure contact with the internal heat chill shown in Figures 6.2 and 6.14. This disk was removed after the stub ID was machined.

This procedure was used to produce the demonstration sample for the Incoloy 908 stub.

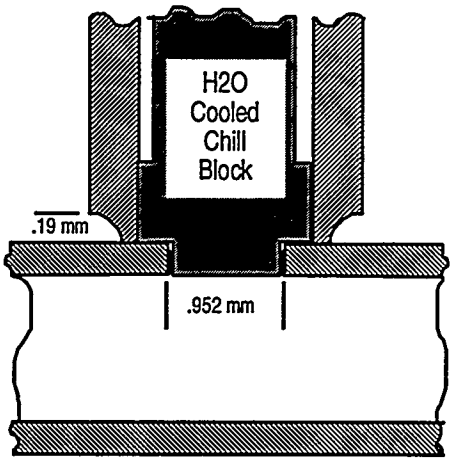


Figure 6-14 Sketch of the Internal Chill used during the welding of the helium stub.

7. VERIFICATION TESTING

7.1 PROCESS DEMONSTRATION

The test sequence for the demonstration samples of NbTi cable in both Incoloy 908 and 316LN was as follows:

1. Monitor the temperature using thermocouples installed in cable where possible (It was not possible at AAI due to the high frequency starts damaging the chart recorders).
2. Leak test the sample using a helium mass spectrometer lead detector at sensitivity of at least 3 X 10-10 atm-cc/sec Helium)
3. Pressure test (hydraulically in conformance with UG99 ASME-sect. 8) to 1.5 times the maximum expected pressure of 20 atm.
4. Thermal shock the samples 5 times with LN2.
5. Releak test
6. Remove conduit without cutting strands, mount and inspect weld.
7. For Nb_3Sn, impregnate the sample before cutting, cut through conductor, mount and inspect weld and strands for damage.

   The initial plan was to use the same sample instrumented with thermocouples for the critical current measurements. Unfortunately the short length was not

suitable for accurate Ic measurement so a separate sample was produced for this purpose.

7.2 CRITICAL CURRENT SAMPLES

The critical current of twenty strands was measured at 5T and 7T. Four of the strands not located near the weld were measured as control samples for the test. The remaining sixteen strands were located somewhere at the interface between the sheath and the cable and directly in CONTACT with the foil and the sheath. The layout and location for these strands are illustrated in Figure 7.1. Only those

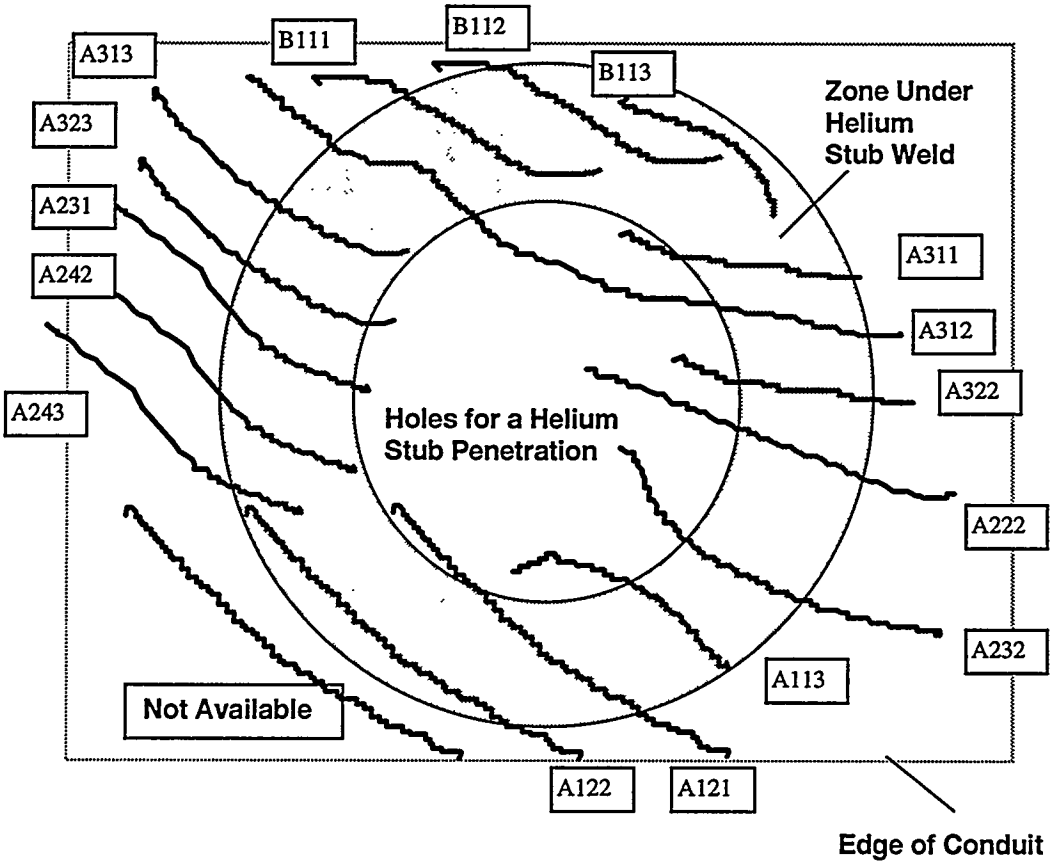


Figure 7-1 The location and layout of the strand for which the critical current was measured. The strand identifiers refer to the location in the cable starting with the largest subcable indicated by a letter. The view is from the top of the helium stub underneath the sheath.

strands that actually came to the surface in the weld area were selected for critical current measurement. The labeling notation followed the cabling construction: The letter designates one of the final six 5x4x3 cables, the next number one of the five 4x3 subsubcables, and so on. In this sample one of the 5x4x3 subcables, designated A, was centered under the weld with another subcable B on one edge. The other subcables were not involved.

During the disassembly of the cable, we noticed that the triplet was improperly formed. One of the strands was wound around the other two probably due to reduced back tension of that strand on the cabler. This resulted in severe mashing and distortion of the strand. Often times the strand appeared to be almost pinched off. One of the attributes that was recorded for all the strands was whether or not the strand was over twisted.

It was also noted that the piercing operation left dimples in three of the wires, A312, A313 and A323. Two of the strands, A222 and A312, were heavily flattened at the surface presumably due to compaction of the cable by the sheath.

The tabulated results of the critical current measurements taken at 5T and 7T are given in Table 7.1 These measurement have been ordered in sequence starting at noon on the above diagram and moving around in a clockwise fashion. The following observations can be made:

1. Four strands were measured as controls for the experiment. As can be seen, the variation is very small for the strands measured. Even the overtwisted strand yielded the expected critical current.

2. One strand, A312, broke in two pieces before being tested.

3. Six of the strands would not conduct current at all during the test. They acted as open circuits when cooled to 4.2K. This behavior suggests a fractured wire but no evidence of an obvious break could be found when examined after test

3. Of the remaining nine strands, seven performed adequately (the lowest was 82% of its original Ic). Notice that any degradation found was independent of field strength within the normally expected error bars.

4. The last two strands, A322 and A323, showed evidence of current degradation due to annealing of the NbTi. On these strands notice that the degradation at 7T was much greater than degradation at 5T. Annealing of the NbTi would be expected to affect the high field performance more strongly.

Table 7-1 Measurement Of The Critical Current Of Strand Underneath The Stub Weld

Measured at Oxford
8/14/95

Loc #	Wire ID	Weld or not	Over twisted	Jc@7T	Jc@5T	Jc/Jco@7 T	Jc/Jco@ 5T	Notes
1	B113	yes3	yes	0	0	0	0	open circui
2	A311	yes5	no	380	620	0.92	0.92	
3	A312	yes4&6	yes	0	0	0	0	broke durir mounting
4	A322	yes3	no	136	528	0.33	0.78	
5	A222	yes2	yes	0	0	0	0	open circui
6	A232	yes1	yes	0	0	0	0	open circui
7	A113	yes4	yes	0	0	0	0	open circui
8	A121	yes3	no	0	0	0	0	open circui
9	A122	yes2	yes	0	0	0	0	open circui
10	A243	yes11	no	410	672	0.99	1.00	
11	A242	yes10	no	410	672	0.99	1.00	
12	A231	yes9	no	390	644	0.94	0.95	
13	A323	yes8	no	59	330	0.14	0.49	
14	A313	yes7	no	340	560	0.82	0.83	
15	B111	yes 1	no	410	652	0.99	0.97	
16	B112	yes 2	no	412	664	1.00	0.98	
	B121	no	yes	410	672			
	B122	no	no	420	676			
	B123	no	no	410	672			
	A112	no	no	416	680			
	Control average			414	675			

5. All of the strands for which the critical current could be measured were not over-twisted. All of the strands that were over-twisted exhibited the fractured behavior with no current flow.

From this data, it is clear that some thermal annealing is occurring and significant thermal pulses are reaching the wire. The temperature spikes recorded during the welding of the demonstration support this conclusion. The dimples from the piercing operation may be contributing to the very low current of A323. More disturbing though is the absence of current carrying continuity in seven of the strands. This behavior suggests serious physical damage, internal cracking or fracture, which does not completely sever the strand. There does seem to be a strong correlation between the over twisted strands and this lack of electrical continuity. However the solid Ic of the control sample B121 would lead to the conclusion that the combination of the overtwisted state and heating during the welding process precipitate the failure of strand. At the this time the mechanism is not clear.

7.3 HYDRAULIC TESTING

The three helium cooling stub samples were subjected to hydraulic pressures up to 100 atmospheres without failure or leaks.

7.4 LEAK CHECKING

All three stub samples were leak checked before and after thermal cycling and pressure testing using a helium mass spectrometer leak detector with sensitivity of less than 1 x10-10 cc He/sec. No detectable leaks were found either before or after cold shock.

8. CONCLUSIONS

Minimization of heating during welding must continue. Intermittent welding offers significant temperature reduction over the standard process without apparent compromise to the leak tightness. Better use of the internal heat sink has the potential for further improvements. Improvements are isolation from the stub itself so as to better cool the cable and avoid being a conduit of heat from the weld to the cable.

Water cooling of the conduit, header and conductor with chill blocks lowers the time that the conductor is at significant temperature but does not significantly affect the peak temperature. The duration of the welding arc is primary variable in limiting the temperature of the superconductor.

Gas flow inside the conductor improves the weld penetration and provides important cooling of the cable.

Piercing of the sheath can be effectively accomplished using new, sharp tools. The Roto-broach is the preferred tool giving the smallest burr.

Optimization of the contact pressure from the Roto-broach must be optimized further to minimize burr while giving space between the cable and the sheath.

Machining of the inside of the cooling stub is required for the Incoloy908 to remove crack initiators due to the viscosity of the Incoloy 908 puddle. Implementation of that step to 316LN welding provides increased assurance of a strong and tough joint.

9. RECOMMENDATIONS

Implement further improvements to the welding procedure to lower the temperature to acceptable levels.

Perform analysis on CS conductor to determine the effect of the helium stub on the local conduit stresses.

Perform analysis to determine the stresses resulting from joining the 316 stainless tube to the Incoloy stub header. The most severe case is during heat treatment.

The issue of a dead flow zone directly across from the helium stub inlet was considered and was judged not to be a problem however it should be reviewed in phase 2.

APPENDIX A

EVALUATIONS OF INCOLOY 908 AND 316L STAINLESS STEEL HELIUM ENTRANCE STUB ATTACHMENT TECHNIQUES TO THE TPX COIL

Westinghouse-STC Order #34-97576-PY
Arc Applications Order #95032

Prepared For:

Westinghouse Electric Corp.
Science and Technology Center
1310 Beulah Road
Pittsburgh, PA 15235

Prepared By:

Jonathan T. Salkin
Welding Engineer

August 9, 1995

TABLE OF CONTENTS

Section Page

Work Performed..... 1 - 2

Discussion of Results..... 3

Conclusions..... 4

Recommendations..... 5

Appendix I - Figures

WORK PERFORMED

Full Weld Penetration Tests

The initial series of Phase II stub attachment weld tests run were based on the methods that W-STC developed for attaching 316L stainless steel stubs to 316L sheathing. For these tests Incoloy 908 stubs were machined with the general dimensions of Item 3 in the attached W-STC Sketch RJH071495. These were held in place by a water cooled copper chill block, Figure 1, and then welded to 908 sheathing. The welds were made in short sections of less than 45o around the stub. The weld progressed around the stub and was not sequenced to balance the deposit.

After making several stub welds varying weld length and amperage it was found that full penetration was extremely difficult to achieve due to the sluggish weld pool characteristics of the 908.
The groove was also found to be too narrow for these tests.

In order to gain greater access to the root of the groove a series of stubs were machined with larger grooves. This was accomplished with extended lands and an angle instead of the full radius, Figure 2. These stubs were then welded to the 908 sheathing in the same manner as the first tests. The wider groove configurations provided improved accessibility to the root but the characteristics of the 908 prevented full penetration. The wider grooves would also require a second and possibly a third layer to fill the groove.

Since full penetration was not achievable a series of 908 buildups were deposited and machined to provide weld preps, Figure 3, eliminating the "T" attachment configuration. Although the two prep designs produced a much wider stub attachment groove which was undesirable, they were welded to determine if penetration could be achieved.

Both the original stub groove and the wider stub grooves were welded to the buildups. While some intermittent penetration was achieved, the 908 welding characteristics continued to inhibit penetration.

In order to compare these results to those gained by W-STC with 316L, a test was prepared with a 316L buildup made around a pre- drilled .375 hole in the sheathing wall. For comparative purposes a 908 buildup was made around a .375 hole. Both buildups produced sufficient heat to melt part of the edge of the .375 holes.

After machining a 316L stub was welded to the 316L buildup in the same manner as the 908 tests. The 316L produced a more controllable weld pool which was more fluid that the 908. While 100% fusion was not achieved for the full 360o, the results were significantly better that those of the 908 tests. The width of the groove would require additional layers to complete. Overall the buildup and groove weld introduced what was felt to be excessive heat.

Partial Weld Penetration Tests

Based on the results of the full penetration welds an alternate attachment method was considered. This employed a stub with an undersized ID, Figure 4. For this evaluation a 316L stub was used. The stub was welded to the 908 sheathing without to much difficulty. Since the ID was smaller than the previous tests a copper chill block was not used. While there was more heat buildup than desired the intent was to evaluate the attachment method. After completing the weld, half the deposit was blended to the 908 surface to generate a smooth transition.

This attachment method was the most straight forward of all tests run to date. With copper chill blocks and the additional base material of the modified stub it was felt that the overall heat transferred into the conductor would be minimized. Based on this a test was run on the W-STC supplied 908 with the pre-drilled through wall hole.

For this method the procedure was as follows:

1. A maximum material condition stub was machined.
2. A copper disc was placed in the pre-drilled hole .020 inches thicker than the 908 wall.
3. The stub and copper chill blocks were aligned for welding. In addition to the stub chill place a chill block on either side of the square sheathing. Argon is passes through the length of the strands at 10 cfh.
4. The stub was welded with low amperage segmented welds. One minute cooling between welds was imposed.
5. After welding the ID of the stub was machined down to the surface of the sheathing, removing the notch and producing a full penetration weld. The copper disc is then removed.

Due to the small size of weld beads deposited it took three layers to complete the stub weld. However, by using 70-90 amps and making approximately 8-10 welds around the stub per layer the overall heat buildup was minimal. The was some oxide film formation which required some light grinding. After welding the stub was machined out to approximately .410 inches. Except for one small area on the root it appeared to have provided the full penetration weld required.

DISCUSSION OF RESULTS

The completed stub attachment tests showed that low heat input, full penetration welds were impractical with Incoloy 908 material. While the 316L welds showed improved welding characteristics, the heat generated by this attachment methods was felt to be greater than desired. In addition the skill levels required made repeatability very difficult. The difficulties encountered show that the full penetration "T" attachment with or without a buildup is an undesirable configuration to weld. The partial penetration method was a straight forward technique for eliminating the full penetration requirement.

The partial penetration attachment allowed maximum cooling to be employed while significantly reducing the skills required to make the weld. The copper chill block inside the stub and the disc placed in the pre-drilled hole provided cooling directly to the strands in addition to the ID of the stub. By having a flat surface on top of the stub, not a weld prep, there was more surface area for contact with the chill block. Even though multiple layers were required to complete the weld, maintaining low interpass temperatures was not difficult with the low amperage segmented welds. By designing more effective cooling blocks to nest around the 908 square sheathing, for with increased surface contact, it may be possible to reduce the overall temperature cycles.

After welding machining of the ID of the stub to the required diameter down to the surface of the sheathing produced the full penetration weld condition. In production the stub weld could be blended and the required weld prep machined on the top of the stub.

The test, run as described was more straightforward than the previous melt through techniques. Since no penetration was required it was not a problem to make short length passes. The groove was slightly tight and could be opened a little to provide more accessibility.

CONCLUSIONS

1. A partial penetration stub attachment weld was the most straight forward of all tests run to date.

2. Full penetration stub attachment welds were extremely difficult to achieve due to the sluggish weld pool characteristics of the 908.

3. Use of wider groove configurations and attachments to weld deposited buildups were not effective in improving the ability to achieve full penetration.

4. The partial penetration attachment allowed maximum cooling to be employed while significantly reducing the skills required to make the weld.

5. Maintaining low interpass temperatures was not difficult with low amperage segmented welds and water cooled chill blocks.

6. More effective cooling blocks to nest around the 908 square sheathing could further reduce the overall temperature cycles.

RECOMMENDATIONS

The partial penetration is considered the best method for attaching the stub to the sheathing. While additional work is recommended to determine the required dimensions, procedure and cooling, a development program to finalize the stub attachment procedure should not be difficult.

APPENDIX I

FIGURES

TDS Page

Distribution List

Science & Technology Center

*A. Melissaratos, 801-3C54
S. D. Harkness, 801-3C54C
C. J. Heyne, 501-3Y56A
D. T. Hackworth, 501-3Y56B
O. S. Taylor, 501-3Y56C
J. R. Repp, 501-3Y56D
S. K. Singh, 501-3Y56E
J. L. Wu., 501-3Y56H
*W. F. Hannan, 501-3Y59
M. P. Krefta, 501-3D24
D. C. Johnson, 501-3D30
D. J. Hall, 501-3E25
T. Kupiszewski, 501-3E29
O. R. Christianson, 501-3D34
T. J. Fagan, 501-2Y29
J. F. Lowry,.501-3Y31
J. F. Roach, 501-3Y25
P. A. Sanger, 501-3D22
J. H. Parker, Jr., 501-3D28
W. J. Carr, Jr., 401-3A13
Library (3)

MARD - Sunnyvale, CA

C. B. Armstrong
*R. Ryan

PGBU - Orlando, FL

*D. A. Bartol
*F. P. Bevc

PGSD - Pittsburgh, PA

*P. J. Craig

* TDS Page Only

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

This report has been reproduced
directly from the best available copy.

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information
P.O. Box 62, Oak Ridge, TN 37831
Prices available from (615) 576-8401, FTS 626-8401

Available to the public from the
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Rd.,
Springfield, VA 22161

Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.