COMPOSITE TECHNOLOGY DEVELOPMENT, INC.

ENGINEERED MATERIAL SOLUTIONS

Advanced Insulation for Fusion Magnet Systems

Presented to:

Princeton Plasma Physics Laboratory

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Lafayette, Colorado
May 6, 2004

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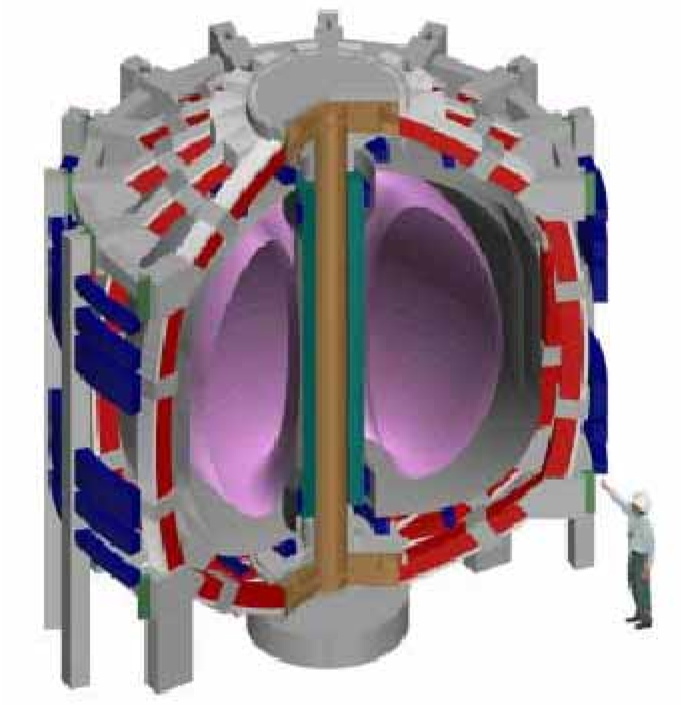
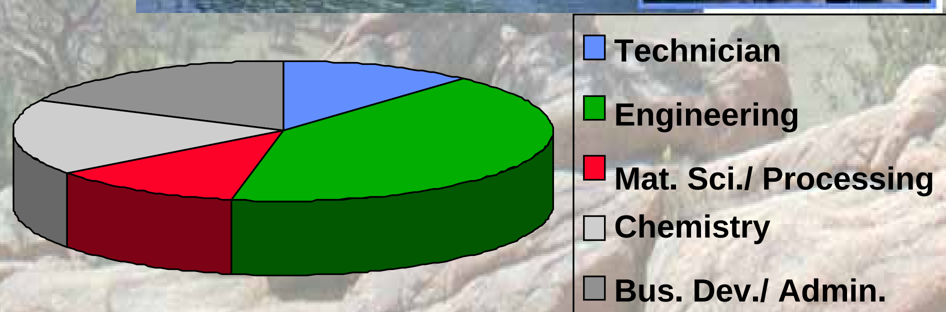
Outline

- Introduction to CTD
- Commercial Materials
- Current Insulation Research Programs
- New Material Development Proposals
- Additional Insulation Activities
- Discussion



Update on CTD

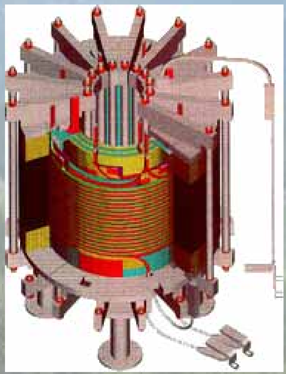
- **Incorporated in 1988 - to develop novel engineered materials**
- **Integrated Systematic Approach**
  - **Concurrent multi-disciplinary activities developing purpose-designed materials**
  - **Data, test methods, models, engineering methods**
- **Highly skilled, multi-disciplinary staff**
- **Efforts leveraged by collaborations and key consultants**
- **18,000 ft^2 state-of-the-art R&D facility in Lafayette, Colorado**

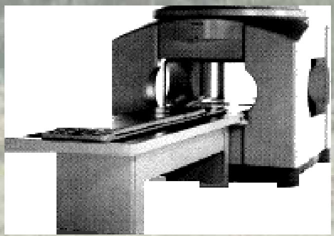


"Engineered Material Solutions"

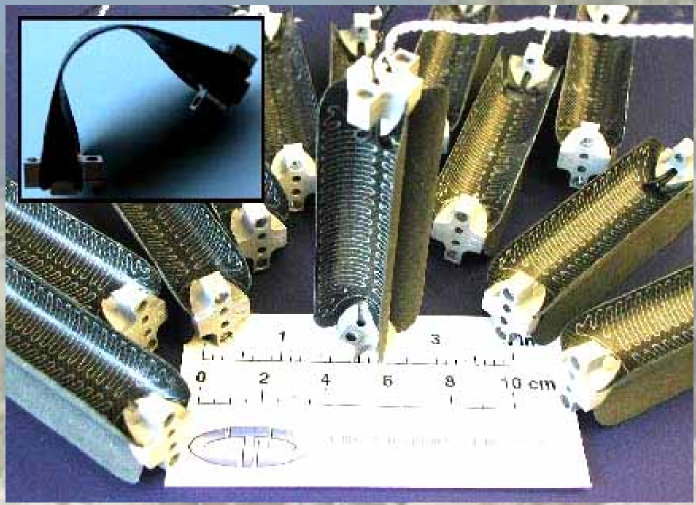
CTD is a unique company where the development of original materials is fused with incisive engineering to provide innovative solutions for our customers' technology and system needs.

For CTD, development of new materials is an engineering tool

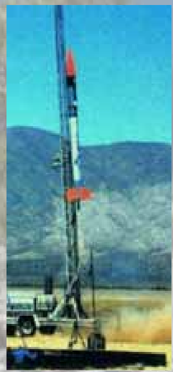




Electrical and Thermal Insulation



Elastic Memory Composites



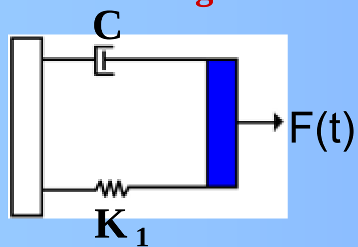
Composite Pressure Vessels

Product Development Tools

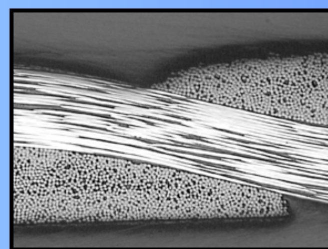
Define Requirements and develop conceptual component design

Engineering

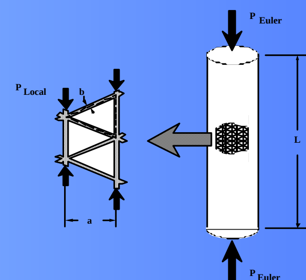
Micro-Mechanics Modeling



Laminate Design



Component Design



Fabricate First Article

Nano — **Micro** — **Milli** — **Centi** — **Meter**

Materials & Product Development

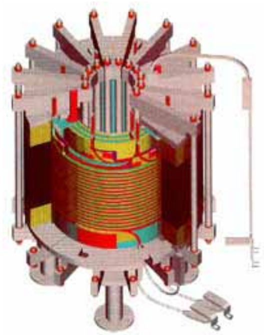
Polymer Synthesis

Polymer Evaluation

Laminate Evaluation

Coupon/Component Testing

In the beginning...

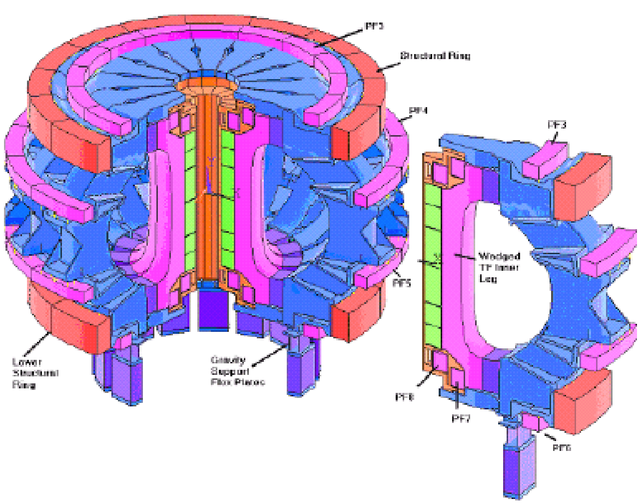


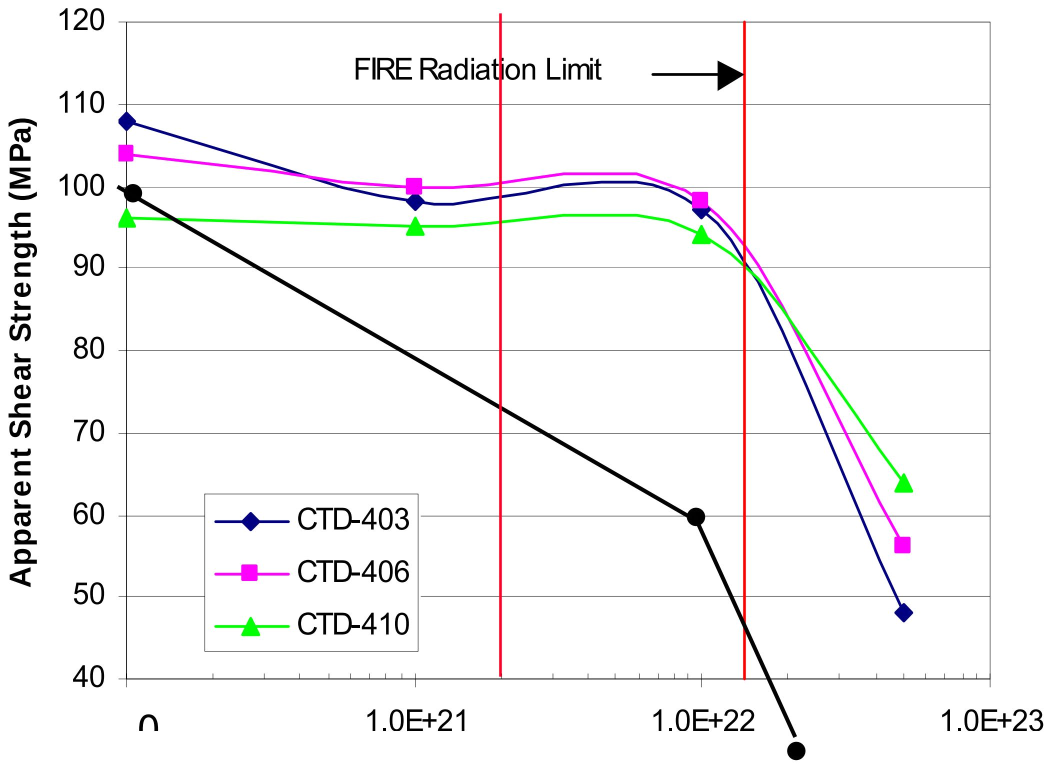
Developed electrical insulation for superconducting magnets exposed to radiation

- **Sponsored by DOE**
  - **Supporting fusion and high energy physics**
- **Developed epoxy based glass-reinforced composite materials**
  - **Cryogenic performance**
  - **Resistance to radiation**
- **CTD's efforts**
  - **Formulated resin**
  - **Designed composite material**
  - **Developed evaluation tests**
  - **Verified insulation performance**
  - **Developed application process**
  - **Supported construction**

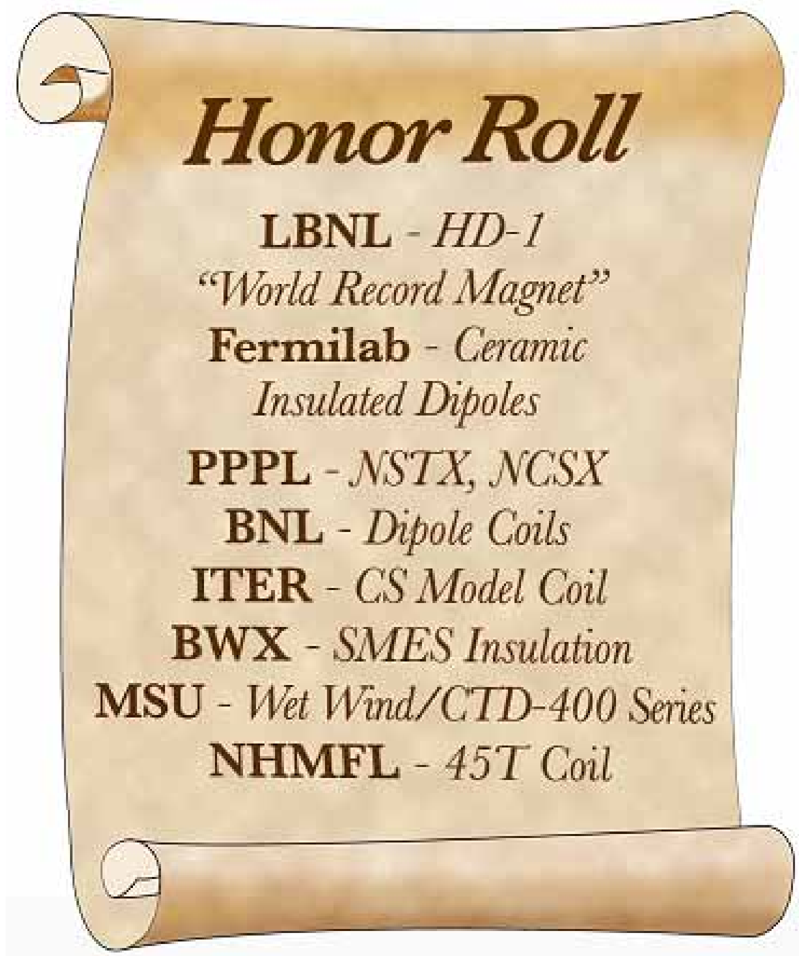
10 Fold Increase in Radiation Resistance

- **Irradiation Test Results - Shear**
  - **Cyanate Ester resins versus Epoxies**
  - **Tested at Liquid Nitrogen temperature**





CTD Magnet Insulation History



Insulation Products

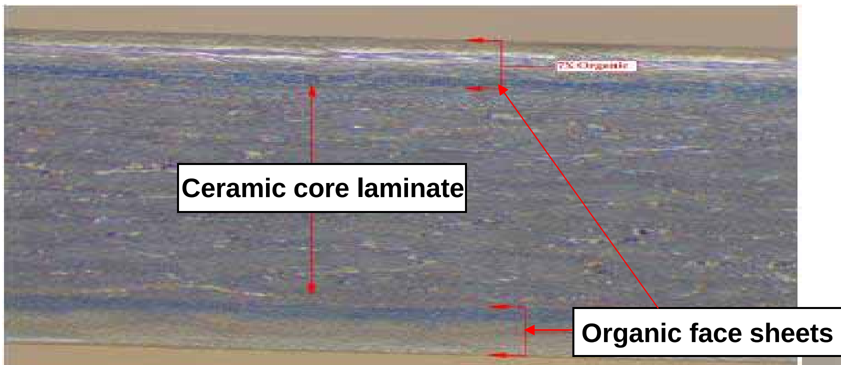
- **Developing insulation to meet the needs of fusion magnets**

Fabrication Method / Conductor Type	Vacuum Pressure Impregnation	Pre-preg	High-Pressure Laminate	Coated Polyimide Film (Kapton)	Co-processed Ceramic Hybrid	Wet winding
Copper/NbTi	CTD-101K CTD-403 7056-BCP	CTD-115P CTD-121P CTD-10X	CTD-HR3 CTD-7X	CTD-121		CTD-521 CTD-540 CTD-422-FM6 CTD-500XA
Nb_3Sn	CTD-101K CTD-101 CTD-403 7056-BCP	CTD-115P CTD-121P CTD-15X	CTD-HR3 CTD-7X	CTD-121	CTD-1008X CTD-1012PX 7057 DX-2	CTD-521 CTD-540
HTS	CTD-101K CTD-403 CTD-528	CTD-115P CTD-121P		CTD-121		CTD-521 CTD-540

Commercial Product	Developmental Product	Not Available

Current DOE Insulation Programs

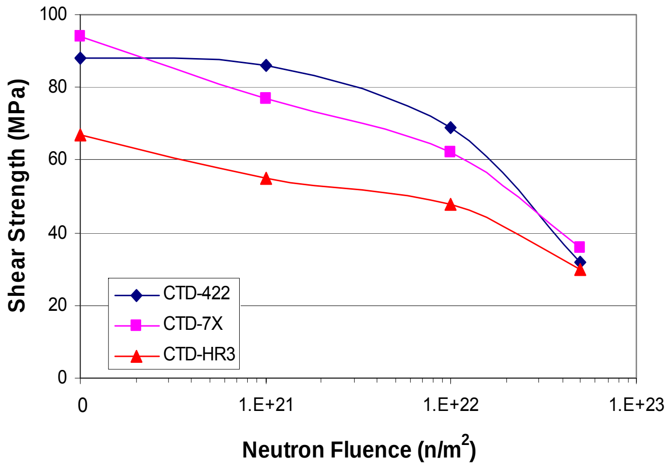
DOE Phase II SBIR – Radiation Resistant High Pressure Laminate Insulation

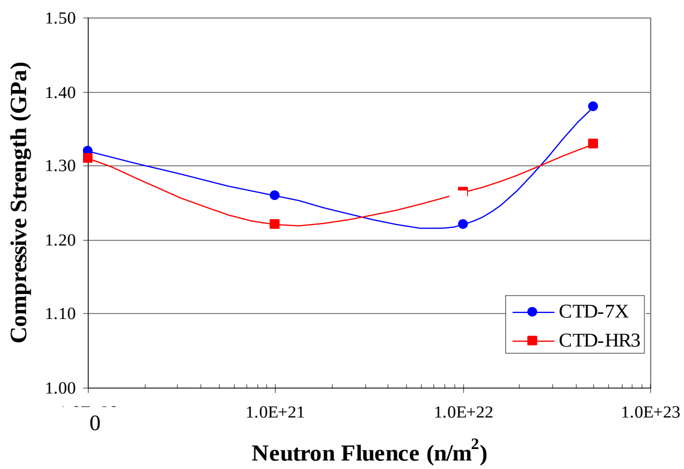


- **Material development**
  - **Cyanate Esters**
  - **Polyimides**
  - **Bismaleimides**
  - **Ceramic Hybrids**

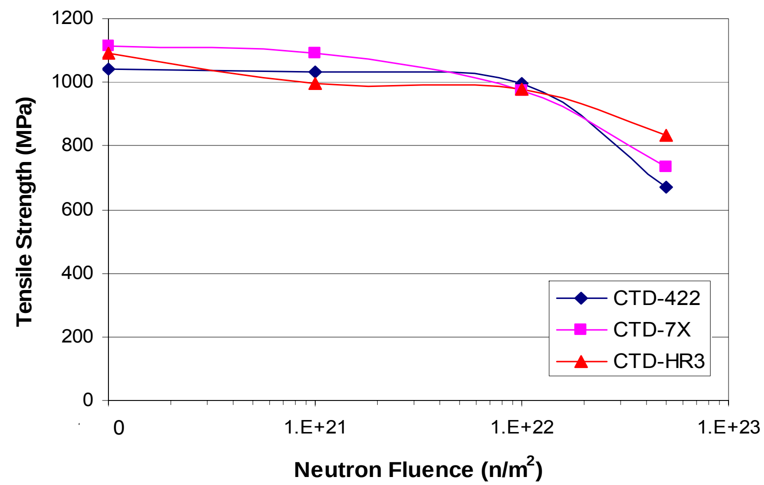
- **HPL process development**
  - **Pre-preg fabrication**
  - **High-pressure fabrication**

Radiation Resistant HPL Insulation



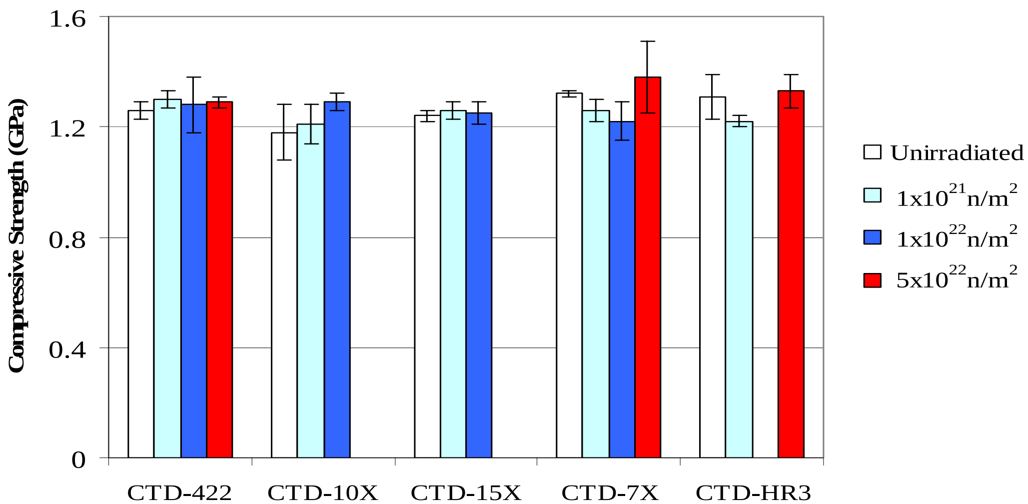


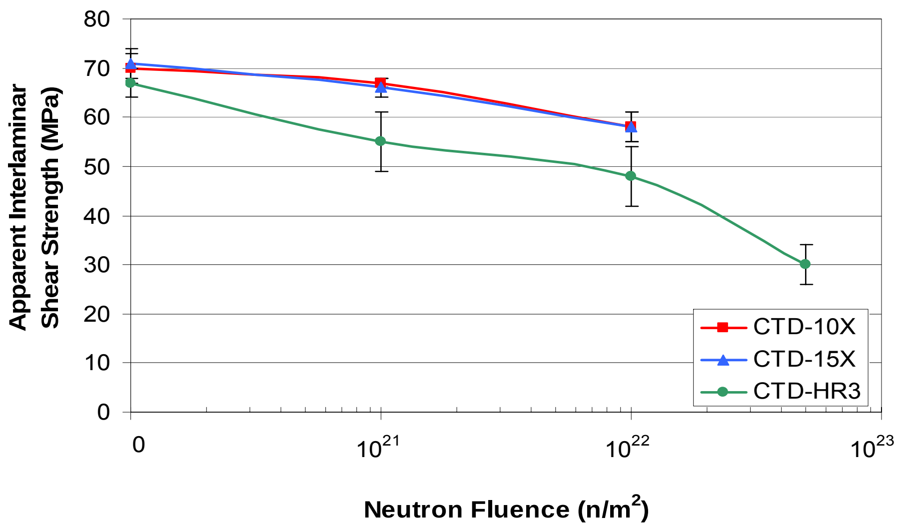
- **HPL Systems**
  - **CTD-7X, CE/PI/Epoxy**
  - **CTD-HR3, CE/PI**
- **VPI System**
  - **CTD-422, CE/Epoxy**



- **Austria TRIGA Reactor Irradiation**
  - **80% gamma, 20% neutron, 340 K**
  - **10^{21} n/m^2 = 4.7 x 10^8 Rads**
  - **10^{22} n/m^2 = 4.7 x 10^9 Rads**
  - **5 x 10^{22} n/m^2 = 2.3 x 10^{10} Rads**

Radiation Resistant Insulation Systems





- **VPI System**
  - **CTD-422, CE/Epoxy**
- **Pre-Preg Systems**
  - **CTD-10X, CE/BMI**
  - **CTD-15X, CE/Epoxy**
- **HPL Systems**
  - **CTD-7X, CE/PI/Epoxy**
  - **CTD-HR3, CE/PI**

- **Austria TRIGA Reactor Irradiation**
  - **80% gamma, 20% neutron, 340 K**
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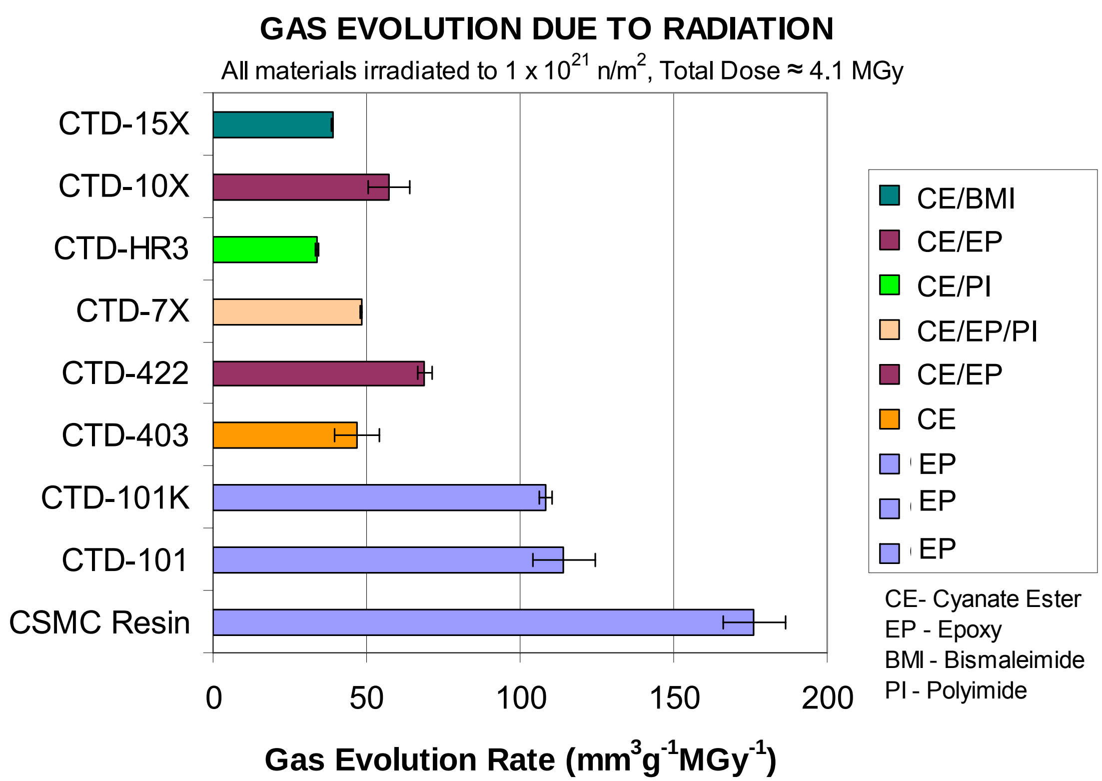
Gas Evolution Due to Irradiation



Irradiation and gas evolution testing performed by the Atomic Institute of the Austrian Universities, Vienna, Austria

Current DOE Insulation Programs

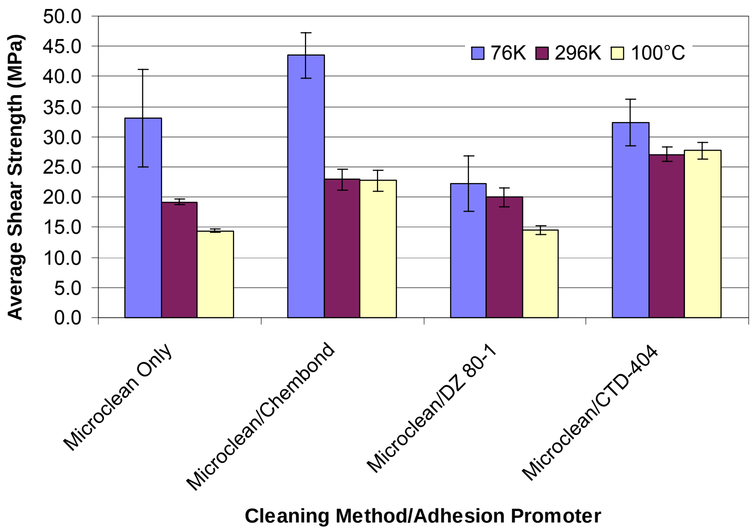
DOE Phase II SBIR – Improved Adhesion of Insulation to Copper

Oxidized Cu

Microclean Alkaline cleaner

Microclean cleaner/Acid etch

- **Surface preparation/primer development**
  - **Cyanate Esters**
  - **Oxide layers**
  - **Ceramic coatings**



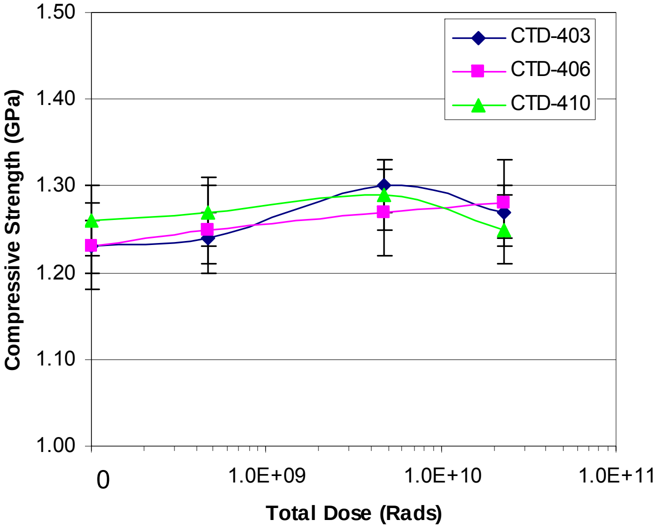
- **Adhesive/Primer process integration**
  - **Surface prep/cleaning**
  - **In-line primer application**

Proposed DOE Insulation Programs

DOE Phase I SBIR – New, Low-Cost Radiation Resistant Polymer

- **Cyanate ester resins most resistant to radiation of current organic**
- **Problem: High cost in comparison to epoxy systems**
- **Possible solutions**
  - **Dilute with epoxies – cuts radiation resistance**
  - **Alternative chemistries with similar properties**

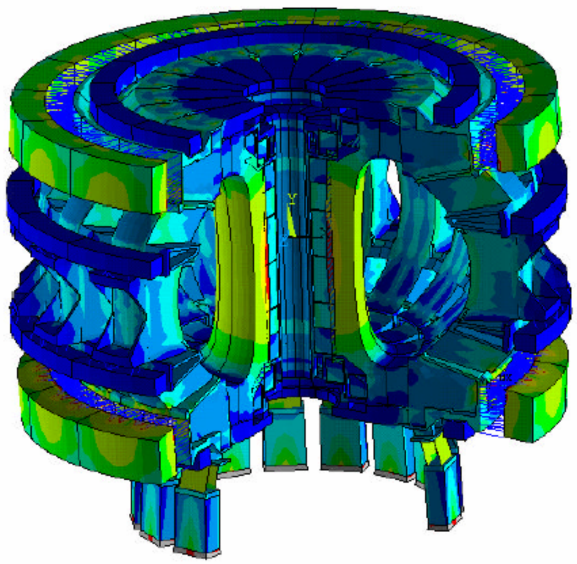
- **New polymer chemistry**
  - **Aromatic structure – stable**
  - **High cross-link density**
  - **Thermal stability**
  - **Expected radiation resistance, low outgassing**
  - **70% cheaper than Cyanate esters**



Proposed DOE Insulation Programs

DOE Phase II SBIR – Block Copolymer Organic/Inorganic Resin

- **Combination of organic and inorganic polymers**
  - **Inorganic converted to ceramic through chemical catalyst**
  - **Avoids high temperature ceramic conversion**
  - **Increased ceramic content provides**
    - **Increased operational temperature**
    - **Increased radiation resistance**
    - **Increased elastic modulus**
- **Adequate processing properties**
  - **Suitable for VPI , pre-pregs**
  - **Good resin flow**
  - **Capitalizes on Cyanate ester properties**
- **Good mechanical and electrical properties**
  - **Good low temperature properties**
  - **Improved properties at elevated temperatures after ceramic conversion**



Block Copolymer Insulation System

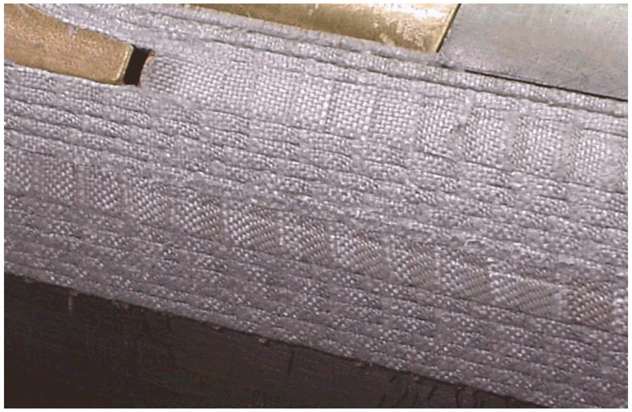
	Prior to Phase I		After Phase I Development	After Phase II Development†
Property/Material	**Epoxy**	**Cyanate Ester**	**Block Copolymer**	**Converted Block Copolymer**
Processing:				
Resin Type	Organic Polymer	Organic Polymer	Organic/Inorganic Polymer	Organic Polymer/Ceramic
Viscosity	80-100 cPs	50-100 cPs	100-400 cPs	50-100 cPs
Processing Temperature	50-80°C	30-50°C	80°C	50-80°C
Pot-Life	8-16 h	8-16 h	12-16 h	12-16 h
Resin Flow	Excellent	Excellent	Good	Excellent
Mechanical @ 76 K:				
Compression Strength	1100 MPa	1200 MPa	1100 MPa	>1100 MPa
Shear Strength	80-100 MPa	80-100 MPa	60-80 MPa	> 80-100 MPa
Mechanical @ 373 K:				
Compression Strength	Unknown	680 MPa	300-400 MPa	>800 MPa
Shear Strength	Unknown	50-60 MPa	30 MPa	> 80-100 MPa
Through-Thickness Tensile Strength	Unknown	Unknown	Unknown	Good
Electrical @ 76 K:				
Dielectric Strength	50-80 KV/mm	60-80 KV/mm	80-100 KV/mm	80-100 KV/mm
Radiation Resistance:				
To 10^7 Gy	Good	Excellent	Unknown	Excellent
To 10^8 Gy	Fair	Good	Unknown	Excellent
> 10^8 Gy	Poor	Fair	Unknown	Excellent

† Predicted

Proposed DOE Insulation Programs

DOE Phase II SBIR – Low Cost Ceramic Pre-preg Insulation

- **Ceramic matrix resin can be co-processed with Nb_3Sn superconductor**
  - **Inorganic converted to ceramic during SC heat treatment**
  - **Uses an organic VPI resin after heat treatment for additional strength**
- **Formulated a lower cost ceramic matrix system**
  - **Pre-polymer ceramic**
  - **Less than half the cost of original**
- **Lower cost reinforcement**
  - **Previously used custom woven ceramic fabric tape**
  - **S-2 glass, Basalt reinforcement alternatives**
  - **10% of ceramic tape cost**
- **Need improved strength**
  - **Fiber/matrix interface critical**
  - **Must be fusion compatible**
  - **Enable graceful failure**



CTD-1012PX ceramic pre-preg as applied on FNAL half-coil

Low Cost Ceramic Pre-Preg Insulation

Material Component	Prior to Phase I	Prior to Phase I	After Phase I Development	After Phase II Development
Ceramic Matrix	CTD-1002X	CTD-1002X	7057-DX	7057-DX-2
% of Total Cost	28	37	60	40
Normalized Cost	1.00	1.00	0.40	0.40
Reinforcement*	CTD-CF-100	CTD-CF-100	CTD-GF-1X	CTD-GF-2X
	(ceramic)	(ceramic)	(S2-glass)	(S2-glass or alt.)
% of Total Cost	47	63	40	40
Normalized Cost	1.00	1.00	0.06	0.10
Interface**	BN***	None	None	CTD-FI-X****
% of Total Cost	25	0	0	20
Normalized Cost	1.00	0.00	0.00	0.30
Compression Strength	1.00	0.60	0.52	>1.0
Shear Strength	1.00	0.15	0.17	>1.0
Total Normalized Material Cost	1.00	0.75	0.20	0.30 - 0.40

* Cost of reinforcement includes custom weaving of thin tape.

** Cost of interface includes cost of application process.

*** Boron-nitride applied via chemical vapor deposition (CVD).

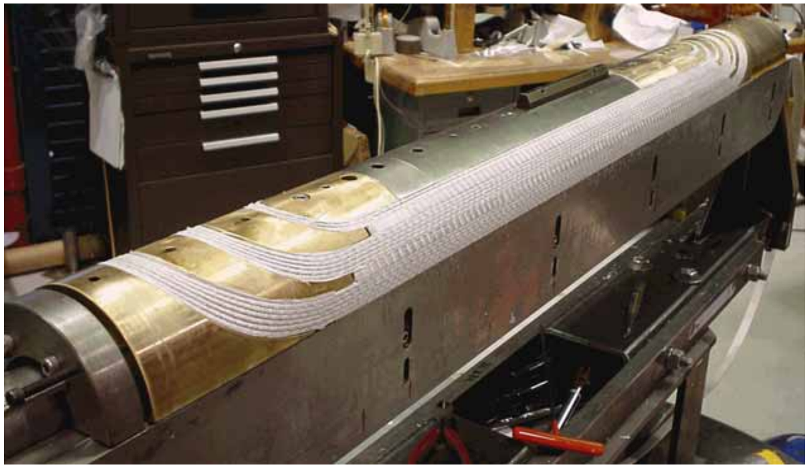
**** Fiber interfaces applied via liquid precursor deposition (LPD).

Predicted Values

Additional Insulation Activities

- **High Energy Physics Applications**
  - **Fermi National Accelerator Laboratory**
    - **Ceramic matrix insulation systems**
    - **Co-processible with Nb_3Sn accelerator magnets**
    - **VPI resin systems**
  - **Lawrence Berkeley National Laboratory**
    - **High radiation applications, VLHC, etc.**
    - **Ceramic matrix insulation systems**
    - **VPI resin systems**

LBNL sub-scale coil fabricated using CTD ceramic insulation and CTD-101 VPI resin



FNAL half-coil fabricated using CTD-1012Px insulation system

- **Industrial Applications**
  - **NMR & MRI Magnet Fabrication**
    - **CTD-121P long outlife pre-preg**
    - **CTD-500 series refinements**

Collaboration with CTD

- **Cooperative research between PPPL and CTD**
- **Magnet Insulation Needs**
  - **Materials**
  - **Testing**
  - **Processing**
  - **Application**
- **Communicate Needs to Department of Energy and CTD**
  - **High Energy Physics and Fusion**
  - **Listing in SBIR Solicitations**
- **Collaborate with CTD on SBIR proposals**

"Enabling Technology for the Magnet Industry"

Discussion

Range of Products

- VPI Systems
  - CTD-101K - Widely used, low viscosity, long pot-life epoxy system
  - CTD-400 series - Cyanate ester based, low viscosity, long pot-life systems, highly radiation resistant
  - CTD-528 - Room temperature cure system, limited pot-life
- Pre-Preg Systems
  - CTD-115P - Hot-melt epoxy system, comparable to CTD-112P used on ITER CS Model Coil
  - CTD-10X - New cyanate ester based hot-melt system
- High Pressure Laminate Systems
  - CTD-7X - New cyanate ester based HPL system
  - CTD-HR3 - Cyanate ester based System

Range of Products

- Co-Processed Ceramic Hybrid Systems
  - CTD-1008X/1002X - Ceramic system used with an organic VPI system
  - CTD-1012PX - Ceramic Pre-preg system used with organic VPI system
- Hand Lay-up/ Wet Winding/ Pultrusion Systems
  - CTD-500 series - Room temperature cure organic resin systems
  - CTD-540 – Room temperature, accelerated cure system
  - CTD-422PC – Radiation resistant potting compound
- Adhesive Systems
  - CTD-620 series - Filled or neat resin, good cryo adhesive
  - CTD-920 - Filled system, good over large temperature range
  - CTD-900 series - High temperature systems