Cryogenic Dielectric Materials Strategic Research

2006 Annual Peer Review

Superconductivity Program for Electric Systems
U.S. Department of Energy

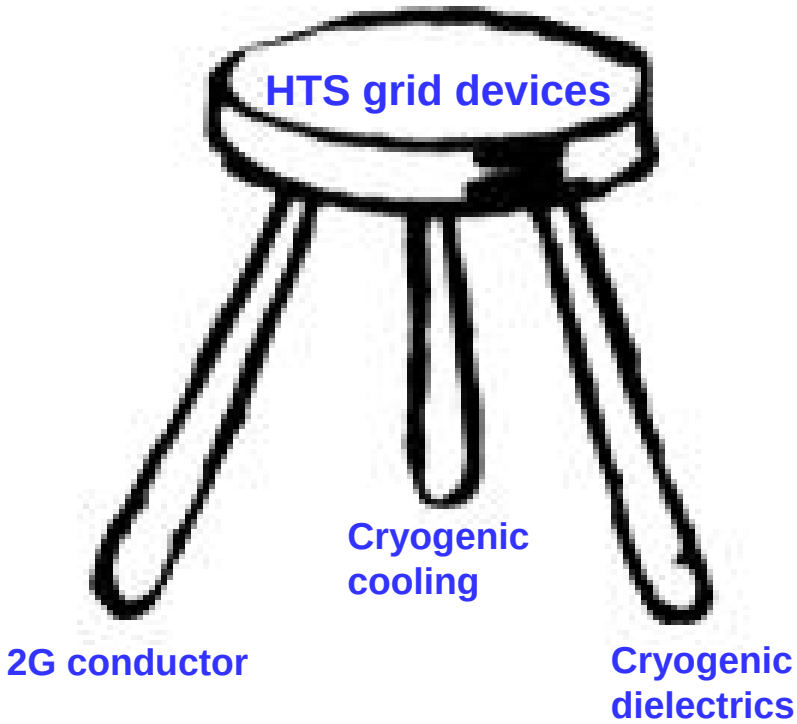
July 25-27, 2006
Washington, DC

Why Cryogenic Dielectrics R&D?

- **Power has two components: P = I V**
  - **HTS carries the current– only half the story.**
  - **Cryogenic dielectrics must hold off the voltage.**
  - **Survival of an HTS quench or lightning impulse also requires moderate to high voltage capability for short times.**
  - **AC grid applications require high voltage standoff for the component lifetime**
    - **about 10^{11} ac cycles for 30 years**
- **Without viable cryogenic dielectrics, there are no HTS grid applications**

Project Goal

- **Perform strategic cryogenic dielectrics and high voltage research that will benefit all HTS grid projects**
- **Make electrical engineering routine for HTS grid applications**



Project Objectives

- Provide knowledge base on existing dielectric materials extending the dielectric properties data base to cryogenic temperatures, to include ac operation (Partial Discharge, PD) and to higher voltages
- Develop new composite materials that can be tailored to cryogenic applications
- Develop design rules
  - Provide reliable data on scaling issues going from small samples to sub-scale and full scale design
- Develop diagnostics that can identify problems or defects in dielectric materials
- Coordinate activities such as workshops to facilitate discussion on the industry HV needs for HTS grid applications

FY 2006 Plans: Cryogenic Dielectrics Initiative

- Initiate multiyear strategic research program involving national labs, industry and universities
- Proposed research falls into four broad categories,
  - High voltage testing and characterization of currently available materials
  - Development of new materials, specifically designed for cryogenic HTS applications.
  - HV Design rules and scaling properties for commonly used matrl's
  - Diagnostics for fault location, condition monitoring, etc
- Host cryogenic dielectrics workshop
  - Bring together SPI engineers/researchers with dielectrics experts to discuss current status and future needs
  - October 2005 in conjunction with the IEEE Conference on Electrical Insulation and Dielectric Phenomena to be held in Nashville, TN USA.
- Establish web site for SPI teams to use with design rules, etc

Unique experimental facilities for cryogenic dielectrics research

ORNL Cryogenics High Voltage and Dielectrics Test Facility

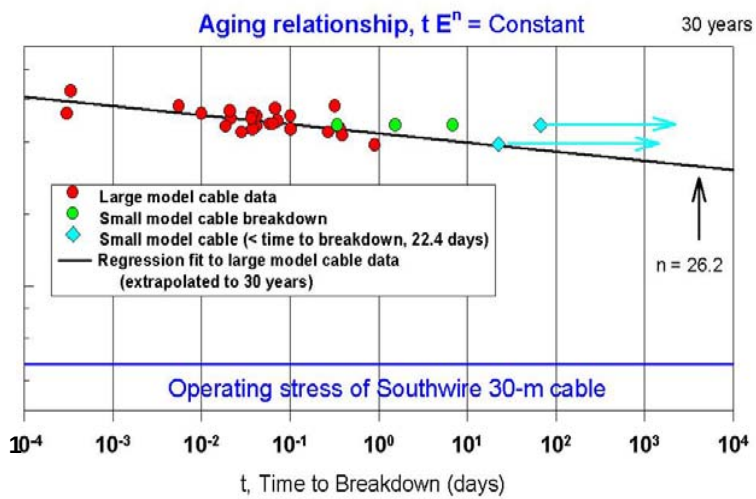
- **High voltage chambers and cryostats for testing vacuum, gas, liquid and solid**
- **AC withstand (to 200 kV) and lightning impulse (to 800 kV)**
- **Breakdown studies on plastic film sheets and tape in pressurized LN2**
- **Model HTS cables breakdown and long-term aging studies**
- **Partial discharge studies, phase and amplitude resolved**

1.3-m model cable for aging studies

Small model cable dewar for long term aging studies and partial discharge (PD)

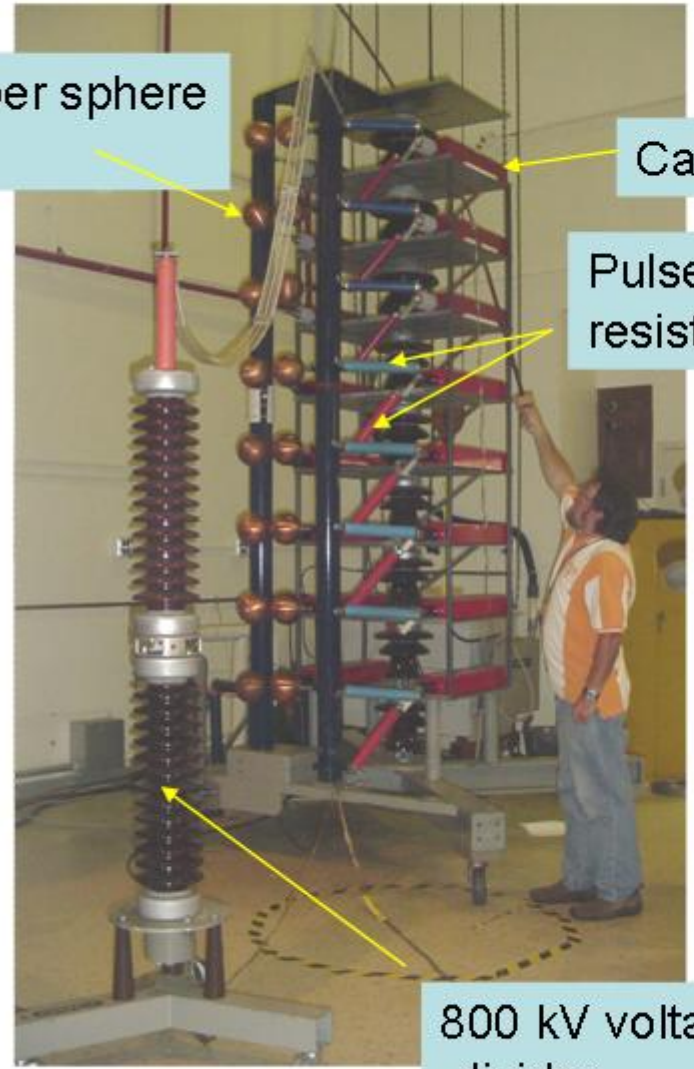
- **Dedicated system for aging studies and PD characterization.**
- **Automated high pressure LN2 fill system**

150 kV Phenix power supply control
PD detector



Equipment upgrade in 2006

800 kV Impulse Generator



- New capabilities included added stages to impulse generator to over 700 kV
  - scaling to practical scale in LN2 (longer gaps, higher BIL)
  - larger material thicknesses
- 30” Dewar
  - Low press, ~1-2 bar
- 138 kV bushing

Cryogenic Dielectrics Workshop

Workshop on Cryogenic Dielectrics

- October 16, 2005, Nashville
- about 50 attendees
- 10 talks + panel discussion
  - Presentations on a CD
- Co-sponsored by
  - IEEE/DEIS and IEA Implementing Agreement on Superconductivity
- Concluding session led by Alan Wolsky (ANL) was a panel discussion of the cryogenic dielectric needs.
  - Needs include dielectric characterization of existing materials and the development of new materials that can meet the thermal and mechanical requirements and high electrical stresses at both continuous and impulsive voltage applications. Dielectric materials need to be reliable and the technology should be "routine".

Cryogenic Dielectrics Workshop

PROGRAM
Cryogenic Dielectrics Workshop
Sunday, 16-Oct-05

9:00 AM	**Welcome**	**Alan Wolsky (Argonne National Laboratory)**
9:05-10:45 AM		
M. Gouge	USA	*Superconducting Grid Applications and Cryogenic Dielectrics*
O. Lesaint	France	*Prebreakdown and Breakdown Phenomena In Liquid Nitrogen, and Consequences For High Voltage Insulation.*
N. Hayakawa	Japan	*Partial Discharge Measurement and Characteristics in Cryogenic Electrical Insulation for HTS Power Apparatus*
T. Takahashi	Japan	*Tests of HT Superconducting Cables*
10:45-11:00 AM	**Break**	
11:00-12:15 PM		
D. Swaffield	UK	*Cryogenic Dielectrics and HTSC Power Apparatus: Research at the University of Southampton*
M. Nagao and Y. Murakami	Japan	*Electrical Insulation Performance of Paper-Ice Composite Insulation System at Cryogenic Temperature*
B. Hou	China	withdrawn
12:15-1:30 PM	**Lunch**	
1:30-3:10 PM		
S. Fink	Germany	*Long-Term High Voltage Tests of the Conductor Insulation of a Superconducting Magnet*
K. Tekletsadik	US	*High Voltage Design for a 138 kV Superconducting Fault Current Limiter*
S. W. Schwenterly	US	*AC High Voltage Dielectrics for HTS Transformers: A Work In Progress*
T. Tanaka	Japan	*Bubble Problems in Liquid N2 Impregnated Systems--Views from 30 Years Back*
3:10-3:30 PM	**Break**	
3:30-5:00 PM	**Panel**	**Alan Wolsky (lead)** — **Future needs**
		Steiner Dale — (R&D Director, Engineer, CAPS-FSU)
		Naoki Hayakawa — (Research Scientist, Nagoya Univ.)
		Swarn Kalsi — (R&D Director, Engineer, motors, American Superconductor)
		Sam Mehta — (R&D Director, Engineer, transformers, Waukesha Electric)
		Olivier Lesaint — (Research Scientist, CNRS Grenoble)
		Bill Schwenterly — (Research Scientist/Engineer, ORNL)
		David Swaffield — (Research Scientist/Engineer, Univ of Southampton)
		Kasegn Tekletsadik — (Research Engineer, IGC-SuperPower)

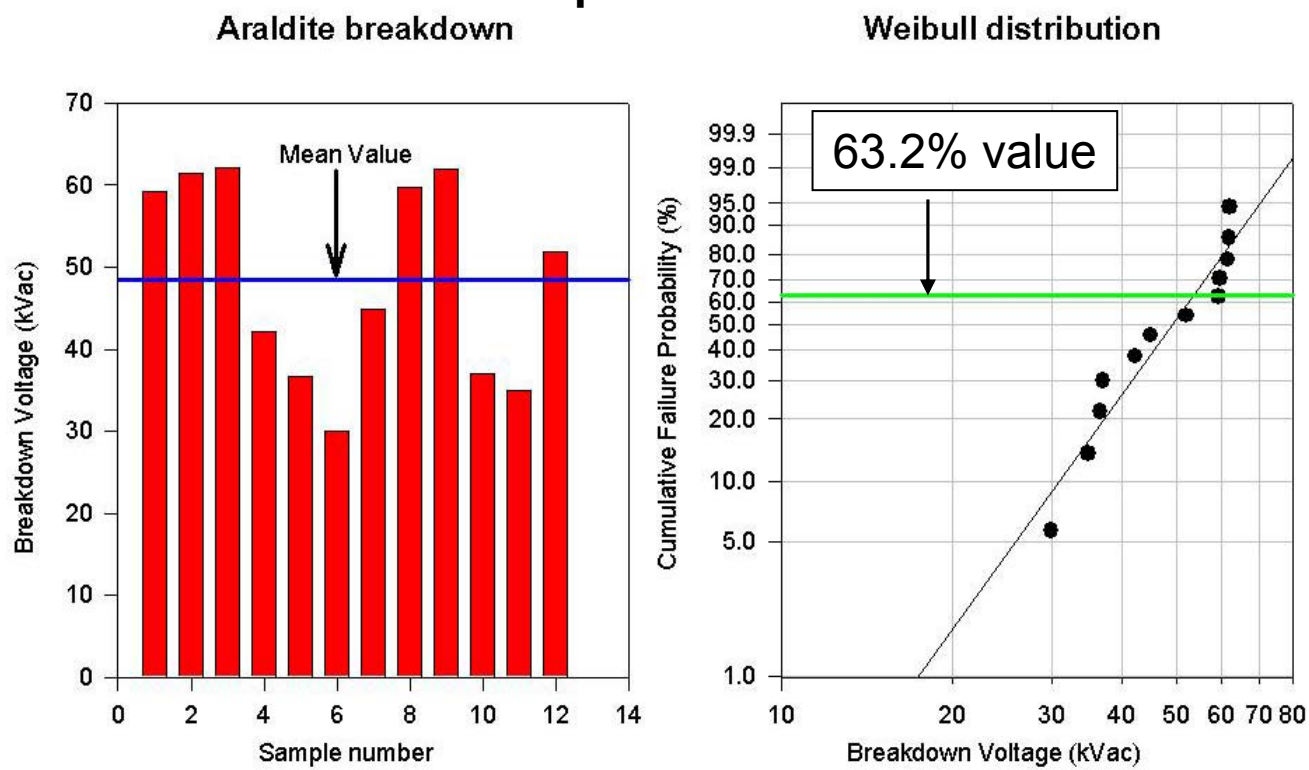
Program agenda for the Cryogenic Dielectrics Workshop (October 16, 2005, Sheraton Downtown Nashville, Nashville, Tennessee, USA).

Breakdown Strength of Materials

Breakdown Strength of Materials – statistics

- **Araldite 5808 is a good cryogenic epoxy that does not crack in LN2**
- **Breakdown strength increases at low temperature**
- **Mean breakdown values do not provide information on safety factors**
- **Distributions such as Weibull provide more information for scaling and design rules**

room temperature data



Araldite samples are 0.5 mm thick; multiply breakdown voltage by x2 for Field strength

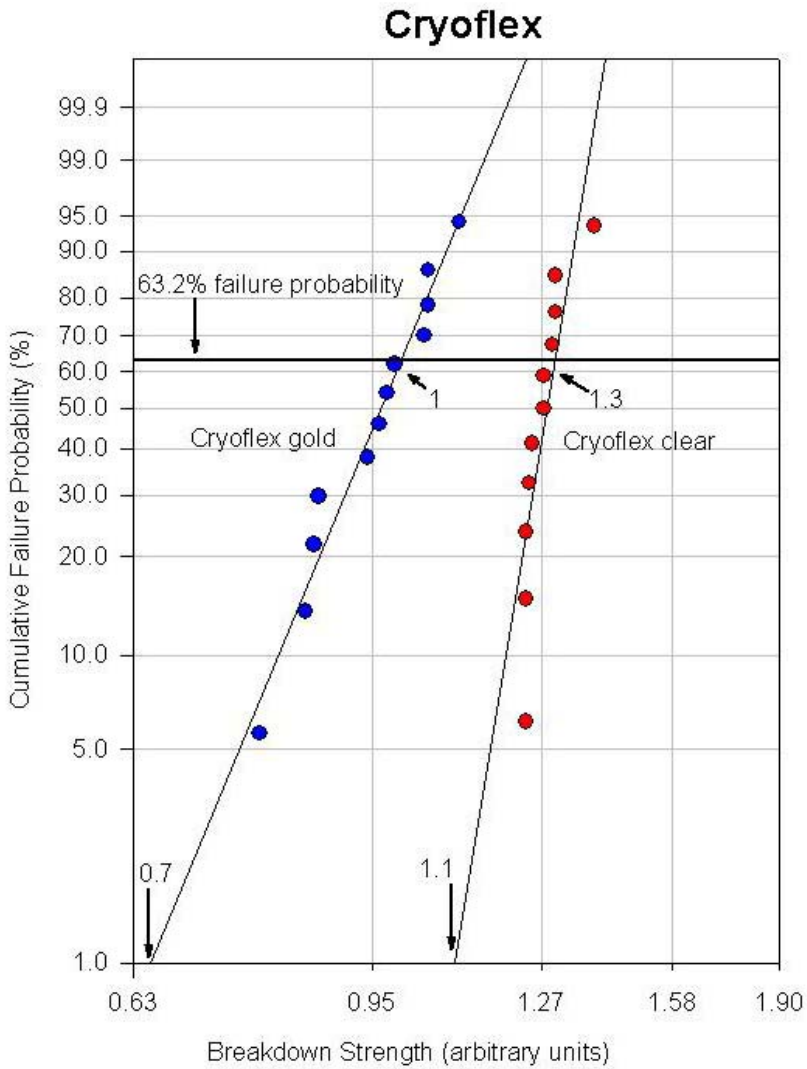
Experiment set up for multiple BD measurementson film samples

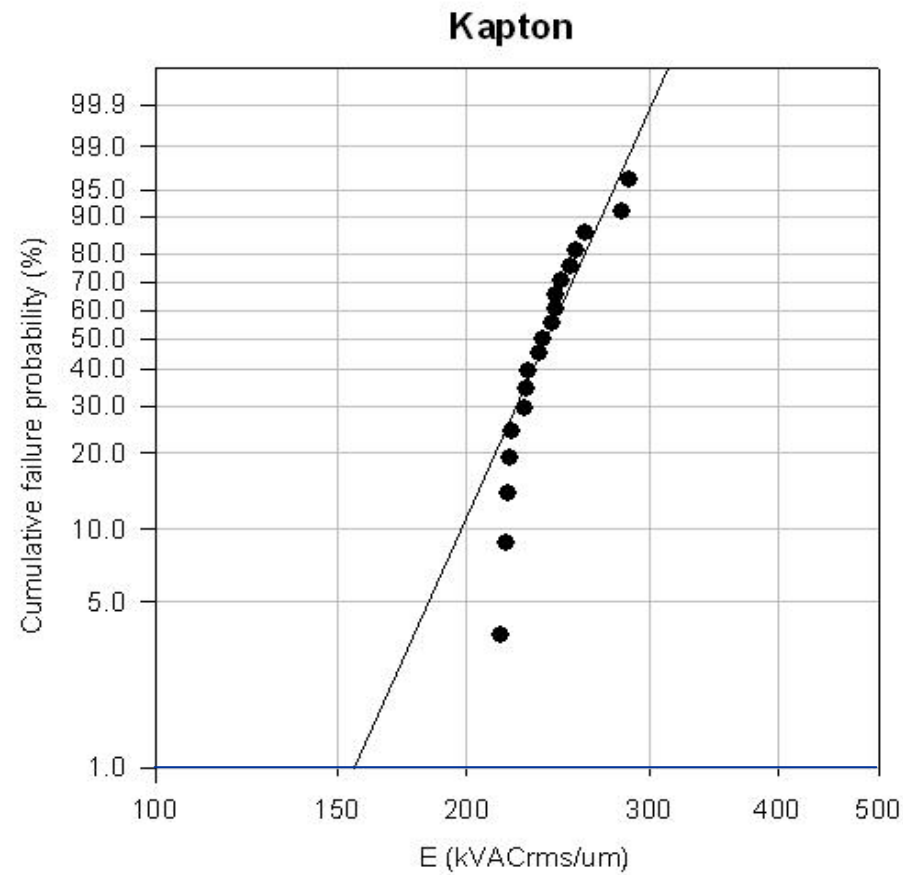
- **Multiple electrodes evaporated on polymer film permits multiple breakdown measurements**
- **Permits measurements without removing sample from LN2**
- **Statistical data allows assessment of data spread and resulting safety factor using, e.g. 1% breakdown probability or 0.1% or some other criteria**

Kapton film with 19 silver electrodes.

multiple electrode system in LN2

Breakdown Data on Cryoflex and Kapton in LN2:





Property	Units	Dielectric Material	
		Material A	Material B
Electrical			
Dielectric Strength*	kV / mm (short time)		
Dielectric Constant (1kHz)			
Permittivity			
Dissipation Factor (1kHz)	tan-delta 10^(-6)		
Electrical Resistivity	Ohm-cm		
Arc Resistance	sec (ASTM D495)		
Physical			
Density	g / cm^3		
Sp Gravity			
Sp Vol	cm^3 / g		
Water absorption	%		
Melting Point	Deg C		
Mechnical			
Tensile Strength	MPa		
Yield Strength	MPa		
Compressive Strength	MPa		
Flexural Strength	MPa		
Elongation	%		
Tensile Modulus	GPa		
Flexural Modulus	GPa		
Impact Strength	Izod (J / cm of notch)		
Hardness	Rockwell R		
Thermal			
Thermal Conductivity	W / m-K		
Coef. Of Thermal Expansion	10^(-6) m / m-C (at 20 C)		
Thermal Expansion	% (293K - 80K)		
Deflection Temperature	Deg C (at 1.8 MPa)		
	Deg C (at 0.46 MPa)		
Flamability Rating	(UL94)		
Specific Heat	J / g-C		
Maximum Service Temp	Deg C		
Minimum Service Temp	Deg C		

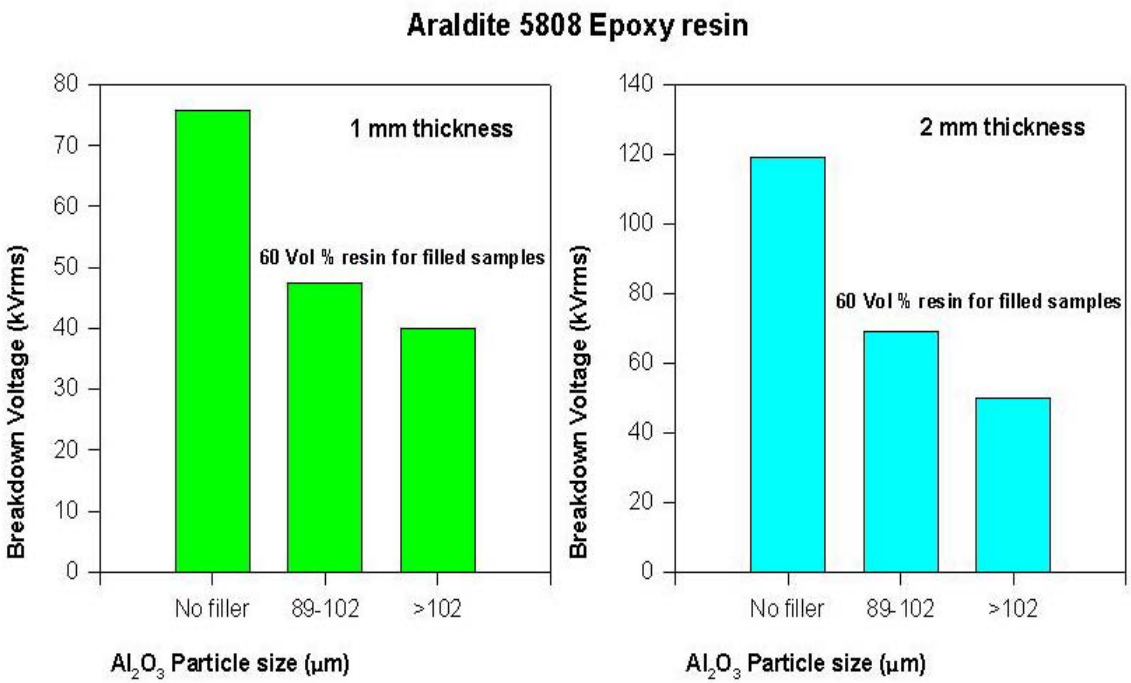
Data base similar to one put together for another project

* Dielectric strength cannot be expressed as one single value for a material

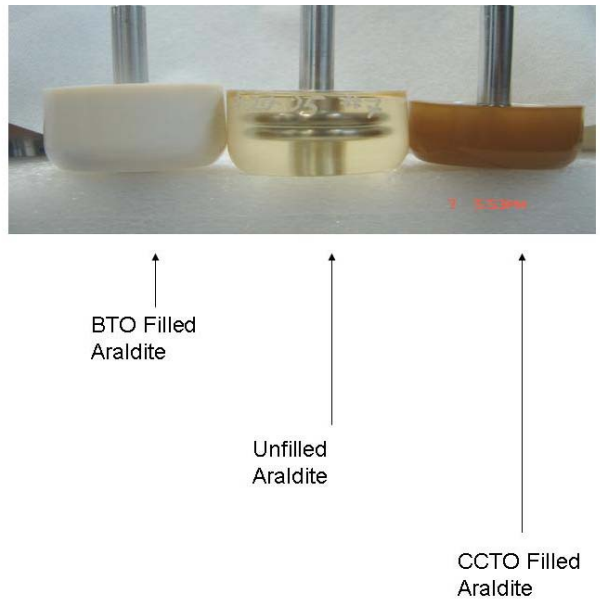
- AC, DC, impulse, thickness, stressed volume, creepage, PD inception, etc.
- Function of Temp

New dielectric materials have been developed

Conventional fillers typically lower breakdown strength



room temp

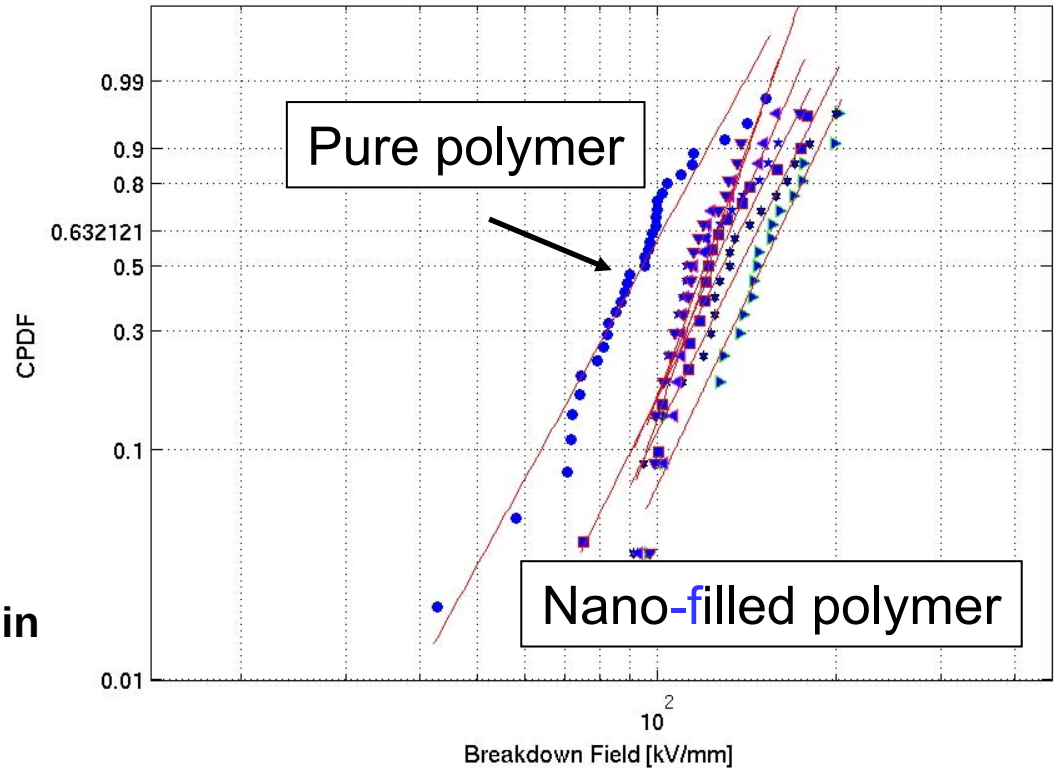


Note also the less than linear improvement with thickness

New dielectric materials: nano dielectrics

Varying concentrations of precursors in aqueous solution used for making nanoparticles in polymer *in-situ* and avoids the problem of particle mixing and the subsequent problems with dispersion and agglomeration.

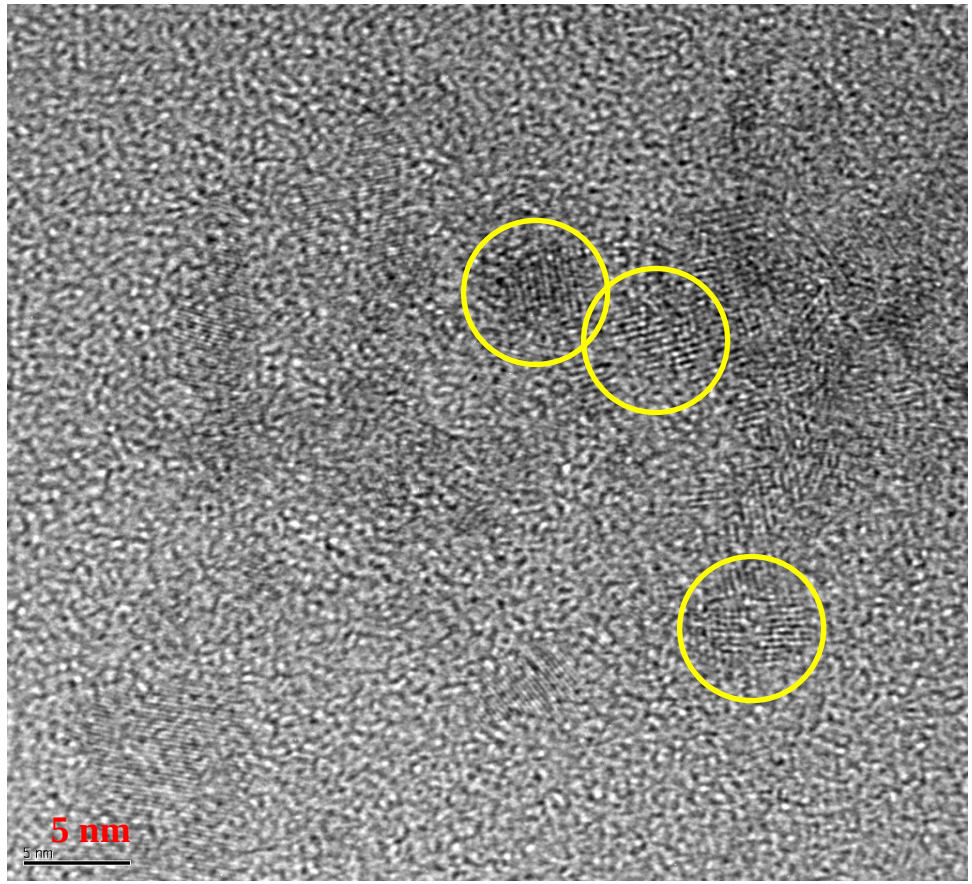
Breakdown in LN2



Weibull distribution plot of breakdown in pure and filled polymer showing higher breakdown strengths for filled polymer

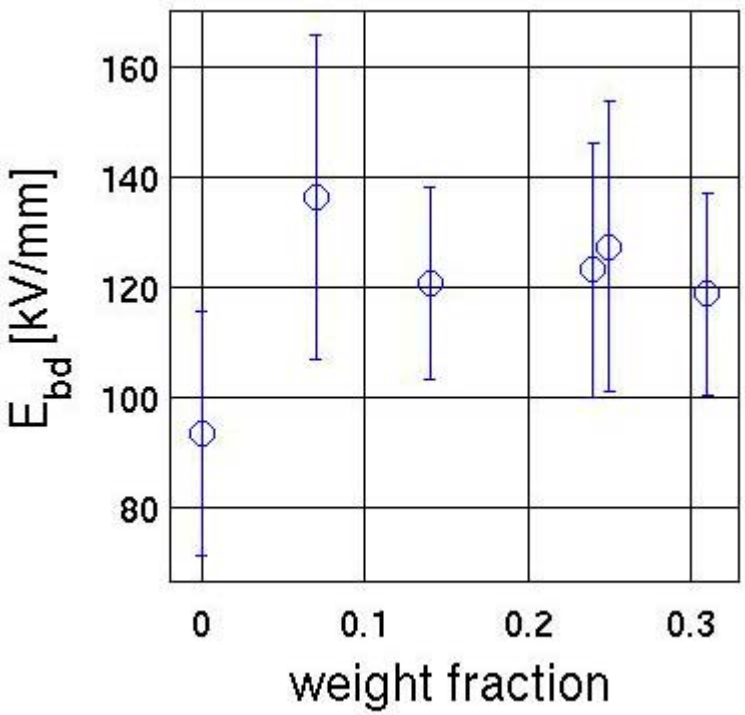
TEM images confirm presence of nano particles

- Transmission Electron Microscopy (TEM) show crystalline structures indicative of particles
- Particle size on the 5 nm range
- Dispersion of particles looks good
- TEM image consistent with improved breakdown results



Breakdown strength increases with nano filler

- **Breakdown results show <u>increased</u> breakdown strength when nano particles are added as filler in polymer dielectric films**
- **40% increase in breakdown strength of nano filled versus unfilled polymer**
- **Polymers generally decrease in strength when conventional filler (micron sized) is used**
- **Nano particles fill free volume and lower trapping potential of charges**



Statistics of breakdown

Important for design rules based on dielectric strength

Breakdown statistics – needed for design

Electrical breakdown of dielectric materials is a statistical process due largely to undefined factors in the manufacture and processing of these materials (including, for example, impurities, non-uniformity and voids).
We need to:

- Understand the statistical nature of breakdown
- Use statistical methods which can best describe the data
- Develop tools for assigning appropriate safety factors in the dielectric design.

Data from dielectric breakdown of polyimide at 77 K was studied to examine the applicability of the standard Weibull distribution.

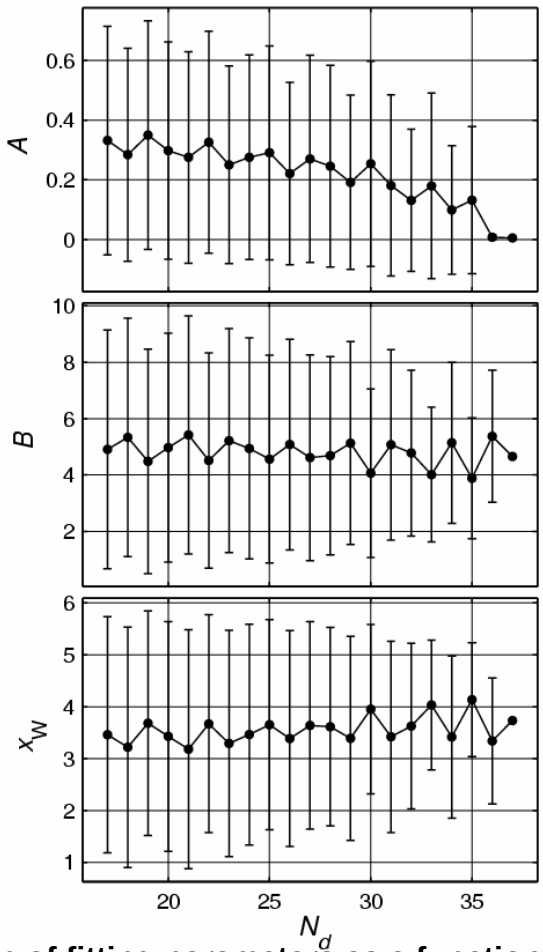
Issue with Weibull – no convergence of fitting parameters with sample size

- New distribution function proposed
- Proposed expression is shown to be superior to the Weibull one as shown explicitly with the presented numerical procedure.

Improved Breakdown Statistics

$W(x) = \exp[-A(x - x_W)^B]$; where $x \geq x_W$

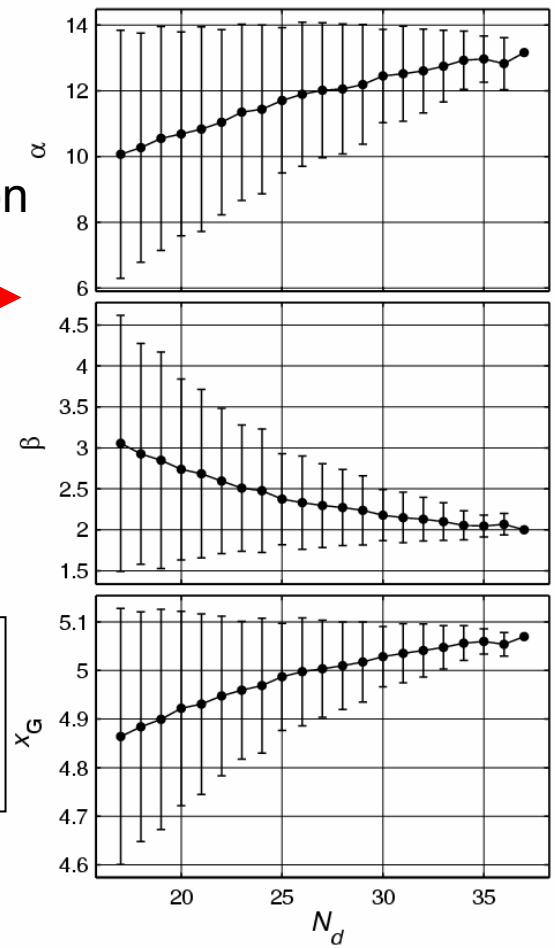
$G(x) = \alpha x^{-1} \exp[-(x-x_G)^{-\beta}]$, where $x \geq x_G$



Alternative distribution
Converges

Weibull
No convergence

parameters should converge with larger sample size

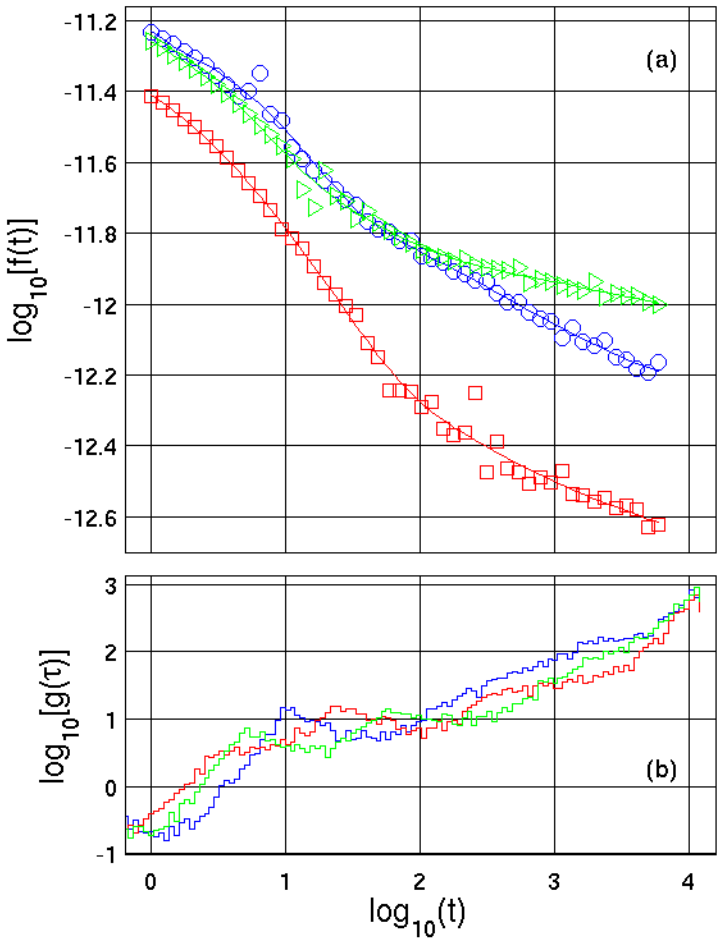


Mean of fitting parameters as a function of number of observables Nd in the Monte Carlo method for the Weibull expression. The data are presented as error bars which are calculated from the standard deviation of the data.

Mean of fitting parameters as a function of number of observables Nd in the Monte Carlo method for the proposed expression.

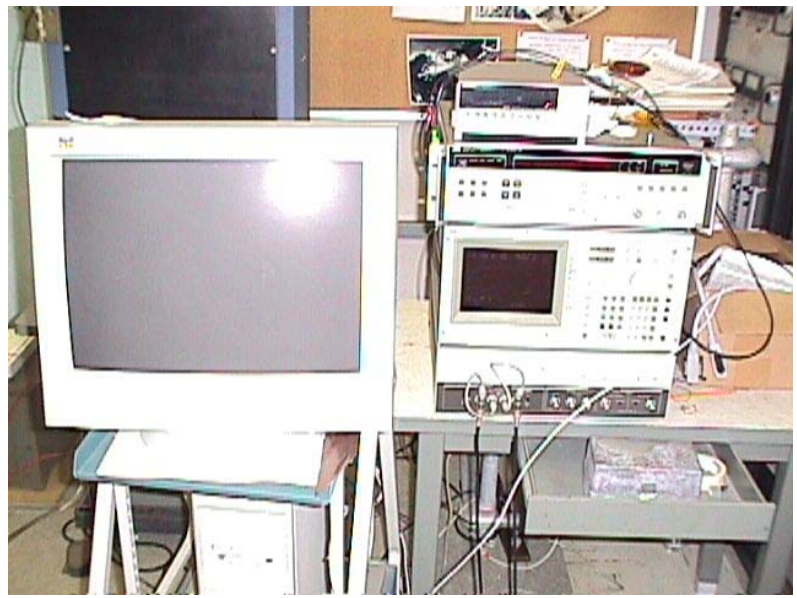
Polarization/relaxation

Time domain polarization and depolarization measurements on dielectric materials



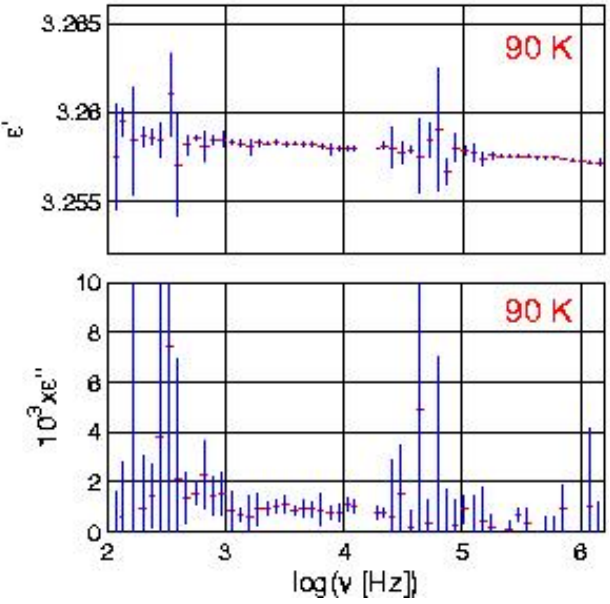
Time domain data of the pure araldite (blue) and its composites with micro (green) and nano (red) BTO particles. (b) The distribution of relaxation times obtained from the numerical analysis.

Material properties related to partial discharge



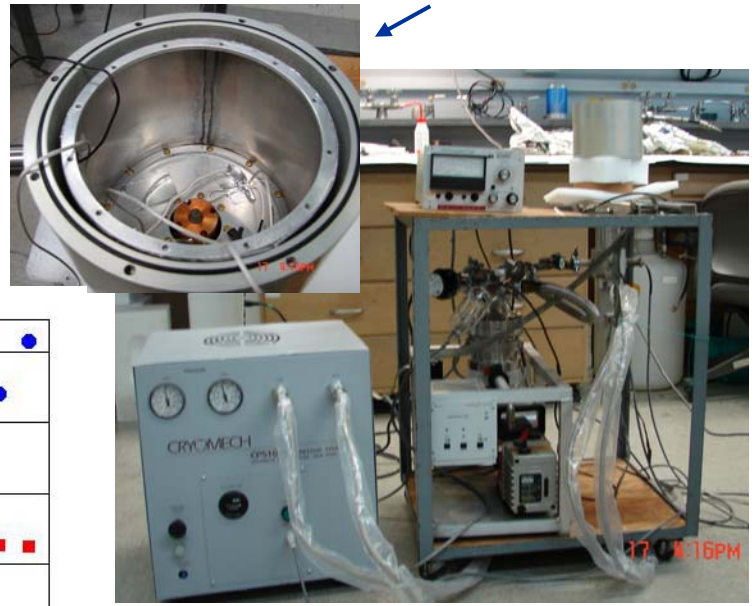
Assess space charge and partial discharge

Complex permittivity can be measured as function of frequency and temperature

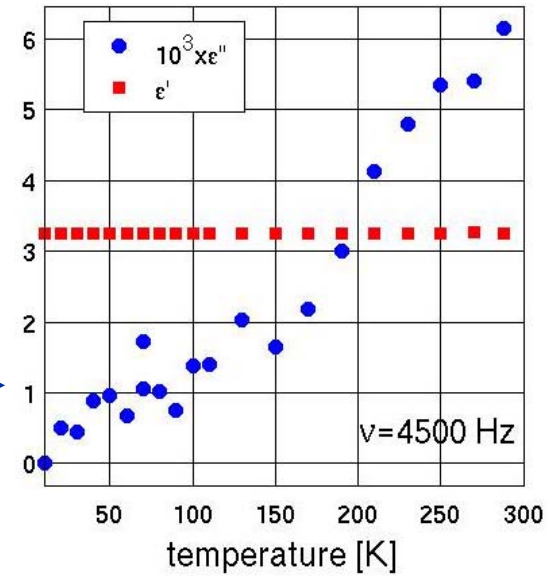


Permittivity and loss factor as a function of frequency at 90 K

Top of chamber showing cold head, additional space for PD and permittivity measurements



Permittivity and loss factor as a function of temperature from room temperature down to about 20K



Cryo-refrigerator designed for dielectric measurements down to 20ºK

Papers for ASC 2006

- High Voltage Testing of a 5 meter Tri-axial HTS Cable**, I. Sauers, D. R. James, A. R. Ellis, M. O. Pace**
- Breakdown and Partial Discharge Measurements of Some Commonly Used Dielectric Materials in Liquid Nitrogen for HTS Applications, **D. R. James, I. Sauers, and A. R. Ellis, Oak Ridge National Laboratory, and K. Tekletsadik, Consultant, SuperPower, Inc.**
- Electrical properties of semiconducting tapes used in HTS power cables, **Enis Tuncer, Isidor Sauers and D. Randy James**
- Tri-axial HTS Cable System Design for the AEP Bixby Project, **J.A. Demko, I. Sauers, D.R. James, M.J. Gouge, ORNL; D. Lindsay, M. Roden, J. Tolbert, D. Willén, C. Træholt, Ultera**

Papers submitted for the 2006 CEIDP (Kansas City, October 2006)

- Electrical properties of a commercial resin**, Enis Tuncer, Isidor Sauers, D. Randy James and Alvin Ellis**
- Partial discharge measurements in a high temperature superconducting triaxial 5-m model cable at liquid nitrogen temperature, **Isidor Sauers, D. Randy James, Enis Tuncer, and Alvin Ellis**

Papers submitted for the 2006 CEIDP (Kansas City, October 2006) (Cont'd)

- Non-Uniform Field Breakdown and Surface Flashover in Liquid Nitrogen Gaps for HTS Applications**, D. R. James, I. Sauers, E. Tuncer, and A. R. Ellis, ORNL; K. Tekletsadik, Consultant, SuperPower, Inc., and D. W. Hazelton, SuperPower, Inc**
- Breakdown statistics of polyimide at low temperatures,**Enis Tuncer, Isidor Sauers, D. Randy James and Marshall O. Pace**

FY 2006 Results Summary

- Cryogenic dielectrics workshop held in Nashville
- Study of breakdown strength of materials initiated providing statistical data
  - cryoflex, kapton, semiconducting materials, G10
- New materials developed based on nano-composite technology
  - Nano dielectric material with significantly increased breakdown strength at lower weight fractions
- In addition to breakdown strength, other dielectric properties have been measured, including permittivity over frequency range 100 Hz to 10 MHz and polarization/depolarization
- Breakdown statistics were examined in an effort to establish reliable safety margins and design rules
- 8 papers have been submitted to two conferences
  - ASC and CEIDP

FY07 Plans

- Continue measurements on commonly used materials such as epoxies, films, FRPs, and LN
  - breakdown statistics, puncture strength, flashover, other dielectric properties, in LN2
- Improve statistical analyses for small sample sizes
- Examine volume and thickness dependencies
- Continue new materials development based on nano technology
- Extend R&D program to include outside participants such as industry and university
  - contingent on full funding of Cryogenic Dielectrics Initiative
  - issue RFPs (see next slide on cryogenic dielectrics program structure)
- Initiate plans for web-based data base

Cryogenic Dielectrics Initiative Proposed Program Structure

Integrated team from DOE and possible other agency national laboratories, universities and industry led by ORNL.

- Issue two Requests for Proposals,
  - one for industrial participation: cost share at 20% level
  - one for university participation
  - proposals reviewed and team implemented by month four of program
  - kick-off meeting at ORNL.
- Cryogenic dielectrics initiative program structure
  - ORNL (team leader)
  - 1-2 additional national labs (DOE, NIST, DOD)
  - 2-3 industrial members
  - 1-2 universities
- Industry advisory panel formed to provide review and feedback on R&D needs for this initiative.
  - Advisory panel meet twice per year: e.g. day three of Annual DOE Peer Review and day two of January Wire Development Workshop.
- **Was not funded in 2006 due to program budget issues: *needed in 2007 to support present and next round of HTS grid projects.***