LEGIBILITY NOTICE

A major purpose of the Technical Information Center is to provide the broadest dissemination possible of information contained in DOE's Research and Development Reports to business, industry, the academic community, and federal, state and local governments.

Although a small portion of this report is not reproducible, it is being made available to expedite the availability of information on the research discussed herein.

**AN INTERIM REPORT ON THE MATERIALS AND SELECTION
CRITERIA ANALYSIS FOR THE COMPACT IGNITION
TOKAMAK TOROIDAL FIELD COIL TURN-TO-TURN
INSULATION SYSTEM**

Volume 1

V. W. Campbell
J. B. Dooley
J. G. Hubrig
C. J. Janke
T. J. McManamy
D. E. Welch

Applied Technology Division

Date Published—January 1990

Prepared by the
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831-7294
operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-84OR21400

MASTER

CONTENTS

ABSTRACT	vii
LIST OF FIGURES AND TABLES	v
INTRODUCTION	1
BACKGROUND	2
INSULATION-SHEET MANUFACTURING AND BONDING-ADHESIVES STUDY	2
SUBSTRATE SURFACE PREPARATION	3
Copper/Inconel Turn Composite Insulation Sheet	3
Composite Insulation Sheet	4
Primer	5
BONDING AND TOLERANCE TAKE-UP	6
Adhesive Systems	6
BONDING-ADHESIVES SUMMARY	12
VACUUM-IMPREGNATING SYSTEMS	14
S-Glass Product Forms	14
S-Glass Fabric Criteria for Vacuum-Pressure Impregnation	15
Epoxy Impregnating Resin and Hardener	16
INSULATION-SHEET ASSEMBLY CONFIGURATION	16
INSULATION-SHEET/CONDUCTOR-TURN MANUFACTURABILITY STUDY MATRIX	20
MATERIALS TEST PROGRAM	22
PRELIMINARY GENERIC MATERIALS COMPARATIVE ANALYSIS	22
TEST PROGRAM	23
Wet-Out and Drop-Spread Evaluation	23
Compatibility	23
Mechanical Test Specimens	23
Coefficient of Thermal Expansion Samples	23
Cylinder-Embedment Samples	25
Neat-Resin Blocks	25
Brookfield Viscometry	25
Compression	25

Flow Infiltration	27
Cryomechanical Fatigue	27
TEMPERATURE CONDITIONS	27
GENERIC MATERIALS	27
Resins	29
Hardeners	29
CANDIDATE SYSTEMS	30
Combination 1	30
Combination 2	30
Combination 3	30
Combination 4	30
Combination 5	30
Combination 6	30
Combination 7	30
Combination 8	32
LABORATORY WORK CONCLUSIONS	32
Wet-Out and Compatibility	32
Viscosity-Time	32
Cure Response	32
Cryogenic Exposure	35
Handling and Cryogenic Exposure	35
Thick-Sample Compression	35
Thin-Section Tests	41
SUMMARY	42
REFERENCES	43
Appendix A. TOROIDAL FIELD COIL SYSTEM DESCRIPTION DOCUMENT EXTRACT	45
Appendix B. BONDED AND UNBONDED REGION LAYOUT FOR TOROIDAL FIELD COIL ASSEMBLY	49
Appendix C. INSULATION SHEET/CONDUCTOR TURN MANUFACTURABILITY STUDY MATRIX	53
Appendix D. MOLECULAR STRUCTURE OF BASIC COMPONENTS ..	65

LIST OF FIGURES AND TABLES

1	TF Field Coil Showing Massive Panel Boundaries	17
2	Nose Bend Region of TF Coil	19
3	Laboratory Wet-Work Summary	24
4	Mechanical Compression Test Setup Schematic	26
5	Viscosity of Bisphenol A Resin as a Function of Temperature	28
6	Material Combinations	31
7	Viscosity vs Time for Resin Hardness Combinations	33
8	Embedment Sample After Cure–No Cryogenic Exposure	34
9	Laboratory Results Summary	36
10	Massive Thermal-Induced Failure–Embedment Sample	37
11	Massive Thermal-Induced Failure–Neat Resin	38
12	Tensile-Dominated Thermal Failure	39

LIST OF TABLES

1	Comparison of Epoxy Systems	13
2	Commercially Available S2-Glass	15
3	Summary of Thick-Sample Comparison Tests	40
4	Compression Failure Mode of System/Cure Combinations	41
5	Thin-Sample Compression Test Results	41
6	Failure Modes of Thin-Compression Samples	42

ABSTRACT

Design criteria for the Compact Ignition Tokamak, Toroidal-Field (TF) Coil, Turn-to-Turn Insulation System require an insulation sheet and bonding system that will survive cryogenic cycling in a radiation environment and maintain structural integrity during exposure to the significant compressive and shear loads associated with each operating cycle.

For thermosetting resin systems, a complex interactive dependency exists between (1) optimum peak value, in-service property performance capabilities of candidate generic materials; (2) key handling and processing parameters required to achieve their optimum in-service property performance as an insulation system; and (3) suitability of their handling and processing parameters as a function of design configuration and assembly methodology. This dependency is assessed in a weighted study matrix in which two principal programmatic approaches for the development of the TF Coil Subassembly Insulation System have been identified. From this matrix study, two viable approaches to the fabrication of the insulation sheet were identified: (1) use of a press-formed sheet bonded in place with epoxy for mechanical bonding and tolerance take-up and (2) formation of the insulation sheet by placement of dry cloth and subsequent vacuum pressure impregnation.

Laboratory testing was conducted to screen a number of combinations of resins and hardeners on a generic basis. These combinations were chosen for their performance in similar applications. Specimens were tested to screen viscosity, thermal-shock tolerance, and cryogenic tolerance. Wet-out of materials of construction and compatibility with the materials were also checked. Cryogenic shock and cryogenic temperature proved to be extremely lethal to many combinations of resin, hardener, and cure. Two combinations survived: (1) a heavily flexibilized bisphenol A resin with a flexibilized amine hardener and (2) a bisphenol A resin with cycloaliphatic amine hardener.

INTRODUCTION

This interim report summarizes activities to date in support of research and development efforts to define insulation system material selection criteria that will identify the candidate generic constituent materials for the Toroidal Field (TF) Coil Insulation System. Recommendations for material handling and processing, through fabrication and assembly, to meet established design in-service performance parameters will be made.

Programmatic approach constraints that limit candidacy to commercially available insulation sheet and bonding system materials and established fabrication methodologies dictate that the turn-to-turn insulation system be either a mosaic insulation sheet (fitted, commercially available S-glass composite panels to achieve a full-sized sheet) or a monolithic insulation sheet (full-sized, S-glass laminate, vacuum/pressure impregnated in place to form a homogeneous composite sheet).

Design performance criteria for the TF Coil Subassembly (coil turn conductor to insulation sheet configuration) raise further programmatic constraints on fabrication and assembly requiring multiple substrate interface bonding and tolerance take-up to ensure no voids or unbonded areas. These fabrication and assembly issues dictate the key handling and processing parameters for the selected candidate generic materials, and these, in turn, further limit the number of commercially available candidate generic materials for the insulation system and impose handling and processing constraints upon them. These processing constraints will differentiate the *in situ*, in-service property performance of the TF Coil Subassembly Insulation System from the optimum laboratory test specimen property performance of the Insulation System's constituent generic materials.

The established programmatic constraints are represented by two candidate generic material chemistries represented by (1) bismaleimide/S-glass mosaic panels formed into a full-sized sheet using an epoxy structural adhesive and (2) S-glass laminate formed in place as a monolithic, full-sized sheet using an epoxy vacuum/pressure-impregnation system. Discriminate substrate interface bonding and zero tolerance take-up represent supplemental candidate material/processing requirements that are unique to each of the two candidate programmatic approaches and must be integrated into the chosen process.

Literature research and laboratory benchtop testing analysis have indicated that highly radiation tolerant epoxy systems can be represented by a limited set of chemistries based on bisphenol A, bisphenol F, and cycloaliphatic epoxy resins reacted with various aromatic anhydride and aromatic amine hardeners and modified with various reactive plasticizers. While all candidate chemistries are compatible with copper, Inconel, and S-glass substrates, performance and processing trade-offs represent major issues compounding the problem of identification of the optimum in-service performance candidate. For example, the chemistry of high-radiation tolerance is associated with high viscosity (which precludes impregnation processing) and rigidity (which mandates the incorporation of reactive plasticizers to survive cryogenic cycling).

BACKGROUND

The Compact Ignition Tokamak (CIT) is the next major United States magnetic fusion device under design and uses a design concept having normal conducting (i.e., non-super conducting) TF coils that are cooled to liquid-nitrogen temperature prior to a discharge. During the ~20 s discharge, these coils heat up to a peak temperature of 330 K and are then cooled back to 77 K within 1 h. The electrical insulation between the conductor turns is subjected to very high mechanical and thermal stresses and radiation dosages.

A concurrent insulation materials test program, under way at the Princeton Plasma Physics Laboratory (PPPL), evaluated the shear stress in compression capability of commercially supplied composite sheets and determined the efficiency of various surface treatments to increase the roughness and effective coefficient of friction for an Inconel surface with organic insulation sheets.

This preliminary review of materials and manufacturability issues, by PPPL was expanded in FY 1988 to evaluate commercially available composite panels and S-glass composite materials. The objective of the expanded study was to more fully understand the relationship between the published optimum properties of commercially available composite sheet materials and their suitability, as a function of their recommended processing parameters, for the candidate fabrication and assembly methodologies. The study was defined in two segments: (1) a manufacturing and bending analysis to identify manufacturability issues that would have to be addressed in forming a full-sized insulation sheet from commercially available composite panels and (2) an S-glass composite material manufacturing study to evaluate alternative insulation sheet fabrication methods. The results of this study identified conceptual detail for (1) substrate surface preparation; (2) optimum, commercially available, composite panel configuration assembly to create a full-sized sheet; and (3) established the basis for the weighted study matrix. These results are preliminary, and laboratory testing is still required to verify the performance of the recommended procedures.

INSULATION-SHEET MANUFACTURING AND BONDING-ADHESIVES STUDY

The baseline design approach for the insulation system was to use commercially obtained sheet insulation between the conductor turns. The nominal thickness in the nose region of the TF coil was to be 0.040 in., and the insulation sheet was to be a laminate of S-glass in a matrix of either a bismaleimide or radiation-resistant epoxy resin system.

The assembly plan required bonding the insulation to the copper-Inconel conductor turns in a controlled pattern over the nose region and over most of the remainder of the conductor turn/insulation substrate interface. To ensure that the shear stresses in the insulation peaked near the horizontal midplane where a high compressive load was concentrated, an unbonded region near the nose on the upper and lower legs of the coil was defined. Because static shear strengths above design requirements have been

demonstrated in small, unbonded samples with a grit-blasted Inconel surface, the bonding objectives were viewed primarily as assembly and tolerance take-up to produce full contact between substrate interfaces, where the plate coils surface variation may be ± 0.005 in. and the insulation sheet thickness tolerance is unknown.

SUBSTRATE SURFACE PREPARATION

Optimum adhesion of Inconel 718 and copper C10700 to a composite insulation sheet is based on the turn assembly as shown in Appendix A. This illustration is drawn from the WBS-F Toroidal Field Coil Systems' Description Document and is shown in Appendix B as an expression of the designated bonded and unbonded regions.

The following mechanical surface treatment is recommended for further laboratory bench-top study as a candidate manufacturing process objective, for inclusion in test specimen preparation for related tests, and for consideration in a full-scale prototype TF Coil Manufacturing Program.

Copper/Inconel Turn Insulation Sheet

1. The entire surface of the copper/Inconel turn is to be degreased with 1,1,1 trichloromethane or other suitable degreasing agent using appropriate handling and safety equipment.
2. Air Dry. (Time cure temperature to be determined based on selected handling methodology.)
3. Mask off unbonded regions of copper and Inconel. (Note: Because the entire surface will need to be machined or ground to taper the Inconel to the copper after the explosive bonding process, it is assumed that a surface finish that will facilitate maintenance of the unbonded region during final fabrication can be specified. Whether the entire surface of the turn or the unbonded regions are machined/ground to a specified surface finish should be answered following an independent manufacturing study.

Zone 1 - Bonded portion of Inconel 718 ("nose region of turn")

1. Grit blast with 36-grit aluminum oxide at 35 psi (nozzle distance, 6 in.); dwell time, 12 s/in.²
2. Wipe down with selected degreaser as noted in item 1.
3. Air dry as noted in item 2.
4. Apply and cure selected primer in accordance with established handling and processing specification.
5. Seal primed surfaces in Kraft paper or suitable plastic film for in-process storage.

Zone 2 - Unbonded portion of Inconel 718 (See Appendix B.)

This area will need to be masked and covered prior to the grit treatment of the bonded regions. Because there is no requirement for a primer, the area should remain sealed throughout the primer application to preserve the specified surface finish.

A 32- μ in. or better surface finish is recommended as a baseline surface finish for the unbonded regions of the Inconel 718. To ensure a slip plane at the substrate interfaces between the Inconel 718 and the composite insulation sheet, it is recommended that the surface finishes of both substrates be optimized.

Laboratory bench-top testing should be employed to determine the adequacy of optimum substrate finishes and whether or not an additional slip plane will be necessary at the interface. The incorporation of a material slip plane requirement would dictate a subsequent comprehensive generic materials study. Such a study would have a major impact upon the established design configuration relationship to handling and processing of generic materials through fabrication and assembly of the TF coil.

Zone 3 - Unbonded portion of copper C10700

The surface preparation of this region is identical to that of Zone 2 (unbonded Inconel 718) and should be accomplished simultaneously.

Zone 4 - Bonded portions of copper C10700

All steps are identical to those of Zone 1 - Bonded Inconel 718, except the grit size is changed from 36 to 80 grit. Nozzle distance and dwell time are the same as those of Inconel.

Composite Insulation Sheet

The entire surface of the composite insulation sheet should be pretreated using an identical degreasing methodology as established for the copper/Inconel turn. (Note: The assumption is made that the individual composite panels have already been fabricated into a full-sized sheet and that surface thickness tolerances do not require surface machining. With even a minimal machining of the Z plane (thickness) to achieve dimensional tolerances, the question of having to employ a primer/sealant is raised. In this case, to achieve an optimum surface finish for affected areas in the designated unbonded regions would require the application of a polymer conformal coating. The issue would be the potential for loss of generic peak physical strength properties in the surface region of the parent composite material at the interface. Machining of the Z plane to achieve dimensional tolerances, either in the designated unbonded region or in excess of the

*A recent review of the Tokamak Fusion Test Reactor Test Program indicates that a lower air pressure may be required.

treatment normally associated with surface preparation for adhesive bonding, would obligate a subsequent materials-selection study and alternative processing specification.

Zone 1 - Unbonded portion of Composite Insulation Sheet

This area will need to be masked and covered prior to the grit treatment of the bonded regions. The assumption is made that the as-manufactured surface finish is adequate and that subsequent handling and processing methodologies must preserve it.

Zone 2 - Bonded portion of Composite Insulation Sheet

1. Abrade surface lightly with 120-grit emery paper or alternative, nonconductive medium to achieve a matte finish.
2. Clean surface with approved degreasing methodology as specified.
3. Seal cleaned surfaces in Kraft paper or suitable plastic film during in-process storage.

Surface preparation refers to treatment of the full-sized insulation sheet/coil conductor interface. It does not address the preparation of Z plane surfaces associated with the assembly of individual composite panels into a full-sized sheet. This issue would have to be addressed in a separate material/application study.

Primer

The in-service performance criteria, which dictate substrate adhesion in the bonded regions of the insulation sheet/conductor-turn interface, raise the issue of employing a primer to the copper/Inconel surface. The commercially accepted premise that a primer will optimize the in-service performance of a structural adhesive in a given application is true only in those instances where the in-service performance failure modes are compatible with the generic properties of the primer and when the mandatory optimum-processing parameters for the primer can be met during fabrication. The question of whether or not a primer is essential and the identification of optimum primer balance issues associated with its optimum property processing during handling balances against processing constraints associated with fabrication and assembly of the TF coil is a requirement for a full system definition. The question is compounded even further by the in-service performance criteria of radiation and cryogenic exposure effects on yet another material and interface.

The incorporation of a primer and the attendant selection and manufacturability issues should be the focus of a separate study that should properly follow a decision as to which programmatic approach to the insulation sheet will be adopted. For example, the vacuum-impregnating system employed in the monolithic insulation sheet would also represent one chemistry of possible candidate primer. In this case, property performance would be driven by the processing constraints associated with its deposition as a separate application at the higher processing temperatures of 150°C vs the lower peak-processing temperatures required during fabrication of the insulation sheet to minimize the

mismatched coefficients of thermal expansion (CTEs). If the programmatic approach selected employs commercially available composite panels, i.e. mosaic insulation sheet, then the primer will be a separate and distinct chemistry from the structural adhesive in the bonded regions of the assembly and may or may not represent the chemistry of tolerance take-up.

A preliminary review of candidate primers is anticipated within the scope of the ongoing test specimen preparation for RAD II. It should be noted that the Ciba Geigy primer, DZ-80, has been withdrawn from the market and will not be included in the study program.

BONDING AND TOLERANCE TAKE-UP

Adhesive Systems

Commercially available adhesives are formatted into the following system types.

1. Two-Part, Room-Temperature Curing Pastes

A. Advantages

- Ease of storage at room temperature.
- Ease of mixing and use.
- Long shelf life.
- Bond-line thickness range, 0.0025 to 0.006

B. Disadvantages

- Pot life (i.e., 25 min to 2.5 h) reduces working life.
- Peak exotherm from large masses (7500 g) may degrade cured properties.
- It is very difficult to reposition the substrates over large areas after pastes are applied.
- Pastes are very difficult to deaerate when applied over large areas.
- Contact pressure is required to ensure intimate substrate interface.

2. Two-Part, Heat-Cured Liquids

A. Advantages

- Tolerance take-up is easily accomplished to zero tolerance.
- Vacuum pressure impregnation of liquids into glass fabric carriers is commercially established.
- Longer pot life than room temperature curing systems (several hours to days).
- Lower viscosity liquids are significantly easier to deaerate than higher viscosity pastes.
- Ease of storage at room temperature.

- Physical properties of heat-cured systems are normally superior to those of room-temperature cured systems.
- Heat-cured systems are more radiation resistant than room temperature systems.

B. Disadvantages

- Adhesive application method must be optimized when using over large areas.
- Liquids must be deaerated to eliminate void areas.
- Impregnation of liquids into glass carriers over large areas requires a long pot life resin with sufficiently low viscosity. (Note: These systems are commercially available but may have to be specially formulated with diluents and toughening agents to yield adequate adhesive properties.)
- Adhesive strengths of liquid systems for bonding copper to polyimide/S-glass substrates must be empirically studied because they are chiefly used only in composite manufacturing processes, including filament winding, laminating, or resin-transfer-molding applications.

3. Two-Part or One-Part Heat-Cured Pastes

A. Advantages

- Adhesive flow and bond-line thickness can be controlled using silica beads or other fillers.
- Longer pot life than room-temperature-curing systems (several hours to days).
- Ease of storage at room temperature.
- Physical properties of heat-cured systems are normally superior to those of room-temperature-cured systems.

B. Disadvantages

- Pastes are much more difficult to apply uniformly over large areas and cannot be vacuum pressure impregnated.
- Pastes are significantly more difficult to deaerate.
- Repositioning of substrates is difficult.

4. One-Part Heat-Cured Films

A. Advantages

- Designed to cover large areas.
- Offered in a wide variety of formulas.
- Films can be supported by carriers that serve to improve handling and application of the films prior to cure, control adhesive flow during bonding, and assist in bond-line thickness control.
- Much easier to apply and are cleaner than liquids and pastes.

- Worklife is longer than with room-temperature-curing systems (i.e., days).
- Better physical and environmental properties than room-temperature-curing systems.

B. Disadvantages

- Films require autoclaves or platen presses for cure at 25 to 45 psi and 200 to 350°F.
- Gap filling with films over areas with high thickness variability are poorer than with liquids.
- Supported films contain radiation-sensitive carriers (i.e., polyester and nylon).
- Some systems must be stored below 0°F.
- Unsupported films are more difficult to apply (will stretch) than supported films.
- Unsupported films have no bond-line thickness control.

The chemical constituency of the commercially available adhesive system formats may be summarized as follows. A listing of major members of the class is followed by general observations.

1. Epoxy Resins

- Bisphenol A
- Bisphenol F
- Tetraglycidyl methylene dianiline

- similar active structures differing only in central portion of molecule.

2. Hardeners

A. Aliphatic Amines

- Diethylenetriamine (DTA or DETA)
- Triethylenetetramine (TETA)
- Diethylaminopropylamine (DEAPA)
- Aminoethylpiperazine (AEP)

- poor radiation resistance;
- recommended for room-temperature-curing systems;
- limited pot life;
- poor elevated temperature (>212°F) properties;
- low viscosity;
- have high vapor pressures but can be used in the form of an epoxy resin adduct, which will lower the vapor pressure but increase the viscosity;
- examples include DTA, TETA, DEAPA, and AEP; and
- the cycloaliphatics have better properties than noncycloaliphatics.

B. Aromatic Amines

- Phenylenediamine (mPDA)
- Methylenedianiline (MDA)
- Diaminodiphenylsulfone (DDS)
 - excellent radiation resistance (DDS > MDA),
 - widely used;
 - most are solids at room temperature, except the eutectics;
 - have longer pot lives than the aliphatics but not as long as the anhydrides;
 - excellent chemical and electrical properties;
 - good elevated-temperature performance;
 - higher-temperature cures and longer cure times are required to obtain optimum properties compared with aliphatic amines;
 - mPDA is the best known and provides the lowest viscosities in the catalyzed resin systems;
 - MDA provides a longer pot life but requires slightly longer cures and has a higher processing viscosity;
 - mPDA and MDA are solids and have to be melted before blending into resin;
 - aromatic amine eutectics based on MDA and mPDA are liquid at room temperature, which provides easier processing but are slightly lower in elevated temperature performance;
 - DDS has a higher melting temperature (342°F), reacts slower, and is normally used with BF₃-MEA (Lewis acid accelerator); and
 - DDS provides the best elevated temperature properties compared with MDA, mPDA, or the eutectics.

B. Aromatic Anhydrides

- Hexahydrophthalic anhydride (HHPA)
- Methyltetrahydrophthalic anhydride (MTHPA)
- Dodecenylsuccinic anhydride (DDSA)
- Nadic methyl anhydride (NMA)
 - are more radiation resistant than the aliphatic amines but not as good as the aromatic amines;
 - have longer pot lives than the aliphatic amines and aromatic amines;
 - most anhydrides require elevated temperature cures and are typically used with BDMA accelerators;
 - are hygroscopic materials, and extended exposure to atmosphere results in hydrolysis of the anhydride to the parent acid, which results in a dramatic reduction in elevated-temperature performance;
 - NMA is preferred for elevated temperature application, and reacts to yield a cured resin system with increased cross-link density;
 - NMA requires a longer post cure than most other curing agents;

- NMA, HHPA, and MTHPA are low in viscosity; and
- DDSA is also low in viscosity and will impart some flexibility to the system, but the heat distortion temperature of the system is lowered.

C. Polyamides

- Dicyandiamide (DICY)

D. Accelerators (catalyst)

- Benzyldimethylamine (BDMA)
- Boron trifluoride monoethylamine (BF₃)

The radiation performance of adhesive systems is directly related to the handling and processing requirements for the system format and to the chemical constituents of the system. The impact of gamma and neutron radiation on various generic chemistries is summarized, from literature review, as follows.

Gamma and neutron radiation resistance of epoxy resin/curing agent decreases in the order TGMDA/DDS > DGEBA/DDS-BF₃-MEA > DGEBA/MDA > DGEBA/acid anhydrides > DGEBA/DICY-BDMA. Generically, radiation resistance decreases in the order TGMDA/aromatic amine > DGEBA/aromatic amine > DGEBA/acid anhydrides > DGEBA/aliphatic amine.

DGEBA/MDA vs DGEBA/TETA

Pulse radiolysis studies determined that MDA (aromatic) possesses greater radiation resistance than TETA (aliphatic).¹

DGEBA/DDS-BF₃-MEA (G-11CF) vs DGEBA/DICY-BDMA (G-10CR)

Flexural (3-point bend) studies determined that DDS-BF₃-MEA (aromatic) is more radiation resistant than DICY-BDMA (aliphatic). Flexural strength after 4.1×10^{21} neutron/cm² is 1224 MPa (177,500 psi) vs 387 MPa (56,000 psi) for G-11CR and G-10CR, respectively.²

DGEBA (Epon 828)-SiO₂ filled/aromatic amine (blended) vs DGEBA/DDS-BF₃-MEA (G-11CR) vs DGEBA/DICY-BDMA (G-10CR)

Flexural and compressive strength studies determined that Epon 828 was more radiation resistant than G-11CR and G-10CR after irradiation at 5 K. Flexural - 1×10^8 Gy (1×10^{10} rads) vs 2.4×10^7 Gy (2.4×10^9 rads) and Compressive - 1×10^8 Gy vs 2.4×10^7 Gy (doses at which flexural and compressive strengths decreased by 25%).³

**DGEBA (Epon 828)-SiO₂ filled/aromatic amine
(shell "Z"-liquid eutectic hardener)**

Gamma and neutron irradiation to a dose of 1.1×10^7 Gy (1.1×10^9 rads) at 4.2 K and 77 K of Epon 828 cured with an aliphatic amine, aromatic amine, or an acid anhydride showed sharp reduction in compressive strengths with the loss being greatest for aliphatic amine hardener. Also, a large decrease in mechanical strength of Epon 828 with blended aromatic amine occurs between $1-10 \times 10^7$ ($1-10 \times 10^9$ rads).⁴

**DGEBA (Epon 828)/aromatic amine vs DGEBA (Epon 828)/acid
anhydride vs DGEBA (Epon 828)/aliphatic amine**

Breaking stress at 77 K after irradiation of 3×10^{17} neutron/cm² and gamma dose of 8×10^8 rad at 5 K was 380 MPa (55,100 psi) for aromatic amine, 370 MPa (53,700 psi) for acid anhydride, and 200 MPa (29,000 psi) for aliphatic amine. Breaking stress at 4.2 K after irradiation of 3×10^{17} neutron/cm² and gamma dose of 8×10^8 rad at 5 K was 320 MPa (46,400 psi) for aromatic amine, 300 MPa (43,500 psi) for aliphatic amine, and 245 MPa (35,500 psi) for acid anhydride.⁵

**TGMDA (ELM-434)/DDS (aromatic) vs DGEBA (Epikote 1001)/MDA (aromatic)
vs DGEBA/DDS-BF₃-MEA (G-11CR) vs DGEBA/DICY-BDMA (G-10CR)**

Flexural (three-point bend) strength studies at room temperature with gamma rays at 60 MGy (6×10^9 rads) dosage. TGMDA/DDS-550 MPa (79,800 psi) vs DGEBA/DDS-BF₃-MEA-200 MPa (29,000 psi) vs DGEBA/MDA-120 MPa (17,400 psi) vs DGEBA/DICY-BDMA-50 MPa (7,250 psi) flexural (three-point bend) strength studies at 77 K with gamma rays at 50 MGy (6×10^9 rads) dosage. TGMDA/DDS-900 MPa (131,000 psi) vs DGEBA/DDS-BF₃-MEA-120 MPa (17,400 psi) vs DGEBA/MDA-100 MPa (14,500 psi) vs DGEBA/DICY-BDMA-50 MPa (7,250 psi).⁶

TGMDA (MY720)/DDS (aromatic) vs DGEBA/MDA (aromatic)

Flexural strengths of glass-cloth laminates after irradiation by 3 MeV electrons at 200 MGy (2×10^{10} rads) - 400 MPa (58,000 psi) for TGMDA/DDS, and irradiation at 70 MGy (7×10^9 rads) - 100 MPa (14,500 psi) for DGEBA/MDA. For resin/hardener only, the flexural strengths were 75 MPa (10,900 psi) at 100 MGy (1×10^{10} rads) for TGMDA/DDS and 10 MPa (1,450 psi) irradiated at 40 MGy (4×10^9 rads) for DGEBA/MDA.⁷

G-11CR is an E-glass laminate incorporating an epoxy resin with an epoxy equivalent weight (EEW) of ~182 to 192 with parts per hundred weight resin of DGEBA/DDS-BF₃-MEA equal to 100/50/1.5. See Dow's Electrical Laminate Brochure and Ref. 3 for more information.

G-10CR is an E-glass laminate incorporating an epoxy resin with an EEW of ~475-575 with parts per hundred weight resin of DGEBA/DICY-BDMA equal to 125/3.5/0.3 with 16.25 parts per hundred weight resin dimethylformamide and 16.25 parts per hundred weight resin DOWANOL PM (propylene glycol monomethylether) used for dissolving the DICY.

Epon 828 is a Shell DGEBA resin with an EEW of 185 to 192.

Epikote 1001 is a Shell (United Kingdom) DGEBA resin with an EEW of 450 to 550.

Sumiepoxy ELM-434 is a Sumitomo Kagaku Co., Ltd (Japan) TGMDA epoxy resin that is chemically the same as Ciba-Geigy's MY 720, MY 721, or RD 87 to 160 epoxy resins.

BONDING ADHESIVES SUMMARY

It was recommended, following an investigative paper study, that vacuum pressure impregnation (VPI) of a liquid epoxy formulation into S2-glass fabric is the ideal method to use for tolerance take-up purposes, and for bonding the insulation system to the conductor. The adhesive systems that were investigated included commercially available epoxies that were in the form of liquids, pastes, and films. In the midst of the study, it was determined that the performance of structural epoxy paste and film adhesives were inherently problematic due in part to difficulties in deaeration and in equipment requirements, respectively.

Three liquid epoxy formulations were chosen as viable candidates for the CIT device after careful consideration of the many processing and in-service performance requirements. These systems were selected principally because of their excellent gap-filling qualities, radiation resistance, and their ease of processing. Three adhesive recommendations for Phase 2 testing were as follows:

- Primary - Epon resin 9405/Epon curing agent 9470
 (DGEBA/AROMATIC - Shell Chemical Company)
- First alternate - RD 87-160 resin/HV 906 curing agent
 (TGMDA/NMA - Ciba-Geigy Corporation)
- Second alternate - RD 87-160 resin/HT 976 curing agent
 (TGMDA/DDS - Ciba-Geigy Corporation)

Table 1 is an abbreviated version of the CIT study matrix region delineating the major differences between the three epoxy resin systems. The numbering scheme of 1, 2, and 3 indicates best resin system to worst resin system (i.e., 1 → 2 → 3), with 1 representing the best system and 3 the worst system.

Table 1. Comparison of epoxy systems

	Epon 9405/9470	RD 87-160/HY906	RD 87-160/HT976
<u>In-service performance</u>			
Mechanical			
Compressive	3 ^a	1 ^a	2 ^a
Shear/torque	3 ^a	2 ^a	1 ^a
Radiation	3	2	1
Thermal cycling	1	3 ^a	2 ^a
<u>Processing</u>			
Working life	1	2 ^a	3 ^a
Viscosity	1	2 ^a	3 ^a
Wet-out	1 ^a	2 ^a	3 ^a
Deaeration	1	2	3
Cure conditions	1	3	2

^aNo conclusive data are available; therefore, a best-educated guess was determined based on information that was available on similar epoxy resin systems.

The major differences between the three systems can be divided into at least two areas—ease of processing and radiation resistance. Numerous technical papers on the damage sustained by epoxy resins after gamma and neutron irradiation indicate that of the three systems that were selected, radiation resistance decreases in the order: TGMDA/DDS > TGMDA/NMA > DGEBA/aromatic.

In terms of processing considerations (i.e., working life, viscosity, wet-out, and deaeration), the relative order is the exact opposite; that is, the most radiation-resistant system is the hardest to process, and the system that offers the best processing properties is the poorest in radiation resistance: DGEBA/aromatic amine > TGMDA/NMA > TGMDA/DDS.

To improve the processing properties of the TGMDA/DDS and TGMDA/NMA epoxy resin systems, the viscosity must be lowered to an acceptable level by elevating the temperature, adding diluents or a combination thereof. There are serious trade-offs that result from these modifications: (1) elevating the temperature significantly shortens the working life and (2) adding diluents to the formulation will result in a reduction of the radiation resistance and the degradation of some of the mechanical properties. The only exceptions to these general trends are that data on other epoxy systems suggest that unfilled resins cured with NMA show a higher compressive strength than those cured with DDS (i.e., 19,000 vs 16,000 psi on unfilled resins). Also, there is information that seems to show that resin systems with higher elongations will perform better under thermal cycling and CTE mismatches between the resin system and the adherends (i.e., insulation

and conductor). Additionally, obtaining optimum properties for the TGMDA/NMA resin system will probably require a longer cure cycle.

Because no data have been generated concerning the adhesive properties of these resin systems bonded to the insulation and to the conductor adherends, further testing is required. This testing might require the addition of toughening agents to the epoxy formulation for increasing the adhesive strengths. There are trade-offs with the addition of these agents into the formulation that involve an increase in the viscosity and a reduction in radiation resistance, depending on how much is introduced into the system.

Radiation-resistant S2-glass fabric will be used as the VPI cloth to (1) ensure a minimum bond-line thickness, (2) act as an impregnation medium, and (3) increase the radiation resistance by reducing the total amount of epoxy resin. There are seven commercially available S2-glass woven fabrics that vary in thickness from 2 to 10 mils, have plain or eight-harness satin weaves, have various constructions, and incorporate different-sized yarns. E-glass fabric is not acceptable because of the degradation caused by the absorption of thermal neutrons by boron resulting in a neutron absorption-gamma emission reaction.

VACUUM-IMPREGNATING SYSTEMS

S-Glass Product Forms

S2-glass, commercially available S-glass, may be summarized as follows:

- S-glass was developed in the early 1960s by Owens-Corning Fiberglass Corporation (OCF) for use in strategic missiles and has been discontinued due to low demand.
- S2-glass was developed shortly after S-glass in 1968 by OCF and is a lower-cost version (\$12/lb vs \$4/lb).
- S2-glass and S-glass differ only in the sizing applied to the fibers and the very stringent quality-control procedures necessary to meet military specifications. The average mechanical properties of S2-glass are only slightly lower than those of S-glass, while the data spread will be somewhat increased. Table 2 summarizes readily available product forms of S2 fiberglass fabric.
- OCF is the sole supplier of S2-glass fiber.
- S2-glass is used by the commercial fabric weavers and is supplied to companies including Spaulding.
- Spaulding uses Style 6781 on their S2/PI laminates.

- Hexel supplies styles 4522 at 54 and 60 in. widths, 4533 at 30 and 60 in. widths, and 4581 at a 30 in. width. All other widths are available up to 60 in. but require a minimum yardage order.
- J. P. Stevens supplies style 16781 at 38, 44, 50, 62, and 66 in. widths. All other widths are available up to 74 in. but requires a minimum yardage order.
- Burlington Glass Fabrics supplies styles 6080, 6581, and 6781 up to 75 in. maximum width, but Style 6080 would require a minimum order of ~5000 linear yards.
- Clark-Schewebel supplies style 6781 up to 60 in. maximum width.

Table 2. Commercially available S2-glass

Style	Weave	oz/yd ²	Mils	Count (warp by fill)	Yarn (S2CT)	Warp (lb/in. width)	Fill (lb/in. width)
6080	Plain		2	60 × 47	450 1/0 × 450 1/0		
4522	Plain	3.7	5.5	24 × 22	150 1/2 × 150 1/2	190	180
4533	Plain	5.6	10	18 × 18	75 1/2 × 75 1/2	300	275
4581	8-HS	8.9	9	57 × 54	150 1/2 × 150 1/2	450	425
6581	8-HS	8.9	9	57 × 54	150 1/2 × 150 1/2		
6781	8-HS	8.9	9	57 × 54	75 1/0 × 75 1/0		
16781	8-HS	8.9	9	57 × 54	75 1/0 × 75 1/0		

Note: 8-HS weaves are more pliable and contourable and have better strength properties than the plain weaves due to lower crimp in the fabric.

S2-Glass Fabric Criteria for Vacuum-Pressure Impregnation

- The reasons for using radiation-resistant S2-glass fabric as the VPI cloth are to (1) ensure a minimum bond-line thickness and eliminate resin-poor areas at the adhesive/adherend interface, (2) act as medium for the impregnation of the resin, and (3) increase the compressive and shear strength (Note: the bond line may be a maximum of 15 mils—it has been reported that shear strength decreases as the bond-line thickness exceeds the 3 to 10 mil range).
- There are limitations on commercial availability of S2-glass fabric in terms of thickness, construction, width, and minimum yardage orders. Additional fabric styles of various constructions are potentially available for use, but these fabrics would have to be specially ordered.
- The VFI S2-glass fabric must incorporate an epoxy-compatible finish that optimizes the wicking action of the candidate formulation and improves the bond between the fiber and the adhesive.

Epoxy Impregnating Resin and Hardener

Processing constraints to achieve successful vacuum impregnation dictate candidate chemistries due to their generic physical properties and may be summarized as follows.

1. The epoxy formulation must be <500 cps during processing, by either elevating the temperature of the formulation and the substrates or by the addition of reactive diluents or both. The epoxy formulation must have a sufficiently long pot life (12 to 16 h) at processing temperatures of 40 to 50°C. Much lower viscosity may permit shorter pot life.
2. Optimum property cure schedule must be discounted at 110 to 130°C to minimize the formation of interlaminar shear stresses during use which result from the substrate mismatched CTEs.

INSULATION-SHEET ASSEMBLY CONFIGURATION

Only one insulation panel type was specifically identified for detailed investigation, Spaulding Composites Company, "Spaulrad S" polyimide/S2-glass composite panels. However, with the exception of the maximum dimensional capability for producing panels of each specific manufacturer, the methods proposed for insulation-sheet manufacture were not found to be dependent on the specific type panel or its manufacturer.

Two proposed methods of insulation sheet manufacture were identified as being viable candidates. They are presented as a primary and as an alternate method of construction.

The primary method of insulation-sheet manufacture is illustrated in Fig. 1. An insulation sheet would be assembled as a mosaic from five separate constant thickness composite panels through five joints. The panel labeled as 1 would be ~115 in. long by 17 in. wide. The panels labeled as 2 and 3 would be ~72 in. wide by 44 in. long. The panels labeled as 4 and 5 would be ~101 in. long by 44 in. wide. This would fall within the maximum panel size capability of Spaulding Composites Company of 120 in. long by 48 in. wide. The warp direction of the fabric used in each panel would be oriented in the direction of the CIT cylinder axis.

The panels would be joined into a complete planar sheet using ~4° angle scarf joints. This would provide a contact length for the joint of ~0.6 in. Scarf joints are recommended over other kinds of joints due to the freedom from high peel stresses that tend to cause delaminations that are found in other types of joints. The 4° scarf angle is the angle usually recommended for composite materials to eliminate peel-stress problems and provide maximum joint strength.

The recommended thickness for the composite panels would be 0.032 in., because Spaulrad S panels are manufactured with laminae thicknesses in multiples of 0.008 in. The required insulation thicknesses of 0.040 in. in the nose region and 0.050 in. in the remaining parts of the coil would be made up by using S2-glass fabric overwraps of two

Fig. 1. TF Field coil showing massive panel boundaries. Parts 4 and 5 are bend transition pieces.

layers of 0.002-in.-thick fabric over the entire insulation sheet, plus an additional layer of 0.0055-in.-thick fabric over the areas of the insulation sheet outside the nose region.

Conformance between the copper turns and the composite insulation sheet would then be accomplished by stacking the copper turns interleaved with the insulation/fabric overwrap to construct a complete turn assembly. During assembly, the composite insulation sheet would bend elastically to accommodate the change of plate angle in the nose region up to a maximum of 8.571° . Providing that the original design bend radius for this transition of 10 in. can be maintained, the maximum flexural strain imposed on the composite material will be 0.16%. This is well within the flexural failure strain for S-glass composite material of ~3%.

Thickness-tolerance take-up would then be accomplished by vacuum potting the assembly by means of radial flow, with the tolerance take-up adhesive flowing radially from the interior surface of the coil "D" to the exterior surface of the turn assembly.

In the event that the design bend radius of 10 in. is not attainable and is actually significantly less than 10 in., the elastic bending strain imposed on the composite insulation sheet may be excessive, and, hence, an alternate method of mosaic-insulation-sheet construction was developed. This method uses panels of varying thickness to construct a nonplanar sheet and is illustrated in Fig. 2.

This approach would enable assemble of an insulation sheet from nine panels using nine joints. The panel labeled 1 would be ~115 in. long by 17 in. wide by 0.032 in. thick. The panels labeled 6 and 7 would be ~44 in. long by 60 in. wide by 0.048 in. thick. The panels labeled 8 and 9 would be ~101 in. long by 40 in. wide by 0.048 in. thick. The panels labeled 4 and 5 would be specially fabricated pieces ~44 in. long by 4 to 5 in. wide, a varying in thickness from 0.048 to 0.032 in., with an integral bend angle varying from 0 to 8.571° to match the angle and thickness transition of the copper turns.

These transition pieces would have to be designed and fabricated using materials similar to those used in the composite panels, using a fabrication method such as pultrusion. Preliminary investigation has suggested this as a feasible method for fabrication of these transition pieces.

Panel assembly would also be accomplished using 4° scarf joints for maximum insulation sheet strength. Joint length would vary from 0.6 to 0.7 in., depending on panel thickness. To minimize joint stresses during handling, it may be desirable to preform all joints except those joining panel 1 to panels 2 and 3 prior to installation and then to dry fit these two joints during the assembly operation, allowing the thickness tolerance take-up adhesive to infiltrate these final joints during vacuum potting.

To fill the annular space between turns, this insulation sheet would receive one layer of 0.002-in.-thick S2-glass fabric over the entire insulation sheet, plus an additional 0.002-in.-thick layer of S2-glass fabric over the 0.032-in.-thick section in the nose region. Thickness tolerance take-up would then be accomplished by radial flow vacuum potting as in the primary construction method.

NOT TO SCALE

Fig. 2. Nose bend region of TF coil. Note simultaneous change of direction and thickness.

INSULATION-SHEET/CONDUCTOR-TURN MANUFACTURABILITY STUDY MATRIX

The insulation-sheet/conductor-turn manufacturability study matrix has been weighted to identify significant interactive dependencies between

1. the optimum in-service performance capabilities of generic materials;
2. the key handling and processing parameters required to achieve optimum in-service property performance; and
3. the suitability of requisite handling and processing parameters as a function of design configuration and assembly method. Refer to Appendix C.

The matrix approach was chosen to provide a concise format for presentation of a large volume of data. Column headings represent the major approaches to producing an insulation sheet. These approaches were then subdivided as various ways of building the sheet were identified. This resulted in elaboration and further subdivision of headings as the choices of ways to build an insulation sheet were made. Inherent in this process was the choice of classes of adhesives and sheet materials. Row headings were a sequential listing of the activities and considerations attending the fabrication of the sheet from the design stage to a finished sheet. After the structure was fixed, a working group considered the impact and cross relationships and rated these on a high, medium, and low scale, where appropriate. This generated a sequence of ratings that could be used to evaluate specific choices of sheet-construction approaches.

After choosing the appropriate columns for construction approach, the specific material system was then chosen. By taking the material system through all the performance and construction issues (row headings) and comparing data (or absence of data) with requirements and criticality judgments, an overall sketch of suitability of the approach was obtained. Where data are missing in high criticality areas, a test or study is warranted.

Note that in the column heading "Baseline Approach 1," commercially available, polyimide/S-glass composite panels are addressed as "mosaic," and filament-wound or tow-placement polyimide/S-glass composite panels are addressed as "monolithic." The principal distinction lies in panel size. The optimum, commercially available panels will require piece fitting to achieve a full-sized insulation sheet (mosaic), while tow placement would enable fabrication of a homogeneous, full-sized insulation sheet (monolithic). "Pultruded" is shown as an alternative fabrication process to tow placement. Pultrusion would permit the fabrication of a full-sized insulation sheet, and in a global programmatic approach would deserve further consideration. However, the established program constraints do not permit pultrusion to be a viable candidate for further study.

The column heading, "Baseline Approach 2 Formed-in-Place" recognizes two additional global baseline approaches that are relevant to interactive issues between materials handling and processing, and design configuration and assembly, "Prepreg" and "Dry Cloth + VPI." Because they would be formed in place, key handling and processing parameters, such as cure temperature, dictate that their chemistry be based on modified

epoxy/S-glass and not polyimide/S-glass. The In-Service Performance properties of these formed-in-place, full-sized monolithic panels would be similar to the published performance profiles for modified epoxy/S-glass composites.

Within Baseline Approach 1, tow placement fabrication of a monolithic, full-sized polyimide/S-glass insulation sheet would be the preferred construction method/generic material systematic approach to optimize material selection criteria identified under In-Service Performance and Assembly and Installation. Employment of a monolithic, instead of a mosaic, full-sized insulation sheet permits a reduction in the number of processing parameters associated with fixturing and eliminates the processing parameters associated with the Edge Bond Adhesive System. However, as noted under Full Sheet Design, the design configuration of the full-sized insulation sheet is not a flat sheet. With differential angle geometry in the nose region of each insulation sheet, significant fabrication tooling cost issues do not permit tow placement to be a viable candidate for further study within the established program constraints. These issues include

1. mandrel costs which may reach \$75 to \$100K,
2. manufacturing tolerances approaching ± 0.012 and may be as high as ± 0.016 ,
3. fabrication objectives for tooling that are understood but not proven, and
4. extensive winding time requiring up to 12 h with a crew of 6 people per ply.

In conclusion, a monolithic, polyimide/S-glass, full-sized insulation sheet represents the optimized matrix candidate within the Baseline Approach 1 but is not economically feasible given the budgetary constraints of the program. Commercially available, polyimide/S-glass composite panels are the only candidate material systems that will address the established In-Service Performance criteria within the budgetary parameters of the present program. However, the mosaic, full-sized sheet raises significant assembly and installation issues that will (1) discount the generic in-service performance properties of the polyimide/S-glass panels and (2) substantially increase the fully burdened cost of fabrication beyond the acquisition cost of the individual panels.

A potential benefit of the mosaic approach is that load-adhesive failure modes may not be catastrophic. There would still be an insulating space between turns.

These assembly and installation issues and failure mode should be the focus of a separate engineering study before selection of the programmatic approach employing commercially available composite panels can be substantiated.

Within Baseline Approach 2, the generic alternative of employing a prepreg system is eliminated based upon the obligatory handling and processing parameters required to optimize the cured property performance of prepreg systems. The fixed resin system content, partially reacted to a "B-staged" cure, is intended to provide surface wet-out under compression sufficient to provide an adhesive bond. It is not adequate to perform a tolerance take-up function. Furthermore, the control of insulation-sheet thickness during assembly, coupled with the temperature and pressure aspects of a cure schedule, would require sophisticated fixture tooling that is considered outside the scope of the program.

The dry-cloth/vacuum-pressure impregnation generic system programmatic approach is a commercially established, performance-proven materials/methodology having handling and processing parameters that meet the anticipated TF coil fabrication and assembly criteria. Furthermore, the adhesive bonding and tolerance take-up functional requirements are met within the same set of processing parameters that form the full-sized insulation sheet. The copper alloy used limits processing temperature to 400°F or less. No polyimide/bismaleimide resin systems process at this lower temperature.

With regard to the in-service performance criteria of mechanical loads, radiation resistance, and thermal cycling the optimum in-service performance capability of the mosaic programmatic approach will be determined, to a large extent, by the construction methodology employed to assembly the individual panels into a full-sized sheet. It will not be the generic, peak value performance of the composite panel but rather the efficiency of the installed system, including joints, varying tolerances, and achievable cure schedules, that will determine the ability of the mosaic sheet to maintain its overall in-service integrity. The cured property performance and handling parameters of the panel bondline adhesive and the tolerance take-up system dictate a modified epoxy-based system, which is the same chemistry employed in the monolithic insulation sheet. Therefore, the ultimate in-service performance capability of the mosaic insulation sheet may be no greater than that of the monolithic sheet, based on the performance contribution of the epoxy adhesives and tolerance take-up systems common to both programmatic approaches. Furthermore, the sheet installation issues associated with sheet fabrication will represent the potential for further discounting of the overall in-service performance of the mosaic sheet when compared with the monolithic sheet. This potential for the discounting the in-service performance of the mosaic insulation sheet based on composite panel assembly may offset the perceived generic radiation-performance benefits associated with bismaleimide composite chemistry of the panels. In fact, the net in-service performance capability of the all-modified, epoxy-based monolithic insulation sheet may well exceed that of the mosaic insulation sheet.

MATERIALS TEST PROGRAM

PRELIMINARY GENERIC MATERIALS COMPARATIVE ANALYSIS

The CIT TF Coil Insulation System is required to survive a very rigorous set of operational conditions. The insulation must tolerate cryogenic soak to liquid nitrogen conditions with rapid resistive heating to room temperature during an operating cycle. The insulation will be subjected to shear loads due to magnetic forces exerted on the coils. The insulation system must survive a total radiation dose of $\sim 10^{10}$ rad. The choice of insulation system (insulating sheet and adhesive) is constrained by the requirement that processing temperatures be held below 150°C to prevent annealing of the copper conductors and minimize interlaminar shear stresses associated with the mismatched CTEs.

These design requirements were combined and included as a part of a study of the entire process of producing an insulation sheet. The format for this study was a study matrix that examined performance and fabrication and handling issues. The matrix

approach caused the questions of actually fabricating parts to be given consideration equal to attainment of desirable performance properties.

During preparation of the study, epoxy-based matrix systems emerged as the most likely adhesive due to the processing temperature limits. The epoxy would be present either as the tolerance take-up and bonding medium for press-formed mosaic sheets or as the impregnation medium for VP.

The laboratory tests were defined by the study matrix where data was missing or not known. In general, these items related to handling and processing of epoxies when used in producing an insulation system. The tests are shown in Fig. 3.

TEST PROGRAM

Wet-Out and Drop Spread Evaluation

To bond with maximum strength, the adhesive must wet the surface. This is partly a function of the adhesive (surface tension, components, reactivity) and partly a function of the surface (finish, grease, and oil). The materials of construction (copper, Inconel, Spaulrad™-sheet and silane-treated fiberglass cloth) were used as substrate for application of the test epoxy. The metals and sheet insulation were sanded with 200 grit sandpaper, washed, and degreased with alcohol. The 0.5 cm³ drops of the resin-hardener mix were placed on each of the materials at 45°C and permitted to spread naturally. Satisfactory wet-out should display a concave leading edge at the drop perimeter. Satisfactory wet-out and drop spread of the resin should run to the perimeter of the sample (or over), and it should fill the weave of glass cloth, completely obliterating the outline of the original drop.

Compatibility

A side benefit, the wet out and drop spread is the production of compatibility samples of the material pairs. Any major incompatibility of the materials should manifest itself as corrosive attack, dissolving of one or both components, or failure of the epoxy to harden.

Mechanical Test Specimens

Compression test samples are prepared and subjected to uniaxial compression testing. These samples are nominally 1-in. squares of unreinforced resin and are nominally 0.125 in. thick. While this is much thicker than the expected film thickness of the neat resin, it is a useful comparison within this study.

Coefficient of Thermal Expansion Samples

CTE of the neat resin is a key input parameter for calculation of sheet behavior. These data are measured on small cylindrical samples from room temperature to liquid nitrogen temperature.

CHEMISTRY		1		2		3		4		5		6		7		8	
CURE		1	2	1	2	N/A	2	1	2	1	2	1	2	1	2	1	2
WET-OUT cloth																	
Inconel																	
copper																	
Insul. sheet																	
BROOKFIELD VISCOMETRY (12 HOURS/ 45 C / 1hr Intvl)																	
STATUS AFTER CURE																	
CRYOGENIC EXPOSURE NEAT RESIN BLOCK																	
WASHER EMBEDs																	
"Mech Test Samples"																	
Coeff Therm Exp SPECIMEN																	

Fig. 3. Laboratory wet-work summary.

Cylinder Embedment Samples

Copper cylinders (1 in. in diam by 0.125 in. thick) are embedded in a resin block ~0.50 in. thick. When subjected to large temperature changes, differences in CTE of resin and metal may produce cracking of the resin. These large temperature changes will occur (1) on return to ambient conditions after cure and (2) during the operating cycle. To evaluate the effects of the thermal transient, these samples are cured and then returned to room temperature. The cryogenic tolerance and thermal shock tolerance are tested by dropping the embedded block into liquid nitrogen.

Neat-Resin Blocks

"Neat" resin refers to a sample made up of resin and hardener only. No other reinforcements are included. These blocks are the same size as the copper-embedded sample block. This pair of blocks permits a comparison between the behavior when in contact with another material of different CTE. These blocks are fabricated at the same time and subjected to the same cure and cryogenic cycle as the embedded samples.

Brookfield Viscometry

Viscosity is a key parameter for impregnation. For epoxies, it is a function of the basic resin and hardener mix and the temperature. The viscosity increases, generally, as curing takes place. Thus, the resin can be expected to flow for a limited time during a VPI operation. The viscometry runs were made for 12 h or until the range (3000 cps) was exceeded. This spans acceptable handling times. The runs were made at 45°C nominal temperatures that were actively controlled by the viscometer.

Compression

Specimens from cured panels of various formulations were subjected to compression testing to provide data on mechanical response of the epoxy. The test procedure was essentially ASTM D1691 using an 0.125 in. thick (nominal) specimen initially. A follow-up series of tests were run using 0.0625 in. thick (nominal) specimens of several epoxy cure/chemistry combinations. These tests were conducted at room temperature.

The sample is aligned between the spherical base and the load cell face as shown in Fig. 4. The sample is lubricated on the contact face to inhibit lock up if specimen flows. The deflectometer measures relative motion of the ram with respect to the test machine frame. This measurement when corrected for machine compliance, is an approximate measure of change in specimen height. This can be used to generate an approximate modulus.

This initial set of tests was chosen as a means to screen the field of possible systems. Two other tests are planned for candidates which perform well on the initial series.

Fig. 4. Mechanical compression test setup schematic.

Flow Infiltration

A serpentine passage ~15 ft long and 0.060 in. high is formed between heated metal plates. The resin/hardener mix is flowed through the passage to determine cure time and flow rate. This provides an environment similar to the actual application (i.e., a small passage between massive metal plates). Possible changes in cure behavior should be stimulated if they are possible

Cryomechanical Fatigue

This extensive test is planned as means to establish resin system performance when exposed to cyclic cryogenic shock combined with intermittent mechanical stress cycles. The test sequence is intended to show thermal cycling effects and whether mechanical loading promotes or accelerates failure.

TEMPERATURE CONDITIONS

Handling

Handling, mixing, wet-out, and viscometry were conducted at 45°C. Figure 5 shows viscosity for plain bisphenol A resin. As may be seen, the greatest decrease in viscosity has occurred by 45°C, which represents a good compromise of handling and cure rate.

Cure Schedules

Optimum properties cure temperature(s) for each system was taken from manufacturers recommendations. In the test results, the cures noted as -1 were optimum property cures. (These temperatures were without material-imposed limits to assess the degree of downgrade that might result from other cures.)

Temperature-constrained cures were uniform for all samples (14 h at 120°C). This represents a long, gentle cure cycle well inside the temperature envelope imposed by the CIT copper. This cure cycle was adopted for the ATF/STX machine and produced satisfactory results. The temperature-constrained cures were designated -2 cures.

GENERIC MATERIALS

The study matrix generated several candidate chemistries for the epoxy system. Literature searches and conversations with technical personnel yielded other chemistries with desirable radiation resistance or cryogenic tolerance or both. These were researched to determine their constituents. The outcome was a reasonable number of resins and hardeners that, when mixed in various combinations, spanned an exceptionally broad class of performances. Structural representations of these basic materials are presented in Appendix D.

Bisphenol A Viscosity vs Temperature

Fig. 5. Viscosity of bisphenol A resin as a function of temperature.

Resins

1. Bisphenol "A."

Diglycidylether of bisphenol A (DGEBA) is a major commercially available epoxy resin employed alone and in a variety of systems in conjunction with both reactive and nonreactive modifiers. It adapts to a wide variety of hardeners and diluents. Partial reactions can generate other resins called adducts.

2. Bisphenol "A" + Monomer Diluent.

Reactive materials (diluents) added to the basic resin flexibilize or change other properties. The reactive diluent is bound into the structure as a part of the cure process.

3. Bisphenol "A" + Ether.

Reactive ethers act as reactive diluents. These are typically larger molecules than the monomer-type diluents.

4. Bisphenol "F."

Bisphenol F epoxies are similar to bisphenol "A" epoxy except for their central backbone. The bisphenol "F" has lower viscosity than bisphenol "A" and possibly better thermal tolerance. It was included here as a recommendation by one manufacturer. Bisphenol "F" has its own hardener (where identity and content were proprietary).

Hardeners

1. Nadic methyl anhydride (NMA) is an anhydride curing agent with known good radiation performance. It is a compact molecule and quite active, tending to produce a brittle epoxy.

2. Amine + Diluent. Amine hardeners tend to be more reactive than other hardeners. This hardener combination carries reactive diluents.

3. Dodecenylsuccinic anhydride (DDSA) is an anhydride hardener with a long chain organic "tail." This tail acts as a spacer within the structure and thereby flexibilizes the resin.

4. Methylenedianiline (MDA) is an amine-type hardener. It is included here to represent the undiluted amine. MDA is an aromatic amine.

5. Mentane diamine (MnDA) is a cycloaliphatic amine hardener. It combines a different ring structure with the amine hardener properties.

CANDIDATE SYSTEMS

The basic chemical constituents were combined to produce eight basic formulations for testing as shown in Fig. 6. The specific rationale for each:

Combination 1

This mixture of bisphenol A resin and NMA hardener is a baseline system that produces good radiation-resistant epoxy with strong aggressive adhesion. The TF Test Reactor used this resin and hardener with nonreactive diluents.

Combination 2

Combination 2 is a heavily flexibilized bisphenol "A" with "non-MDA" amine hardener. The flexibilization is by reactive diluents in both resin and hardener.

Combination 3

Bisphenol A plus NMA plus DDSA is the chemistry used with Advanced Toroidal Facility/Superconducting Toroidal Experiment. This is a good handling system with good thermal tolerance above ambient temperature. No -1 cure exists for this system because only a constrained cure was used.

Combination 4

Bisphenol "F" plus its special hardener constitute this candidate. The manufacturer believed this to be more tolerant of thermal shock than bisphenol A-based chemistries.

Combination 5

This combination mixed NMA with the ether diluted bisphenol A. Good handling was combined with some flexibilizing effect.

Combination 6

Use of inert filler to help match CTE was the goal of this mixture. Basically, it is Combination 1 with the addition of microscopic glass beads. Problems obtaining the filler delayed evaluation of this system.

Combination 7

Bisphenol A combined with MDA produces the analog of one of the most radiation-resistant resins Known as TGMDA.

MATERIAL	COMBINATION							
	1	2	3	4	5	6	7	8
RESINS								
Bis A (Shell 828)	X					X	X	X
Bis A + diluent (Shell 9485)		X						
Bis A + BGE (Dow 324)					X			
Bis F + 77 (Shell Res-1645)				X				
HARDENERS								
Research Hardener 77 (Shell Res-763)				X				
MSA (Buffalo Color)	X		X		X	X		
Amino + diluent (Shell 9476)		X						
DDSA (Buffalo Color)			X					
MDA (methylene dianiline)							X	
MDA (n eutane dianiline) (Rohm & Haas)								X
ACCELERATOR								
BOMA	X		X		X	X		
FILLER								
Micronized fillers (Whitaker, Clark)						X		
LOW VISCOSITY ANALOG OF MDA CURED SYSTEM - cycloaliphatic amine curing agent (liquid) replaces solid MDA								8
ANALOG OF TGMDA (TGDDM) SYSTEM - known very good radiation resistance, but poor handling								7
FILLED SYSTEM FOR RAD RESISTANCE and CTE - small amount inorganic filler for mechanical and thermal tailoring								6
ETHER FLEXIBILIZED RESIN SYSTEM - viscosity reduced by reactive ether								5
BIS F POTTING SYSTEM - reduced viscosity, possible better radiation resistant system								4
ATF/STX SYSTEM WITH REDUCED FLEXIBILIZER - known good handling, flexibilizer reduced for better radiation tolerance								3
DOUBLE FLEXIBILIZED SYSTEM ANNE CURED - fully reactive flexibilizers for better temperature tolerance								2
REFERENCE ANHYDRIDE CURED SYSTEM - known good radiation resistance, good handling, but brittle								1

Fig. 6. Material combinations.

Combination 8

Bisphenol A plus MnDA provides very attractive handling properties combined with a desirable structure.

LABORATORY WORK CONCLUSIONS

The results of the laboratory testing are summarized as groups tests.

Wet-Out and Compatibility

All of the resin systems, except combination 7, showed good wet-out, flow, and drop spread on copper, Inconel, and Spaulrad™ sheet. The exception, combination 7, did wet the surfaces but did not flow enough to fully absorb the initial droplet. None of the items showed gross incompatibility.

Viscosity-Time

Viscosity-time curves are plotted in Fig. 7. The combinations studied separate into three distinct families but not strictly along hardener lines. The two lowest viscosities and lowest rate-of-rise systems were the highly flexibilized bisphenol A/amine and ether-cut bisphenol A/anhydride. The shortest rise times were the TGMDA analog (bisphenol A + MDA) and the bisphenol A/MnDA, both amine curing systems. Between these extremes, the remainder of the systems produce classic viscosity rise plots over 10- to 12-h periods.

One candidate suffers particularly badly here. The most radiation-resistant system (Combination 7 TGMDA analog) starts out at a viscosity >800 cps, too high for reliable impregnation by VPI methods. This confirms the qualitative observation from wet-out and flow studies. This system also exhibits an extremely rapid viscosity rise to over 1000 cps in 1 h. This definitely flags the system as unsuited to VPI use.

The other noteworthy system is the bisphenol A/MnDA system. While it exhibits a very rapid viscosity rise, it starts at much lower values. There is a possibility of tuning this system with temperature and reactive diluents to provide longer working life.

Cure Response

Ideally, the resin/hardener system should not self-destruct due to thermal stresses built in as a result of the elevated temperature at which cure is conducted. All of the maximum properties -1 cures were at temperatures well above the constrained -2 cures. Generally, systems evaluated were intact on return to room temperature. Two notable exceptions exist to this. The bisphenol A + NMA (1-1) system cracked in a large halo around the embedded cylinder (Fig. 8) upon cooling to room temperature. The neat resin bisphenol A + NMA also had a few small cracks. The ether-cut bisphenol A + NMA (5-1) cracked around the embedded washer but not in the neat resin. It should be

Fig. 7. Viscosity vs time for resin hardness combinations.

DWG. NO. K/G-
PHOTO NO. K/PH-89-1897
(U)

Fig. 8. Embedment sample after cure - no cryogenic exposure.

reiterated that this was a result of cooling from maximum properties cure temperature to laboratory ambient.

Temperature constrained cures -2 did not produce cracking of any system in either embedded or neat resin. The 120°C cure temperature permits good cure without excessive dimensional changes.

Cryogenic Exposure

The cryogenic exposure cycle for the samples is a combined shock plus tolerance test. Samples were dropped into a dewar flask full of liquid nitrogen and permitted to equilibrate. Upon equilibration, the blocks were removed from the liquid nitrogen and permitted to rewarm to ambient temperature.

The results of this single cryogenic exposure were a distinct separation of systems and cures. As may be seen in the laboratory work summary, Fig. 9, both the embedment and neat resin samples cracked for combinations 1-1, 1-2, 3-2, 5-1, and 5-2. These samples cracked massively, almost to the point of shattering. Figs. 10 and 11 are typical of these massive failures, both of neat resin and embedment samples.

A second mode of failure characterized by a "tri-hub" burst of embedment samples was noted. Evidently these failures were more nearly tensile failures. Corresponding neat resin samples did not crack. Fig. 12 is typical of this failure noted combinations 2-1, 4-1, 4-2, and 8-2.

Another mode of failure was exhibited by combination 7-1 (TGMDA analog at maximum properties). The embedment sample developed a large conical shear surface radiating upward from the periphery of the copper cylinder embedment. This crown-like failure almost propagated to the upper surface.

Handling and Cryogenic Exposure

By the absence of cracking in either the neat resin or the embedded sample, only three combinations of chemistry and cure survived the cryogenic exposure. These were combination 2-2 (highly flexibilized bisphenol A + amine) cured at constrained conditions, combination 7-2 (TGMDA analog) cured at constrained conditions, and combination 8-1 (bisphenol A + cycloaliphatic amine) cured at maximum properties. Because the TGMDA analog had grossly unsuitable flow properties, it was effectively eliminated.

Thick-Sample Compression

The thick compression samples (0.125 in.) displayed a tendency to produce a nearly linear (elastic) response to increasing load up to certain load. At this point, the curve developed a pronounced deviation, appearing much like classic yielding. The load curves then turned upward again until gross failure of the materials occurred. Because of the definite knee in the curve, a figure of 1.75% was chosen as representative of the "yield point," and point of gross failure was defined as the ultimate strength.

CHEMISTRY		1		2		3		4		5		6		7		8	
CURE		1	2	1	2	N/A	2	1	2	1	2	1	2	1	2	1	2
WET-OUT cloth		OK		OK		OK		OK		OK				Wet OK Poor flow		OK	
Inconel		OK		OK		OK		OK		OK				Wet OK Poor flow		OK	
copper		OK		OK		OK		OK		OK				Wet OK Poor flow		OK	
insul. sheet		OK		OK		OK		OK		OK				Wet OK Poor flow		OK	
BROOKFIELD VISCOMETRY (12 HOURS/ 45 C / 1hr intvl)		OK		OK		OK		OK		OK				Too High		Visc OK Short Life	
STATUS AFTER CURE		CRK	OK	OK	OK	N/A	OK	OK	OK	CRK	OK			OK	OK	OK	OK
CRYOGENIC EXPOSURE NEAT RESIN BLOCK		CRK	CRK	OK	OK	N/A	CRK	OK	OK	CRK	CRK			OK	OK	OK	OK
WASHER EMBEDs		CRK	CRK	CRK	OK	N/A	CRK	CRK	CRK	CRK	CRK			CRK	OK	OK	CRK
"Mech Test Samples"		IN PROGRESS		////	////	N/A	////	////	////	////	////			////	////	////	////
Coeff Therm Exp SPECIMEN		IN PROGRESS		////	////	N/A	////	////	////	////	////			////	////	////	////

OK - Denotes property or performance acceptable

CRK - Denotes sample cracked as result of step indicated

Fig. 9. Laboratory results summary.

PHOTO NO. K/PH-89-2283
(U)

Fig. 10. Massive thermal-induced failure - embedment sample.

Fig. 11. Massive thermal-induced failure – neat resin.

PHOTO NO. K/PH-89-2287
(U)

Fig. 12 Tensile-dominated thermal failure.

The compressive-yield strength, modulus, and ultimate strength are shown in Table 3.

Table 3. Summary of thick-sample compression tests

Cure	System 1	System 2	System 3	System 4	System 7	System 8
Stress level (psi) to produce 1.75% offset for system/cure combinations (thick sample)						
-1	16,410	20,201	N/A	25,577	20,786	26,849
-2	27,770	26,587	32,272	25,562	22,956	26,883
"Modulus" (psi) for system/cure combinations (thick sample)						
-1	316,406	312,195	N/A	477,263	342,978	541,520
-2	679,997	582,139	1,274,733	467,906	453,533	513,269
Ultimate strength (psi) for system/cure combinations (thick sample)						
-1	21,913	73,384	N/A	88,849	75,229	90,318
-2	28,032	99,157	32,571	109,207	84,645	108,302

The test data for these thick samples do not follow any simple relationship to cure schedule. This is probably due to differences in actual cure state attained, which is, in turn, a function of the chemical constituents as well as the cure schedule. In some cases, such as combinations 4 and 8, the "maximum-property" cure yields results very close to the "temperature-constrained" cure, indicating that the actual cure state may have been very nearly complete for both cures.

Note that the "maximum-property" cures were taken from manufacturers' data. In general, these cures were specified for maximum tensile properties. There is a finite possibility that the micro-level structure most suitable for good tensile properties may not be most suitable for good compressive properties.

Failure Modes. The thick samples displayed three distinct modes of failure when compressed beyond the yield point: (1) plastic flow – the sample began to compress rapidly and spread across the loading block, (2) chipping – progressive chipping through the thickness on ~45° (shear) planes, and (3) cracking – sudden failure through the thickness of the material. Some system/cure combinations displayed evidence of a mixture of modes. These results are tabulated in Table 4.

Table 4. Compression failure mode of system/cure combinations

Cure	System 1	System 2	System 3	System 4	System 7	System 8
-1	Flow	Crack	N/A	Chip and flow	Chip and crack	Chip and flow
-2	Crack	Crack	Flow	Chip and flow	Chip and crack	Chip and flow

Thin-Section Tests

To assess the magnitude of change in mechanical performance induced by the changes in thickness of the sample, a second set of tests were run using samples of ~0.063 in. nominal thickness. This reduction in thickness was expected to change the measured values somewhat by preventing development of some failure modes.

General Observations. Thinner samples changed the behavior under compression. Most samples showed a uniform increase in deflection under load, stiffening somewhat at higher load levels. The chipping mode was not as pronounced as in the thick samples. The bulk cracking mode was suppressed entirely. All samples went to 140,000-psi load without displaying a distinct ultimate strength.

Elastic range parameters (yield strength and modulus) were also taken on the thin samples. As stated above, the 1.75% criterion was used as a guide for "yield-point" definition. Because the thin samples displayed a tendency to stiffen up, the departure from linearity was upward (less deflection for increasing load), the "modulus" increased. Tables 5 and 6 summarize the data.

Table 5. Thin-sample compression test results

Cure	System 1	System 2	System 3	System 4	System 7	System 8
"Yield" strength (psi) at 1.75% deformation for system/cure combinations (thin section)						
-1	52,016	53,901	N/A	—	54,560	—
-2	49,220	47,266	46,284	52,969	42,669	45,118
"Modulus" (psi) for system/cure combinations (thin section)						
-1	461,428	370,889	N/A	—	427,604	—
-2	651,658	424,824	565,446	387,831	339,000	514,957

Failure Modes. The thin samples did not display a dramatic failure that could be called the ultimate strength. The failure by bulk cracking was also completely suppressed. The failure modes are summarized in Table 6.

Table 6. Failure modes of thin-compression samples

Cure	System 1	System 2	System 3	System 4	System 7	System 8
-1	Flow	Chip and flow	N/A	—	Chip and flow	—
-2	Flow	Chip and flow	Flow	Chip and flow	Chip and flow	Chip and flow

Chipping in the thin samples was limited to small areas on the perimeter—not throughout the bulk material. All samples were taken to the fixture limit of 140,000 lb, where testing stopped. The thin-section mechanical testing seems to show a pattern more like what would be expected—some slight derating due at the cure temperatures. The epoxies perform better in compression as thin films.

SUMMARY

The present programmatic focus on identification of commercially available composite panels that will meet the in-service mechanical and radiation performance criteria of the TF coil design configuration should be augmented to incorporate identification of the candidate chemistries and product formats required for a structural adhesive in both the panel-edge and bonded-region applications and for tolerance take-up in the mosaic insulation sheet programmatic approach. Handling and processing issues associated with these materials and their application may well preclude the mosaic programmatic approach from further study. Candidate material chemistries, having the necessary handling and processing properties to provide *in situ* Z-plane adhesive bonding and tolerance take-up in the mosaic sheet are the subject of an ongoing study. Their in-service radiation and mechanical property performance in conjunction with candidate commercially available composite panels is the subject of the proposed RAD II and RAD IIA study schedule in FY 1990.

These same candidate materials employed as a modified epoxy vacuum impregnation system with a dry S-glass insulation sheet configuration represent the monolithic insulation sheet which is the most likely candidate programmatic approach based upon issues of manufacturability. S-glass dry cloth compositions for a monolithic insulation sheet should be included in further study. Percentage of full-cure condition should be determined by differential scanning calorimeter for the systems under consideration. Only two systems of resin and hardener have survived the laboratory testing.

REFERENCES

1. S. Tagawa et al., *J. Nuc. Matls.* 133 and 134, 785-787 (1985).
2. D. S. Tucker et al., *J. Nuc. Matls.* 133 and 134, 805-809 (1985).
3. M. Watanabe and H. Maeta, *J. Nuc. Matls.* 133 and 134, 800-804 (1985).
4. F. W. Clinard, Jr. and G. F. Hurley, *J. Nuc. Matls.* 103 and 104, 705-716 (1981).
5. G. F. Hurley and R. R. Colman, Jr., *J. Nuc. Matls.* 122 and 123, 1327-1337 (1984).
6. S. Takamura and T. Kato, *J. Nuc. Matls.* 103 and 104, 729-734 (1981).
7. M. Hagiwara et al., *J. Nuc. Matls.* 133 and 134, 810-814 (1985).

Appendix A

TOROIDAL FIELD COIL SYSTEM DESCRIPTION DOCUMENT EXTRACT

Appendix B

BONDED AND UNBONDED REGION LAYOUT FOR TOROIDAL FIELD COIL

51/52

BONDED REGIONS

UNBONDED REGIONS

NOT SHADED

Appendix C

**INSULATION SHEET/CONDUCTOR TURN MANUFACTURABILITY
STUDY MATRIX**

COMPACT IGNITION TOKAMU

BASELINE APPROACH No.1 SH

INSULATION SYSTEM MATERIAL SELECTION CRITERIA	GENERIC IN-SERVICE PERFORMANCE PROPERTIES																SIGNIFICANCE IN-SER		
	COMPOSITE SHEET INSULATION								ADHESIVE / TOLERANCE TAKE-UP SYSTEM								MOBAC		
	PHYSICAL		THERMAL		ELECTRICAL		CHEMICAL		8 STAGED		FILM		PASTE		LIQUID		PANEL SIZE	FIBER ORIENTN	EDGE GEOMETRY
	INITIAL	FATIGUE	INITIAL	FATIGUE	INITIAL	FATIGUE	INITIAL	FATIGUE	INITIAL	FATIGUE	INITIAL	FATIGUE	INITIAL	FATIGUE	INITIAL	FATIGUE			
I. IN-SERVICE PERFORMANCE <small>See Future Studies</small>																			
A. MECHANICAL LOADS																			
1. COMPRESSIVE	↔	↓	↔	↔	↔	↓	↔	↔	↔	↓	↔	↓	↓	↓	↔	↓	LOW	LOW	LOW
2. SHEAR / TORQUE / PEEL	↔	↓	↔	↔	↔	↓	↔	↔	↔	↓	↔	↓	↓	↓	↔	↓	MED	LOW	HIGH
B. RADIATION																			
1. GAMMA	↔	↓	↔	↓	↔	↓	↔	↓	↔	↓	↔	↓	↔	↓	↔	↓	LOW	LOW	HIGH
2. NEUTRON	↔	↓	↔	↓	↔	↓	↔	↓	↔	↓	↔	↓	↔	↓	↔	↓	LOW	LOW	HIGH
C. THERMAL CYCLING																			
1. TEMPERATURE RANGE	↑	*	↔	↔	↔	↓	↔	↔	↔	↓	↔	*	↔	*	↓	*	HIGH	LOW	HIGH
2. TIME RATE of CHANGE	↓	↓	↔	↓	↔	↓	↔	↔	↓	↓	↓	↓	↓	↓	↓	↓	HIGH	LOW	HIGH
II. FULL SHEET DESIGN																			
A. PANEL DESIGN																			
1. SIZE																	HIGH	HIGH	HIGH
2. ORIENTATION																	HIGH	LOW	HIGH
3. SHAPE (X, Y)																	HIGH	LOW	HIGH
4. 2 TOLERANCE MISMATCH																	HIGH	LOW	HIGH
a. PANEL EDGE																	HIGH	LOW	HIGH
b. ANGLE																	HIGH	LOW	HIGH
c. OVERALL																	HIGH	HIGH	HIGH
5. DIFF. W/TE. NOISE ANGLE																	HIGH	HIGH	HIGH
B. FIBER PATTERN GEOMETRY																	HIGH	HIGH	HIGH
C. TURN TO TURN TRANSITION																	LOW	HIGH	HIGH
III. ASSEMBLY and INSTALLATION																			

AK (CIT) TOROIDAL FIELD COIL INSULATION SYSTEM STUDY MATRIX

HEET (PULTRUDED, PRESS-FORMED, or TOW-PLACED) • ADHESIVE • TOLERANCE TAKE-UP

OF CONSTRUCTION METHOD ON IVICE PERFORMANCE					SIGNIFICANCE OF CONSTRUCTION METHOD ON ASSEMBLY, and INSTALLATION							INSULATION SHEET SYSTEM CANDIDATES						
					MOBAC					MONOLITHIC		S GLASS + IMIDE PANEL						
					IN SITU			PRE FAB				DRY FIT PRESSFORMED SHEET MOBAC					LOW PLACED PANEL	
					EDGE ADHESIVE	PANEL SIZE	FIBER ORIENTN	EDGE GEOMETRY	EDGE ADHESIVE	DRY FIT	WET FIT		WET FIT	DRY FIT	SHELL FIBER/SH70			
X,Y	X,Y,Z	ODGERA (OLUENT) + 1 per MDA AROMATIC AMINE/OLUENT	ADHESIVE	SYSTEM							ADHESIVE	SYSTEM			ADHESIVE	SYSTEM		
LOW	LOW	LOW	—	—							○			○		○		
HIGH	LOW	LOW	—	—							○			○		○		
HIGH	LOW	LOW	—	—							*			*		○		
HIGH	LOW	LOW	—	—							*			*		○		
HIGH	LOW	LOW	—	—							○			○		○		
HIGH	LOW	LOW	—	—							*			*		*		
HIGH	—	—	—	—	HIGH	HIGH	HIGH	HIGH	HIGH	—	—	—	—	—	—	○		
HIGH	LOW	—	—	—	LOW	LOW	LOW	LOW	LOW	—	—	—	—	—	—	○		
HIGH	LOW	—	—	—	MED	HIGH	HIGH	HIGH	HIGH	—	—	—	—	—	—	○		
LOW	LOW	—	—	—	MED	HIGH	HIGH	HIGH	HIGH	—	—	—	—	—	—	—		
LOW	HIGH	—	—	—	MED	MED	HIGH	HIGH	HIGH	—	—	—	—	—	—	—		
HIGH	HIGH	HIGH	HIGH	HIGH	LOW	HIGH	HIGH	HIGH	HIGH	—	—	—	—	—	—	—		
LOW	LOW	—	—	—	LOW	LOW	LOW	LOW	LOW	MED	—	—	—	—	—	—		
LOW	HIGH	—	—	—	LOW	LOW	LOW	LOW	LOW	LOW	—	—	—	—	—	—		

BASELINE APPROACH No. 2 FORMED - IN - PLACE									
GENERIC SYSTEMS						INSULATION SYSTEM CANDIDATES S-GLASS			
PRE-PREG		DRY CLOTH - V.P.I.				RESIN - HARDENER			
		CLOTH		RESIN		ATF/STX GENERIC	CIBA-GEIGY	SHELL	GENERIC
E-GLASS	S-GLASS	E-GLASS	S-GLASS	IMIDE	EPOXY	DOESA • (NMA/ODSA) • [ECH • BIS A] • (NMA/ODSA)	TOGOM • DOS • (MDA • DOS • [ECH/MDA] • DOS	DOESA • (ment) • [AROMATIC AMINE non-MDA/eth/ment]	DOESA • AROMATIC AMINE (MDA)
○ ○ ○ ● ○ *	○ ○ ○ ○ ○ *	○ ○ ○ ● ○ *	○ ○ ○ ○ ○ *	○ ○ ● ○ ○ *	○ ○ ● * ○ *	○ * * * * *	○ * * * * *	○ * * * * *	○ * * * * *

	o o o o o o o	o o o o	
	o o o o o o o	o o p o	
	o ● * ● o ● o	o o ● * ●	
	o o o o o o o	o o p o	
	o o o o o o o	o o p o	
	o * * * o ● o	o o ● o	
o		o o	
o		o o	
●	o ● ● ● o o ●	● o ●	
●	o ● ● ● o o ●	● p ●	

Appendix D

MOLECULAR STRUCTURE OF BASIC COMPONENTS

This appendix contains structural diagrams of basic chemicals identified and examined during the course of the preliminary study. Most of the compounds have acquired informal acronyms. These acronyms are not always systematized, so multiple compounds may share the same acronym or multiple acronyms may be applied to the same compound.

The compounds listed below are contained in the diagrams. A very brief description of the use of the compounds is included for each.

DDS or DADPS - diaminodiphenylsulfone - amine curing agent.

DDM - diaminodiphenylmethane - amine curing agent.

mPDA - meta phenylenediamine - amine curing agent.

Diaminotoluene - amine curing agent.

BDMA - benzyl dimethylamine - catalyst used to promote action of anhydride curing agents.

NMA - nadic methyl anhydride - trade name for Buffalo Color's anhydride curing agent, maleic anhydride adduct of methylcyclopentadiene.

Maleic anhydride - simplest anhydride curing agent.

DiCy - dicyandiamide - amine-type curing agent.

DDSA - dodecenylsuccinic anhydride - anhydride curing and flexibilizing agent.

MnDA - menthane diamine - a cycloaliphatic amine curing agent.

DGEBA - diglycidyl ether of bisphenol A - very common epoxy resin. Basis of many systems.

MDA - (4,4') methylene dianiline - aromatic amine curing agent

TGDDM - tetraglycidyl diaminodiphenyl methane - epoxy resin reputed to have high radiation resistance.

TGMDA - tetraglycidyl methylene dianiline - identical to TGDDM. Different selection of naming groups.

Styrene oxide - acts as spacer representative reactive diluent. The single active site stops polymerization process. The ring structure acts as a spacer.

BGE - butyl glycidyl ether - reactive diluent contains a long chain to act as spacer.

ECPE - epoxycyclopentyle ether - component of epoxy resin. Fully reactive. Serves to change viscosity of base resin.

Diglycidyl ether of bisphenol F - epoxy resin based on bisphenol F. Lower viscosity than bisphenol A resins.

Aminopropyltriethoxysilane - typical silane coupling agent used to promote adhesion of epoxy to glass.

CARBOWAX™ 400 - a mixture of polyethylene glycol (waxes) used to flexibilize epoxies. Not reactive. CARBOWAX™ is a Union Carbide Corporation trade name.

DDS**DADPS****Diamino diphenyl sulfone** **DDM****Diamino diphenyl methane** **mPDA****meta Phenylene diamine**

Diamino toluene **BDMA**

Benzyl dimethyl amine
(catalyst for anhydrides)

NMA

Nadic methyl anhydride
Maleic anhydride adduct
of
Methyl cyclo pentadiene

Maleic Anhydride **DiCy
Dicyandiamide** **DDSA
Dodecenylsuccinic
anhydride**

MnDA**MENTHANE DIAMINE**

DGEBA

Diglycidyl ether of bisphenol A

MDA

(4,4') Methylene dianiline

TGDDM Tetraglycidyl diamino diphenyl methane
TGMDA Tetraglycidyl methylene dianiline

Styrene Oxide

BGE**Butyl glycidyl ether
(reactive diluent)**

ECPE
bis (2,3 epoxycyclopentyl) ether

liquid

solid

DIGLYCIDYL ETHER
OF BISPHENOL F

Aminopropyl triethoxysilane

(50 - 50 mix)