Cryogenic Dielectric Materials Strategic Research

2005 Annual Peer Review

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

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Project Goal

Perform strategic dielectrics and high voltage research that will benefit all SPI projects

(Make electrical engineering routine for HTS grid applications)

Why Cryogenic Dielectrics R&D?

- **Power has two components: P = I V**
  - **HTS carries the current– only half the story.**
  - **Cryogenic dielectric must hold off the voltage.**
  - **Survival of an HTS quench also requires moderate to high voltage capability for short times.**
  - **AC grid applications require high voltage standoff for the component lifetime**
- **Without viable cryogenic dielectrics, there is no transmission or conversion of power!**

Insulation failures need to be avoided

Magnet Failures (from Y. Iwasa, *Case Studies in Superconducting Magnets*, New York: Plenum Press, 1994).	
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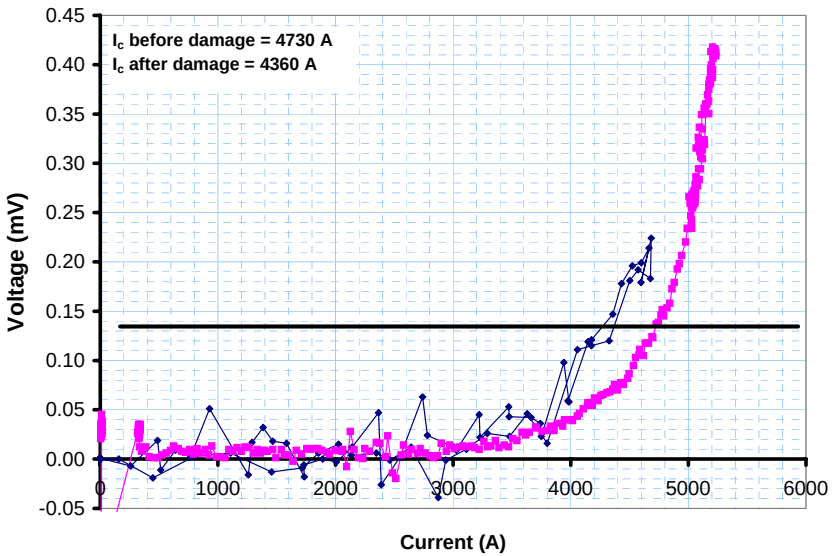
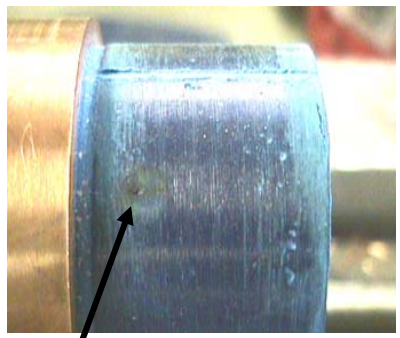
Impact of failures – high current vs. high voltage

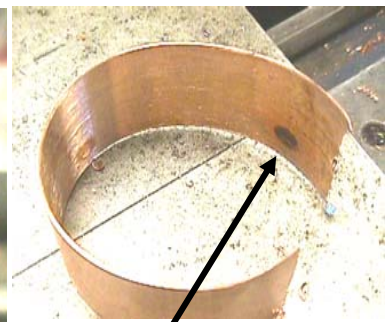
Gradual degradation after intentional damage to single-phase HTS cable.



Lose 4 tapes in a layer-cable remains on line at reduced I_c

epoxy puncture inside of outer copper shell





Breakdown!

Single void in epoxy electrical insulation – HV breakdown
Single-phase trip---then other 2 phases trip off

Project Objectives

- **Provide knowledge base on existing dielectric materials extending the dielectric properties data base to cryogenic temperatures and to higher voltages**
- **Develop new composite materials that can be tailored to cryogenic applications**
- **Develop design rules**
  - **Provide data on scaling issues going from small samples to sub 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 applications**

FY 2005 Results Summary

- **Breakdown strengths and PD of fiberglass reinforced plastic, polyetherimide and epoxy materials have been measured.**
- **Aging and PD tests were conducted on turn-to-turn (or edge-to-edge) insulation on HTS tapes with several different types of insulating material.**
- **Impulse and ac breakdown studies were performed in liquid and cold gaseous nitrogen**
- **Surface flashover studies were also conducted with different geometries.**

FY 2005 Results: ORNL Cryogenics High Voltage and Dielectrics Test Facility

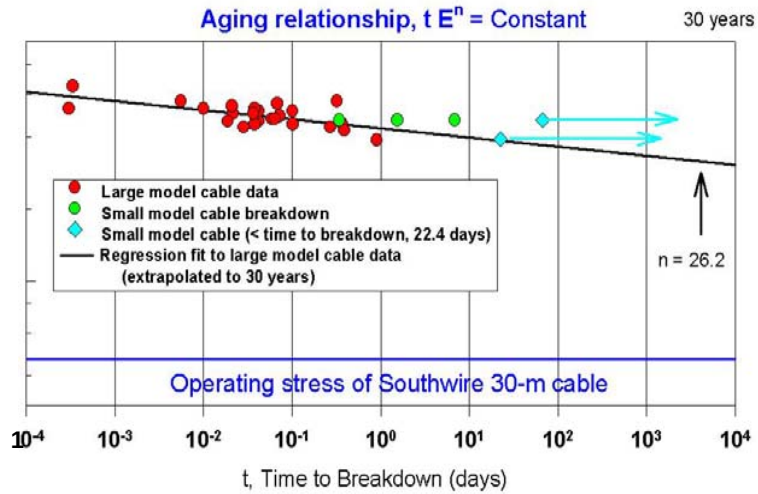
- **High voltage chambers and cryostats for testing vacuum, gas, liquid and solid**
- **AC withstand (to 200 kV) and lightning impulse (to 500/800 kV)**
- **Breakdown studies on plastic film sheets and tape in pressurized LN2**
- **Model HTS cables breakdown and long-term aging studies**
- **Partial discharge studies, phase and amplitude resolved**

1.3-m model cable

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

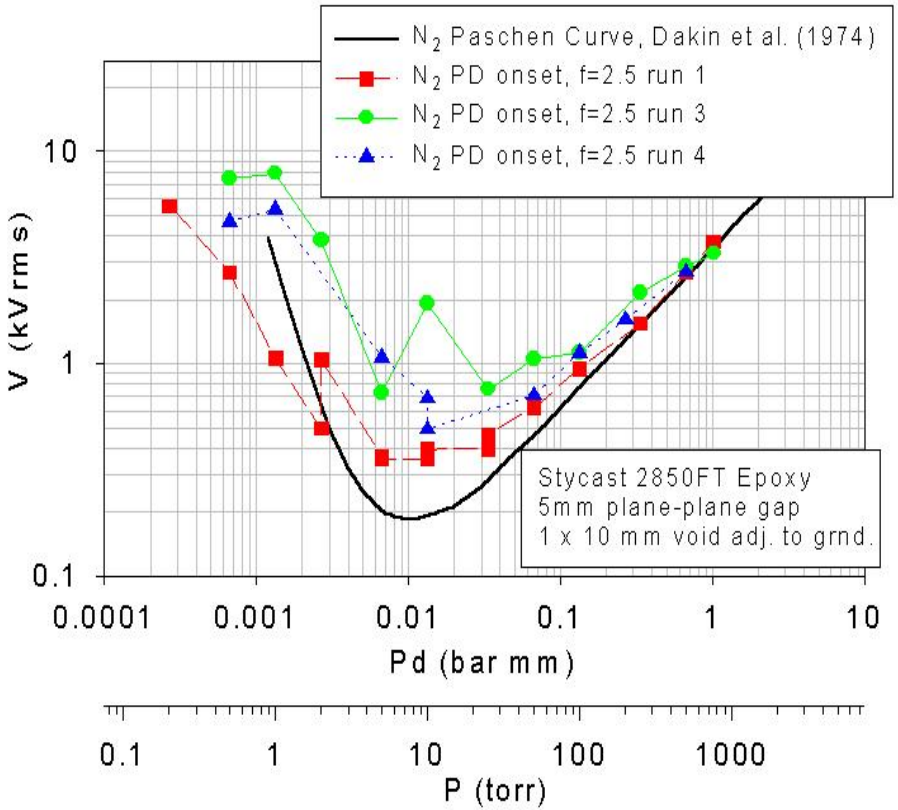
- **Dedicated system for aging studies and PD.**
- **Automated high pressure LN2 fill system installed**

150 kV Phenix Control
PD detector



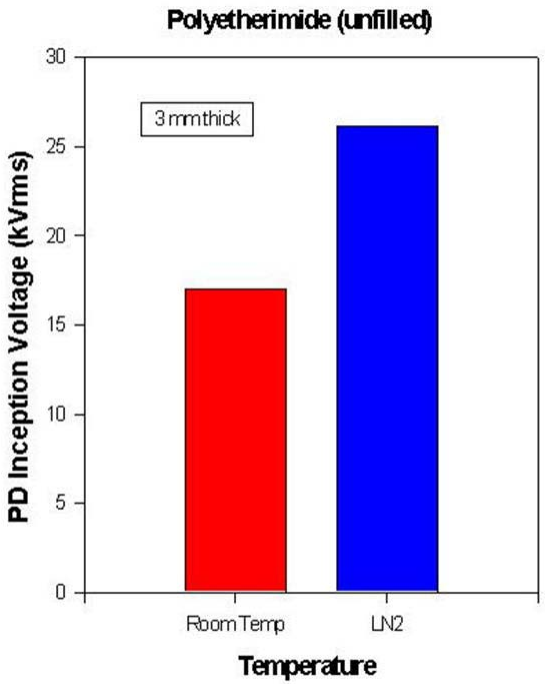
PD Inception Voltage affected by Pressure in Void - Can account for low PD inception

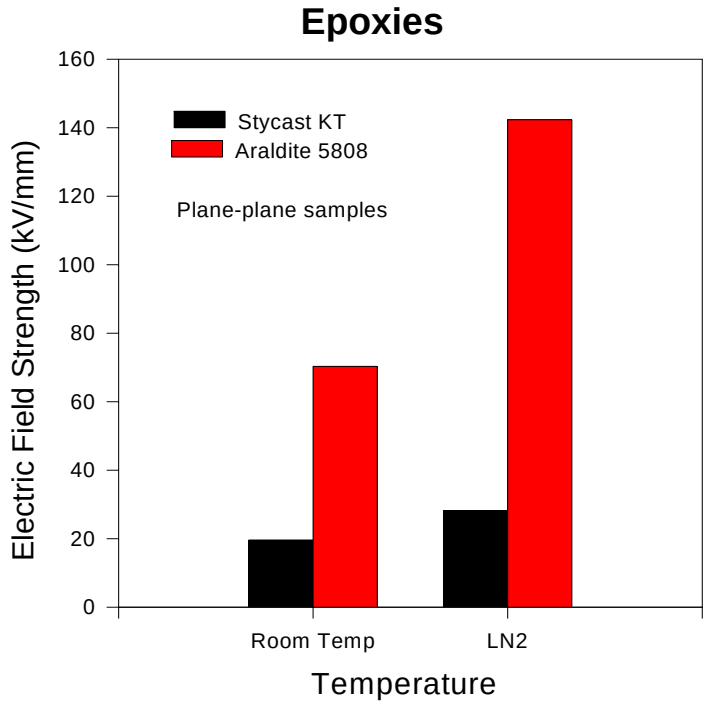
- **PD inception voltage is below 1 kV rms at low pressure**
- **Paschen minimum represents lowest voltage possible for PD inception for uniform field**
- **Field enhancement in void due to difference in permittivity can further lower inception voltage**



Plot of inception voltage versus [press x gap] or pressure for N_2 in 3.2 mm artificial void in solid dielectric

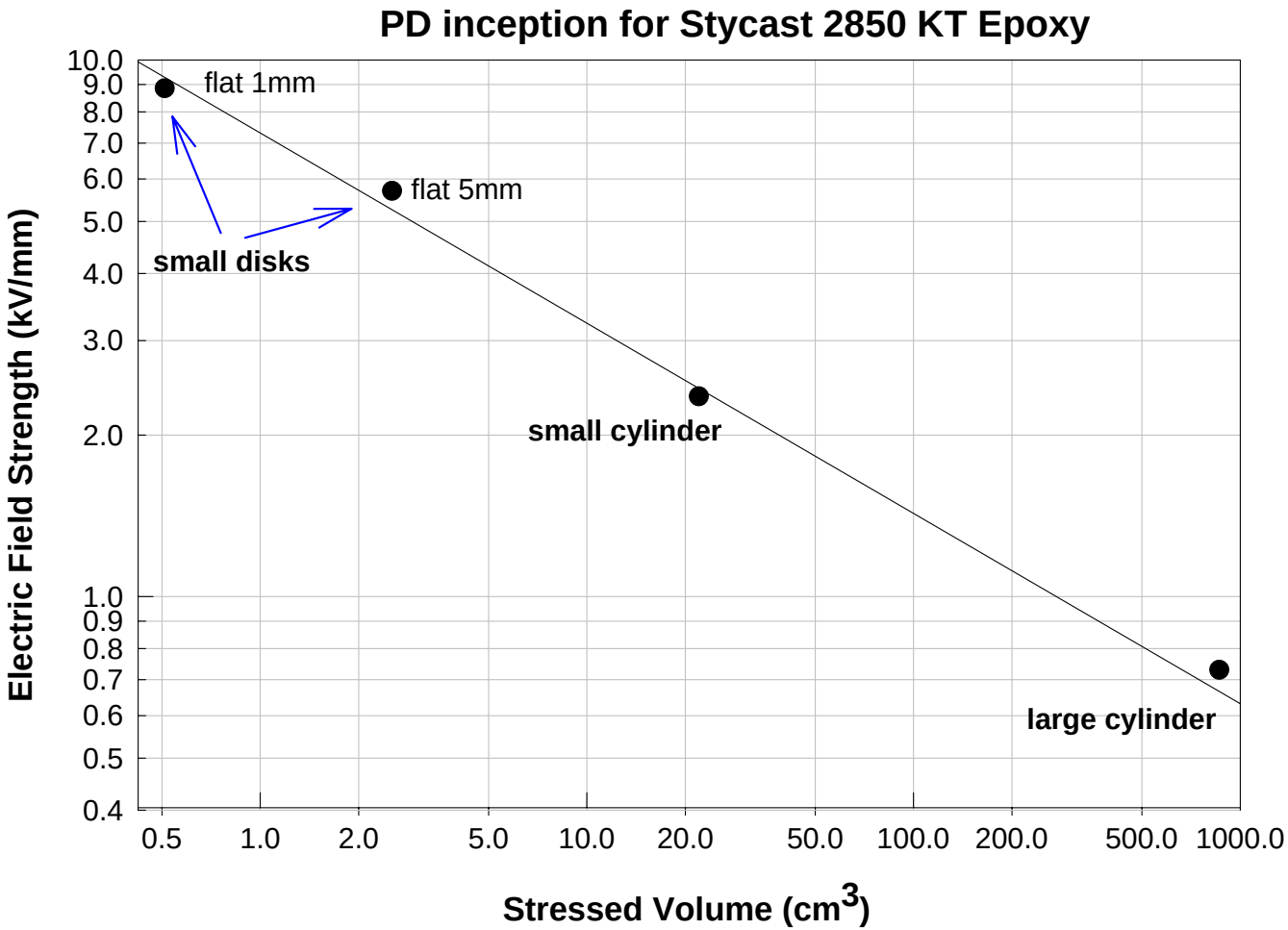
Materials found that increase in dielectric performance at LN2 temperature



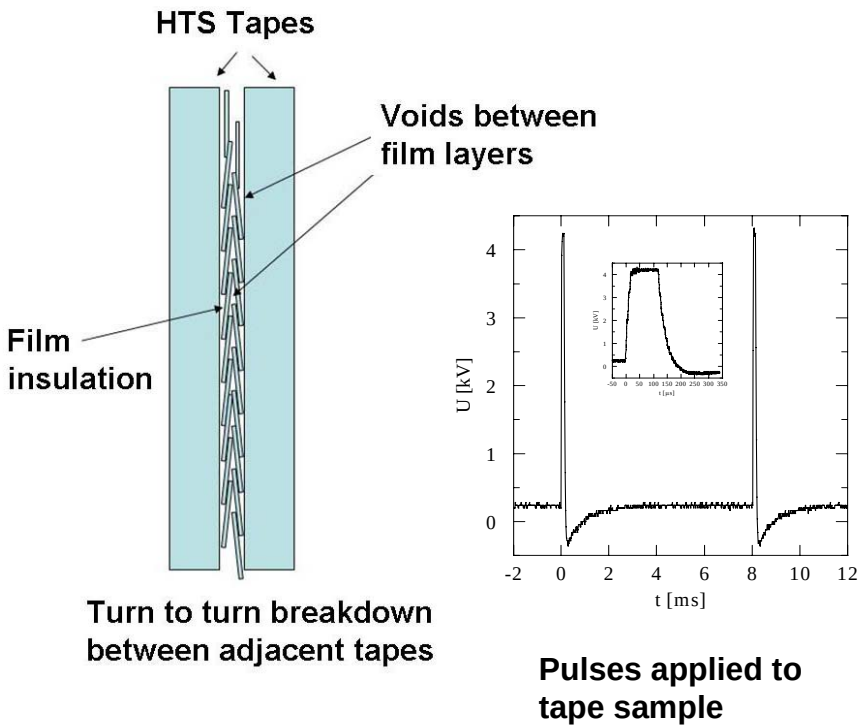


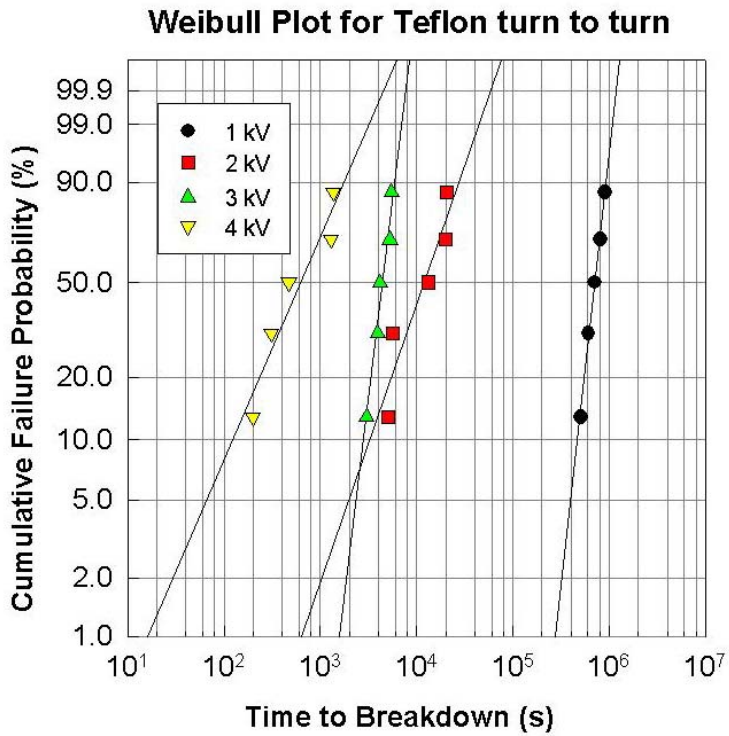
- PD inception and breakdown strength improves at LN2 temperature for some materials, but not all.

Scaling relative to volume for Stycast 2850 KT showing >10x reduction in field strength



Aging plots for turn-to-turn HTS insulated tapes of the same insulation





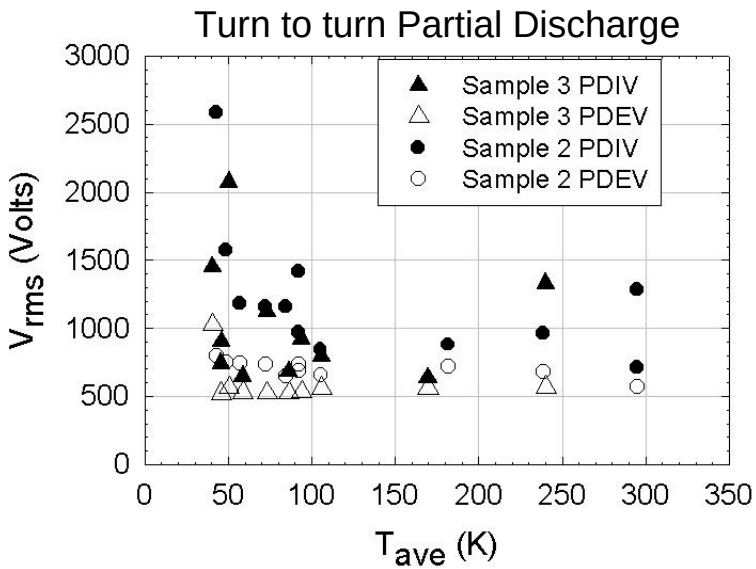
Data useful in estimating end-of-life of insulation

Partial discharge (PD) as function of T shows PD occurs at all temperatures

ORNL can measure PD from room T down to ~40 K

Edge-to-Edge Air Voids

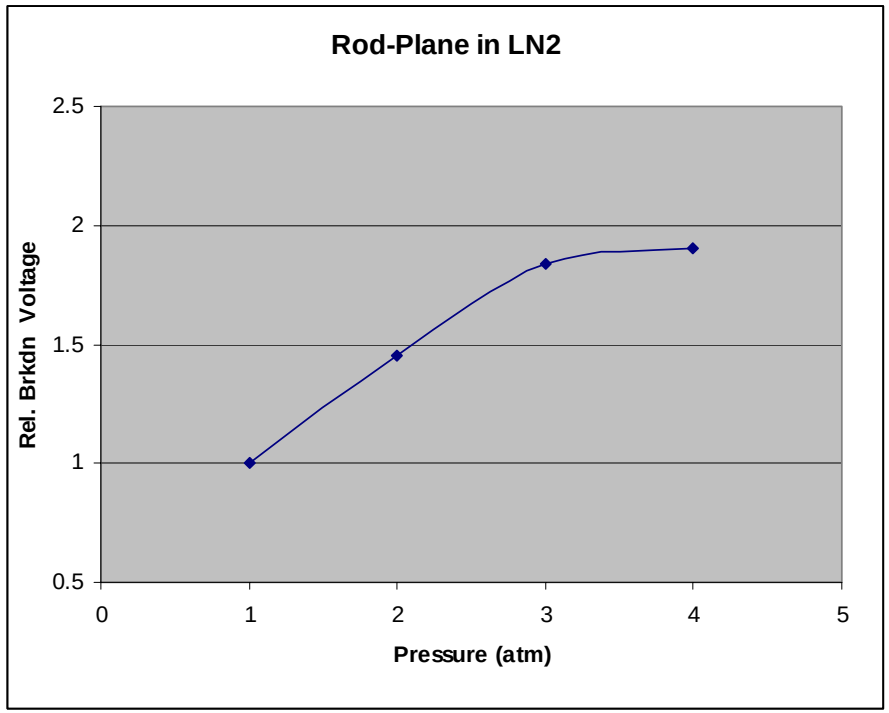
- Inception voltage exhibits more scatter than extinction voltage
- Time lag may affect PDIV more at low P and low T
- Partial discharge observed throughout temperature range studied down to ~40K
- Possible increase at the low temperature



Conclusion: Desorption of air condensate at low T can contribute to partial discharge leading to aging of material

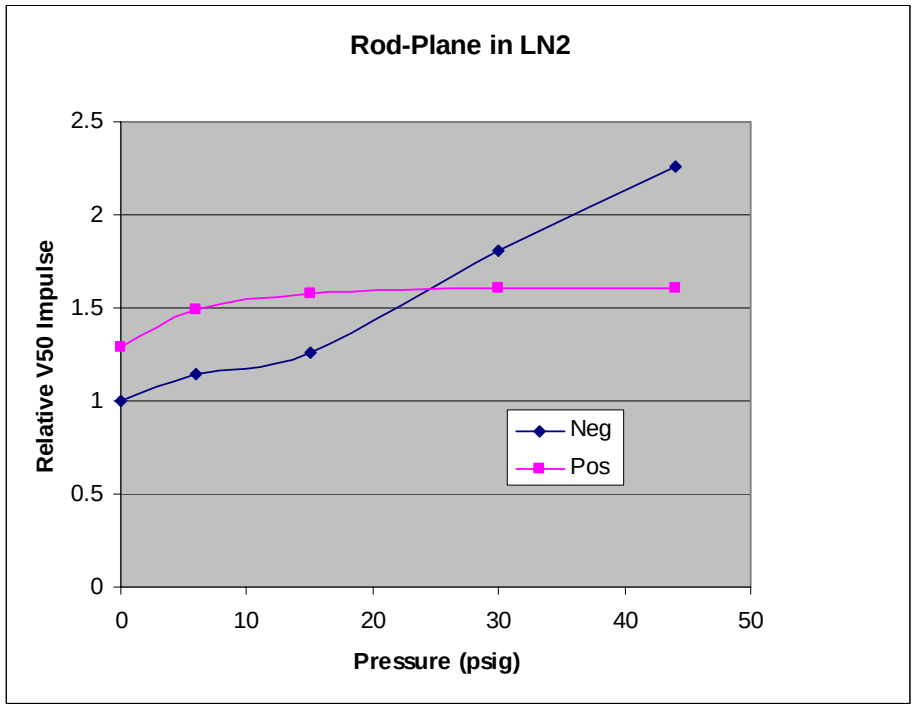
Pressure moderately increases breakdown strength in LN2

- Pressure was varied for a fixed gap
- Higher pressure generally decreases bubble formation and increases Vs
- Rod-plane non-uniform field geometry, ac rms
- Measurements done in high press, HV cryostat
- Vs starts to saturate at ~ 3 atm consistent with literature
- Need to optimize design of gap, triple junction to achieve desired breakdown strength



Impulse voltages show polarity effect as a function of pressure

- Rod-plane gap in LN2 at a fixed gap
- Lightning impulse (1.2 x 50 μs) pos. and neg.
- Neg. polarity impulse lower at low pressure and increases with P
- Pos. is higher at low P and saturates
- Cross over about 20-25 psig
- Needs more study at larger gaps
- Need to design for lowest impulse value



ORNL FY 2005 Performance

FY 2005 Plan

- Measure bd strength of filled epoxy for different volumes
- Partial discharge studies of voids in solid epoxy
- Measured PD in turn to turn insulated HTS tape at cryogenic temp.
- Breakdown in LN2 as function of pressure measured

FY 2005 Performance

- ✓Provided volume scaling data on filled epoxy
- ✓Provided partial discharge patterns characteristic of void and determined the effect of voids on PD inception.
- ✓PD at low temperature is possible due to desorption of ice layers when tapes are cooled to below 77K.
- ✓Saturation effect observed for rod plane geometry confirms prior data for uniform field BD

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**

Cryogenic Dielectrics Initiative – Program Participants

- **Integrated team is proposed**
  - **DOE labs**
  - **Other agency laboratories (NIST)**
  - **Universities**
  - **Industry**
- **Industry advisory panel to be 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.**
- **New program structure must be determined**
  - **Goal is to maximize resources brought to bear on the key issues**
  - **Considering benefits of multi-participant CRADAs**
  - **Emphasize non-proprietary work and provide benefits to participants**

FY 2006: Cryogenic Dielectrics Initiative

Specific ORNL research tasks

- **Surface flashover voltages of FRP and other materials in gaseous and liquid nitrogen**
- **Lifetime and aging studies at cryogenic temperature of selected dielectric materials**
- **A more complete data base of cryogenic insulation needs to be developed and consolidated.**
- **Diagnostic techniques for determining fault location, impending faults, hot spots, bubble formation, condition monitoring**

Research Integration

- **Driving force for strategic cryogenic dielectrics work is the development of HTS power equipment that can operate at high voltage on the grid reliably for design lifetimes.**

- **Significant collaboration with SPI teams, utilities and other labs.**

- **Industry Advisory Panel will be formed to provide review and feedback on R&D needs and priorities for this initiative.**

Research Integration – Partnerships and leveraging

- **HV cryostat provided by Southwire**
- **PD detector provided on loan by Southwire**
- **SuperPower staff visited ORNL and took extensive data using ORNL cryostat and other resources**
- **Tan delta bridge on loan from Waukesha Electric Systems**

Research Integration – Publications and Outreach

- **Presentations and publications during the year**
  - I. Sauers, D. R. James, M. O. Pace, A. R. Ellis, and A. C. Muller, "*High voltage breakdown, partial discharge and aging in lapped tape insulated cold dielectric model cables*", Proceedings of the Cryogenic Engineering Conference and the International Cryogenic Materials Conference, CEC-ICMC 2003, Anchorage, Alaska USA, September 22-26, 2003, AIP Conf. Proc. (USA), Vol. 711, Pt. 2, pp. 889-895, 2004
  - James, D. Randy and Sauers, I., "*Electrical insulation materials for superconducting coil applications*", 2004 IEEE Power Engineering Society General Meeting, IEEE Cat. No.04CH37567, Pt. 2, pp. 2062-4 Vol. 2, 2004
  - R. Grabovickic, D. R. James, I. Sauers, A. R. Ellis, P. C. Irwin, K. Weeber, L. Li, and A. D. Gadre, "*Partial Discharge and Accelerated Pulsed Aging of Insulation between Parallel Plane-Plane Stainless Steel Electrodes and between Bi-Sr-Ca-Cu-O Tapes at Room Temperature*", 2004 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, IEEE Pub. No. 04CH37584, pp. 286-9, 2004
  - R. Grabovickic, D. R. James, I. Sauers, A. R. Ellis, P. C. Irwin, K. Weeber, L. Li, and A. D. Gadre, "*Measurements of Temperature Dependence of Partial Discharge in Air Gaps between Insulated Bi-Sr-Ca-Cu-O Tapes*", IEEE Trans. Appl. Superconductivity, Vol. 15, No. 2, ASC 2004, pp. 3668-3671, June 2005
- **Web Sites**
  - **ORNL Superconductivity Web Site includes Annual Reports, Peer Review presentations and other project information**
    - **www.ornl.gov/HTSC/htsc.html**
  - **High voltage and dielectrics: www.ornl.gov/sci/fed/applied/applied.html**