HTS Power Transformers

Presented to the

2002 DOE Peer Review Committee

For the WES/IGC-SP/RG&E/ORNL Team

by

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Project Participants

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- **IGC-SuperPower**

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  - **Advanced Energy Analysis:**

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  - **Applied Cryogenics Technology**

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- **Rochester Gas & Electric:**

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- **Oak Ridge National Laboratory:**

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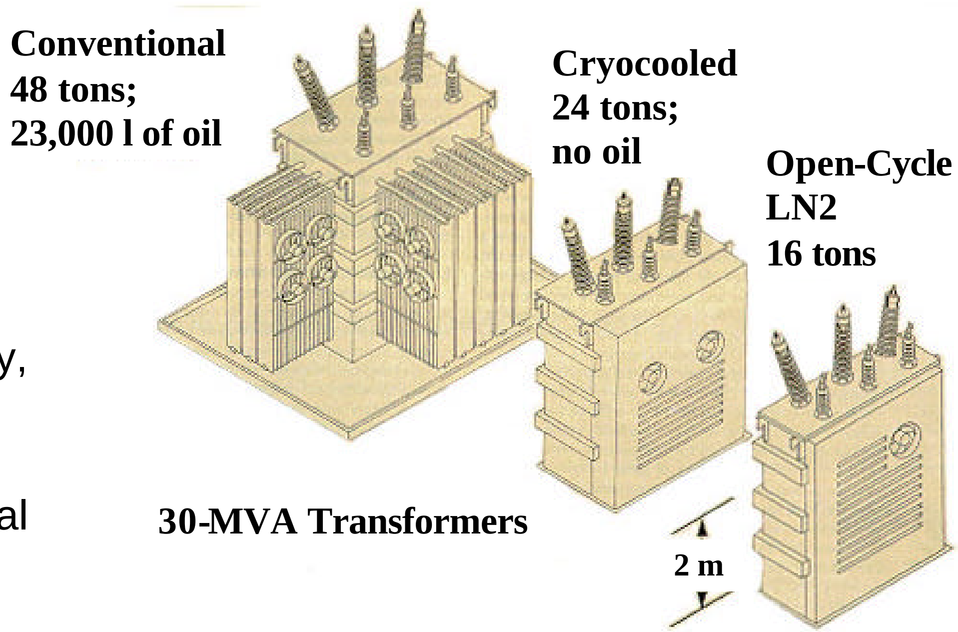
Project Purpose

- To establish the technical and economic feasibility and benefits of **HTS Transformers** of medium-to-large (>10MVA) ratings.
  - Phase I— Paper studies, 1-MVA demonstration transformer design, fabrication, and testing (complete).
  - Phase II— **SPI**— 30-MVA conceptual design, material & component verification testing, 5/10-MVA Alpha prototype design, construction, test.
  - Phase III— 30-MVA Beta prototype design, construction, test.
- At present, the project is in Phase II and focussed on final fabrication of a prototype 5/10-MVA transformer, which will be operated on the utility grid at WES.

HTS Transformers offer economic, operational, and environmental advantages.

- Higher efficiency.
- 2X rating overload capability without insulation damage or loss of life.
- Lower impedance and better voltage regulation.
- Potential for fault current limiting capability, allowing reduced cost for associated switchgear, breakers, etc.
- Siting advantages and lower environmental hazard due to lack of oil.
- Lighter and more compact than conventional units.

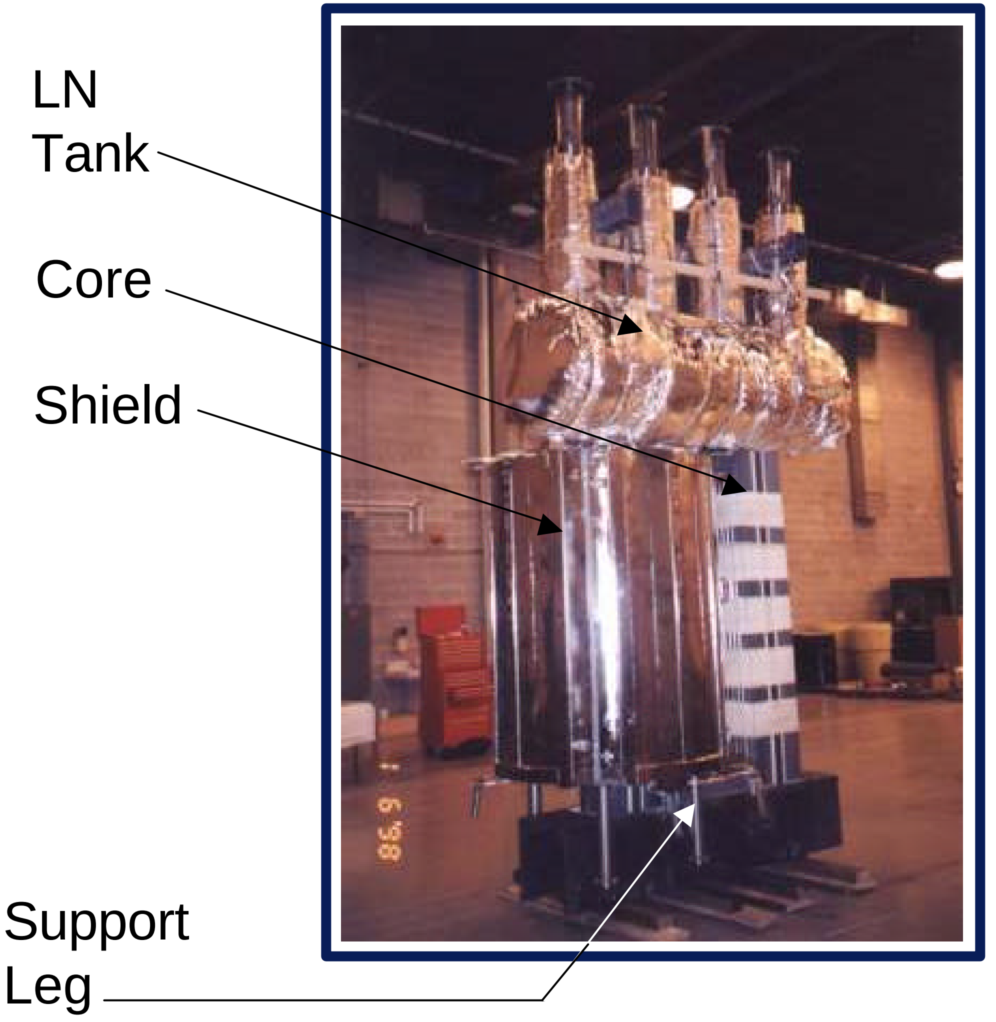


HTS Transformer Program Design Approach and Schedule

- **Cryocooled approach gives design flexibility.**
  - Allows operation from 20 K to 77 K.
  - Best available conductor at a given time can be operated at its optimum temperature.
- **Progression: 1-MVA ® 5/10-MVA ® 30/60-MVA; all at full 30/60-MVA scale.** For each stage of development:
  - Anticipated better conductor and better insulation will allow higher power and higher voltage in same frame size.
  - Better cryocoolers will provide enhanced performance and reliability.
- **The 5/10-MVA SPI project is approaching completion.**
- **Operational tests of the 5/10-MVA unit on the utility grid are scheduled for early 2003.**

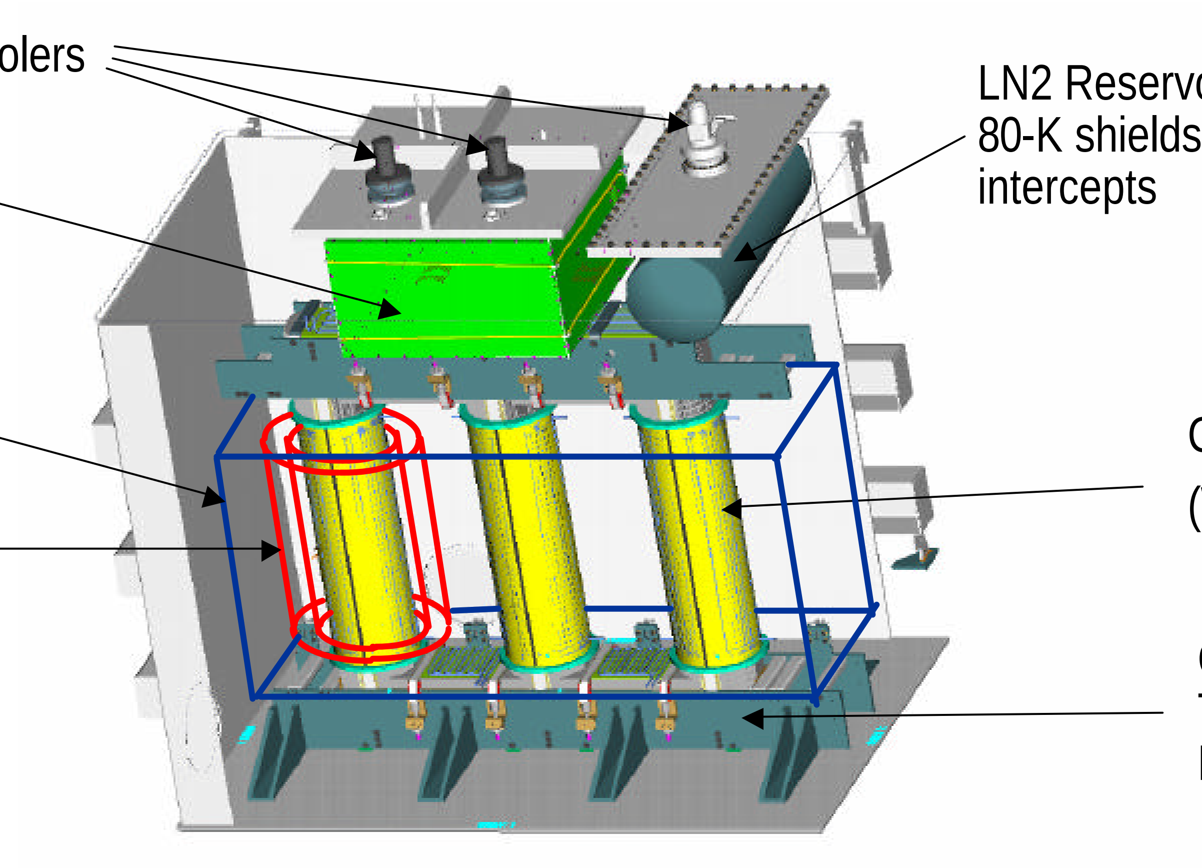
Specifications for the 1-MVA, 5/10-MVA, and 30/60-MVA Transformers show a progression in performance and complexity.

	1-MVA	5/10-MVA	30-MVA
Connection	1-Phase	3-Phase, Δ/Y	3-Phase, Δ/Y
Pri/Sec Voltage	13.8 kV/6.9 kV	24.9 kV / 4.2 kV	138 kV / 13.8 kV
Pri/Sec BIL	N/A	150 kV / 50 kV	550 kV / 110 kV
Pri/Sec Current	72.5 A / 145 A	67 A / 694 A	72 A / 1255 A
Overload Ratings	N/A	2-sec 10X, 48-hr 2X	2-sec 10X, 48-hr 2X
3-Day Power Outage Handling	N/A	Backup Motor/Generator	Backup Motor/Generator
Cooling System	Cryocooler	Cryocoolers	Cryocoolers
Instrumentation	Local	Local	Remote

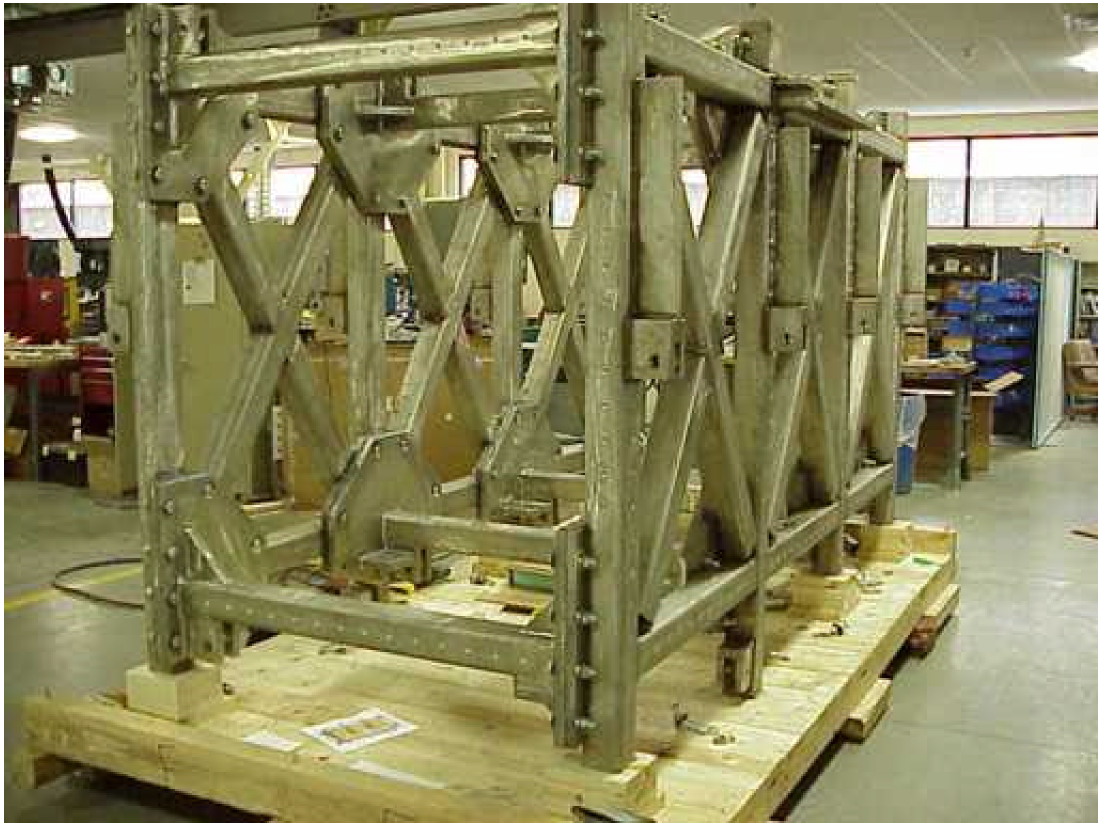


The 1-MVA Transformer Demonstrated All Major Features of the 5/10-MVA Conceptual Design.

Cutaway Showing Major Components of 5/10-MVA Design



IGC-SP Structural Frame Awaiting Assembly Into Transformer



All HV and LV Coils Are Wound and Vacuum Potted

LV Coil As Potted

HV Coil Prepped for Phase Set Assembly

WES is Assembling the Core, Bushings, and Vacuum Tank.

The 5/10-MVA Transformer will be installed and operated on the grid at the WES plant.

Research Integration: Team Effort Is Reflected in the 5/10-MVA Design.

Task	ORNL	WES	IGC-SP	RG&E
Specifications, Objectives	◆	◆	◆	◆
Dielectric Design	◆	◆	◆	◆
Low AC Loss Winding Design	◆		◆	
Bushing/Downlead Design	◆	◆	◆	
Instrumentation & Control		◆	◆	
Cryogenic Cooling Design	◆		◆	
Core Cooling Design	◆	◆		
Winding Development			◆	
Coil Supports, 80-K Shield	◆		◆	

FY 2002 ORNL Plans
(from August, 2001 Peer Review)

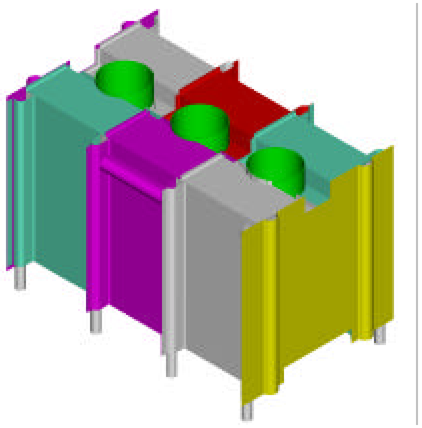
- **Completion and test of the 5/10-MVA cryogenic cooling system.**
- **Participate in assembly, commissioning, and test of the 5/10-MVA transformer at the WES plant.**
- **Carry out ac loss and critical current tests on coated-conductor YBCO tapes or coils as they become available.**
- **Continue high-voltage insulation tests, with focus on 550-kV BIL applications.**
- **Conduct fault current tests when sample coils become available from IGC-SP.**

Summary of ORNL Results This Year

- Activities were focussed on final design and fabrication of the 5/10-MVA transformer.
  - ORNL personnel made several visits to WES and IGC-SP.
- The cooling system module for the 5/10-MVA transformer was completed and successfully tested in a two-week period at at WES.
- Further ac loss tests were performed on the fourth IGC-SP sample coil, to obtain a more accurate ac loss profile.
- Dielectric tests investigated breakdown statistics, partial discharge, and higher-voltage designs.
- YBCO conductor samples received from IGC-SP— tests underway.
- New Task— MLI blankets were designed for the 5/10-MVA transformer coils, at the request of IGC-SP.
- New Task— Core cooling heat transfer studies were carried out for WES.

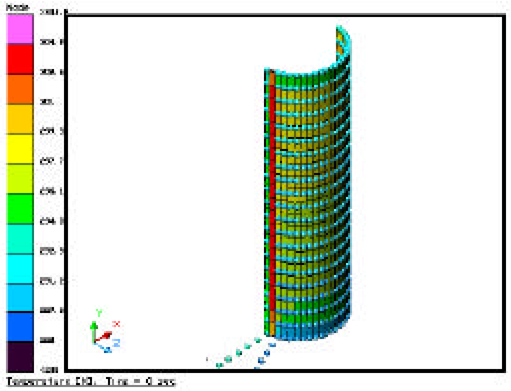
New task— Design of the coil set MLI

- MLI design done for IGC-SP in return for study of mechanical calculations on cooling module suspension.
- MLI is designed in sections separated by insulators, to prevent a shorted path around the core.



New task— Core cooling heat transfer calcs

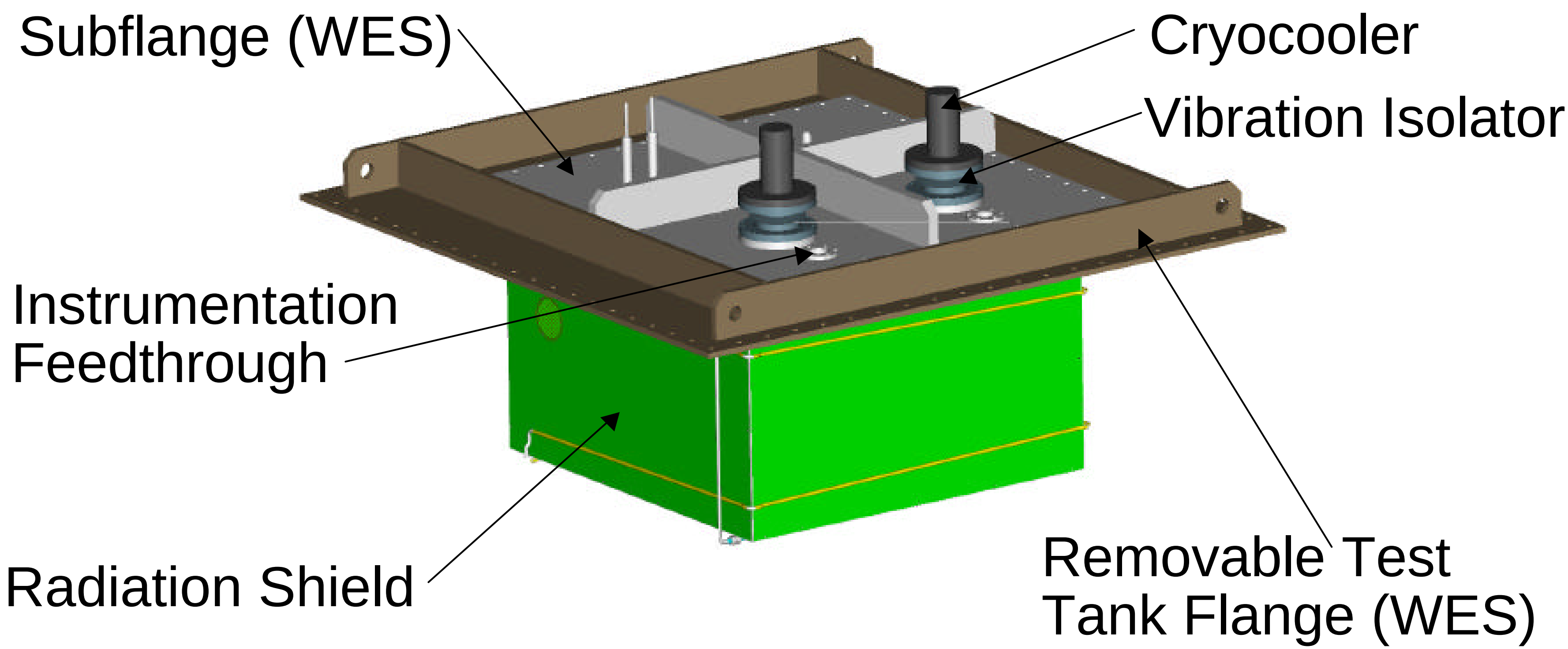
- Finite-element heat transfer calculations made with SINDA code.
- Cooling panels keep maximum core temperature below 35 ºC.
- Cooling water pressure drops are within chiller ratings.



ORNL activities on the Cooling Module in FY2002 included:

- Completion of heat transfer and fluid flow analysis
- Preparation of Pro-E engineering model and shop drawing package
- Procurement of parts and shop services
- Preparation of detailed assembly procedures and shop oversight during during fabrication
- Preparation of cooling module test plan

The Coil Refrigeration System is a Modular Unit That Plugs Into Top of 5/10-MVA Transformer.



Design/Performance Highlights

- Designed in close collaboration with IGC-SP, for application in both 5/10-MVA and larger future commercial units.
  - Pro-Engineer model plugs directly into WES model for transformer.
- Cryocoolers are suspended on bellows & springs for vibration and thermal contraction.
- Electrically-heated 350-W Dummy Load hanging below thermal shield simulated coils in proof test.
- Designed for 3-g horizontal and 0.5-g vertical shipping/handling load.
- Cooling module installs easily in both test tank and 5/10-MVA transformer.

The Cooling Module was shipped from Oak Ridge to Waukesha.

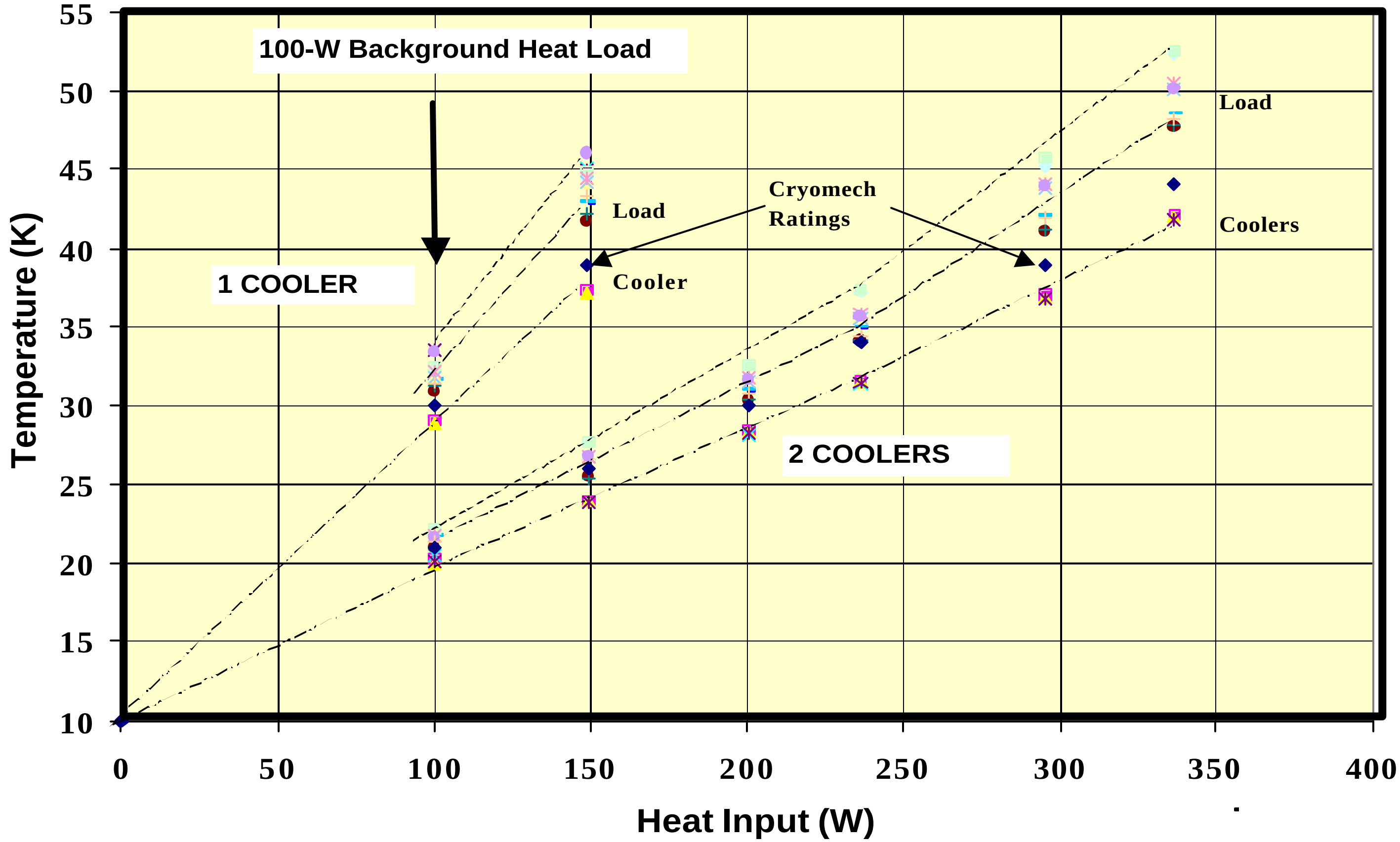
- Unit arrived at WES with no damage.

Installation in the WES test tank went smoothly

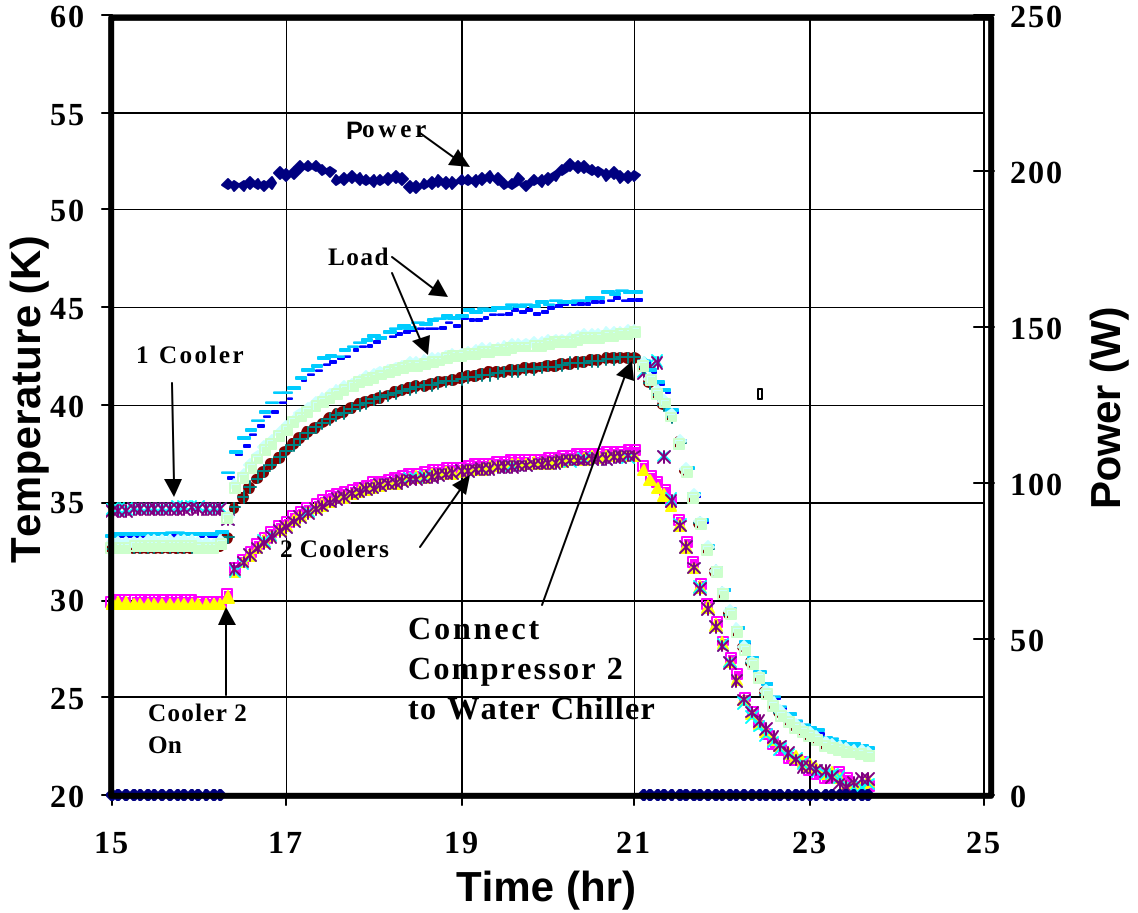
The Cooling System was tested separately before installation in the 5/10-MVA Unit

- Minimum standby mode temperature determined.
- Dummy Load temperature profile was determined for heater power loads corresponding to up to 2X rated operation.
- Stability under non-uniform heating was investigated.
- Tested with one cryocooler operating.
- Tested with both cryocoolers operating.
- Transition from single-cooler normal operation to dual-cooler 2X overload operation was simulated.

Tests showed acceptable operating temperatures and temperature differentials to the coolers.



Transition from single-cooler normal to dual-cooler overload went smoothly



The Cooling Module tests fully qualified the system for transformer operation.

- Cooled down automatically in ~25 hr— unattended overnight.
- Operated overnight unattended for a week.
- Operated with static vacuum— no pumping.
- 100-W Background— 30 K with 1 cooler, 20 K with 2 coolers.
- Maximum temperatures were within acceptable limits up to 350 W total load.
- No instability observed with 25% unbalance on Phase A.
- Transition to 2X overload operation was smooth.

Cryogenic Dielectric Materials for HTS Transformers

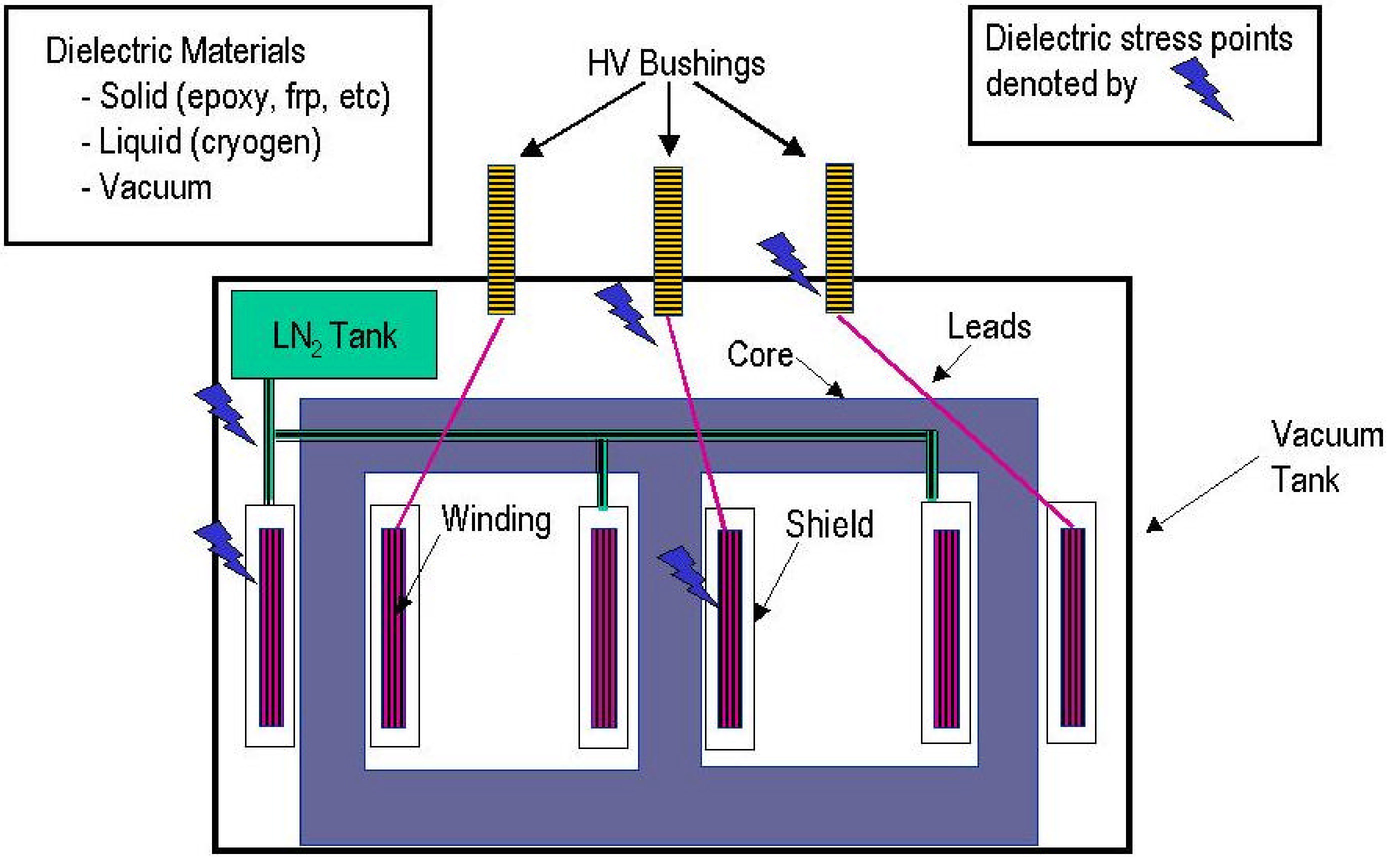
- Desirable properties
  - High dielectric strength
  - Low partial discharge
  - Low dissipation factor
  - Thermal compatibility
  - Mechanical strength for solid materials
  - Thermal conduction
- Measurements underway
  - AC breakdown
  - Impulse breakdown
  - Partial discharge and aging
  - Dissipation factor
  - Thermal shock tests

HV Testing of Solid Samples

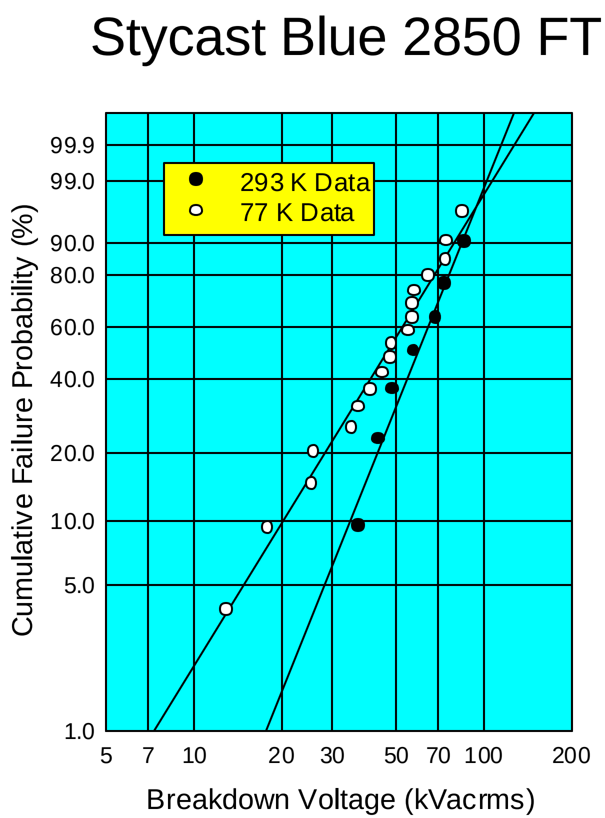
HV Impulse Generator and Large HV Cryostat

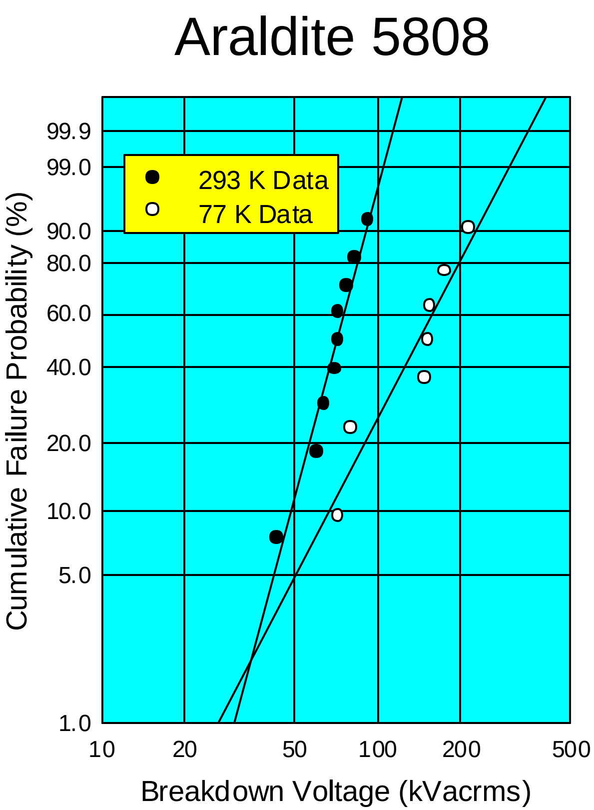
HV AC Power Supply and Partial Discharge Studies

Dielectric Stress Points in HTS Transformer



Cumulative failure probabilities for two epoxies follow the expected Weibull distribution



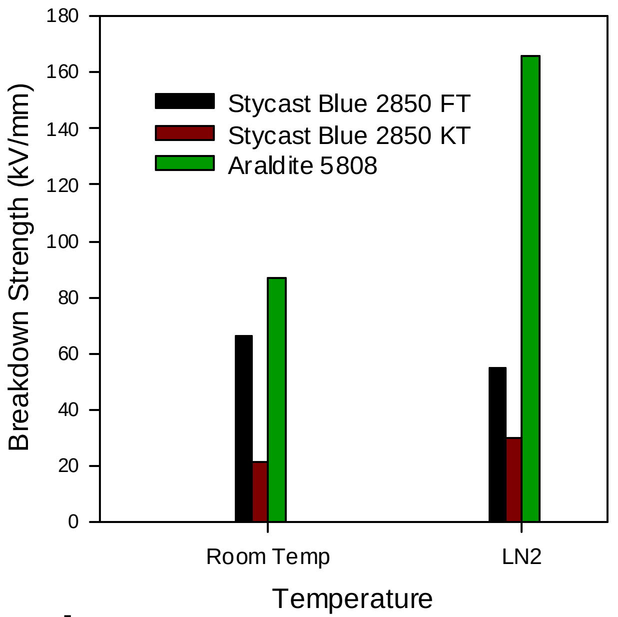


Breakdown data indicate potential materials for high voltage cryogenic applications

Weibull statistical data for breakdown field strengths of epoxy samples

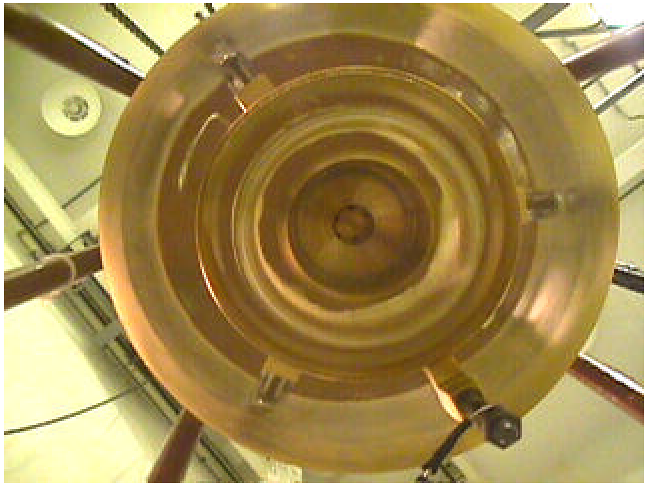
Sample	Temp. (deg K)	Weibull 63.2 %, E_0 (kV/mm)	No. of samples
Stycast® Blue 2850FT/24LV Catalyst	293	65.9	13
	77	54.7	24
Stycast® 2850KT/11 Catalyst	293	21.3	5
	77	29.8	5
Araldite® CY5808/HY 5808 Hardener	293	87	9
	77	166	7

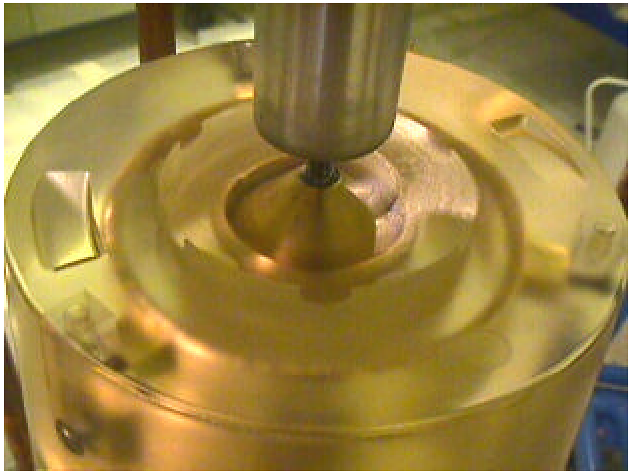
Electric Strength from Weibull Distribution

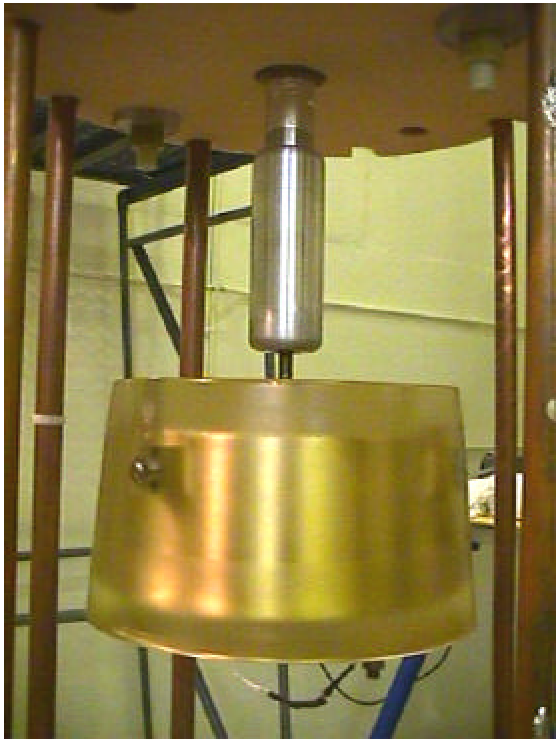


- Statistical data on small samples indicate range and temperature dependence of breakdown strengths
- Observed Weibull distribution or weakest link likely due to voids

Samples made for higher voltage applications



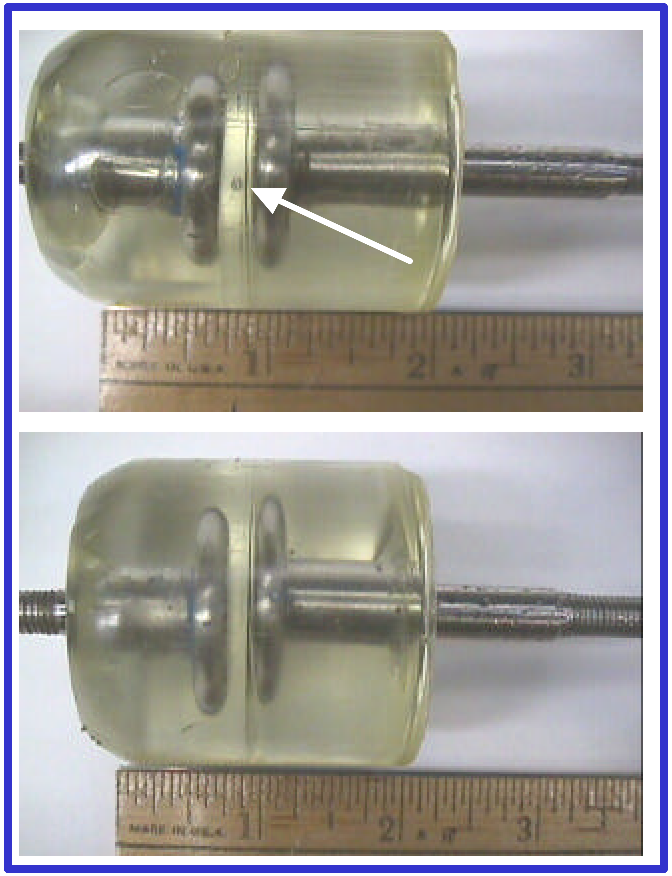




- Araldite 5808 currently being tested under cylindrical geometry
- High voltage tests include partial discharge, AC withstand and BIL
- PD onset voltage increases in LN_2

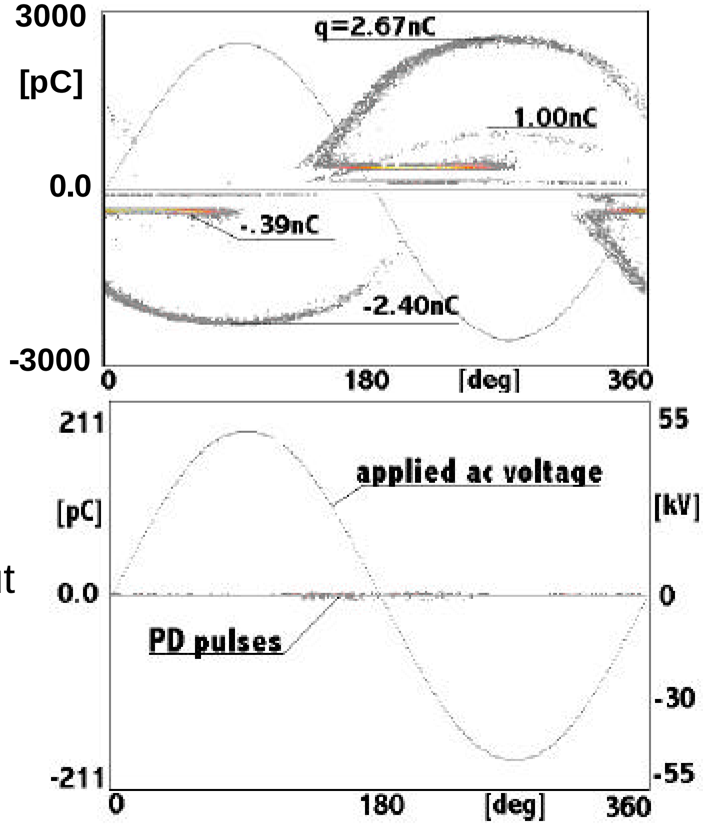
Sample suspended from high voltage bushing for testing in HV cryostat

Partial Discharge data provide diagnostic for the presence of voids in solid epoxy.



With void

Without void



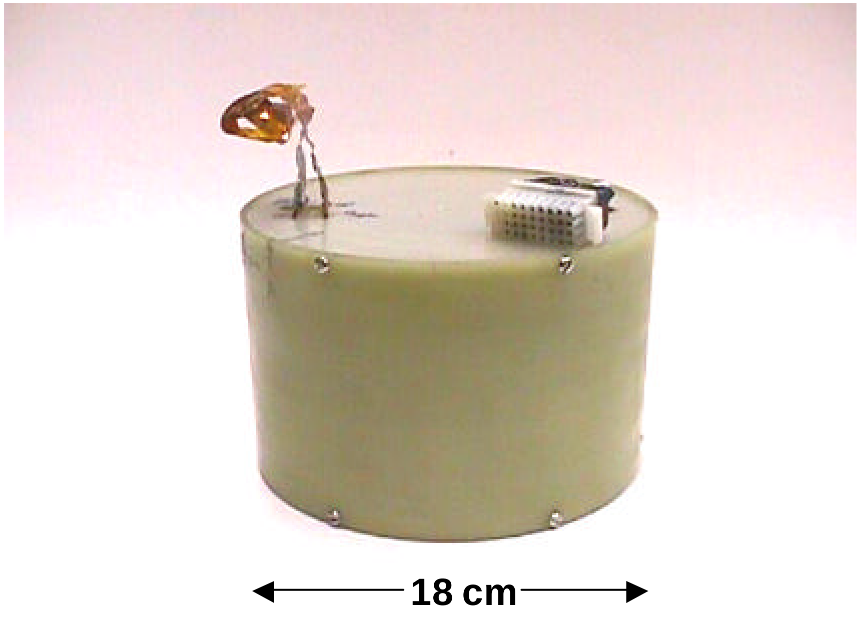
Phase resolved digitized PD data showing typical large arch pattern at room temp

V = 30kV rms

Absence of pattern in samples without void.

More extensive tests were performed on Sample Coil 4 provided by IGC-SuperPower in Phase II

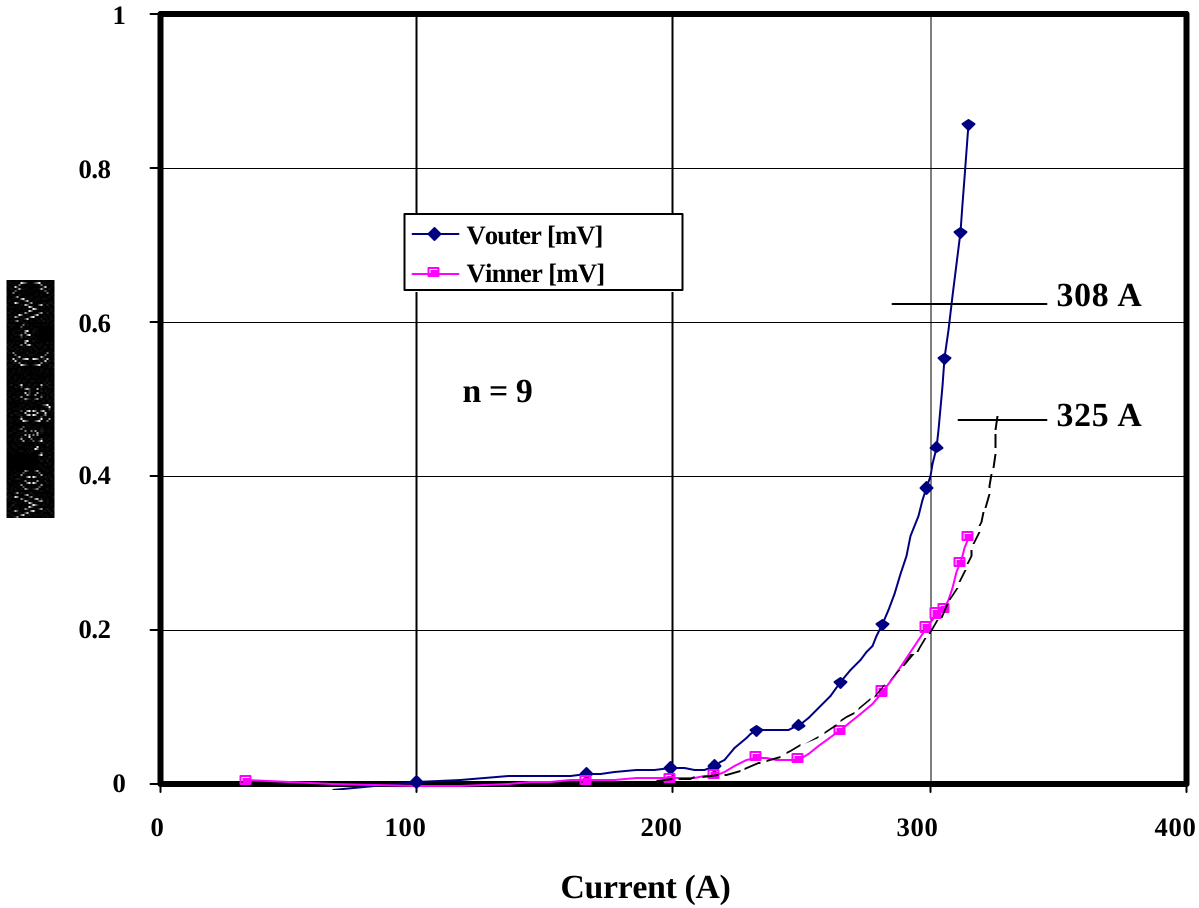
- Data system was modified to accept all sensors, for more accurate loss profile.
- Primary & secondary coils reproduce transformer geometry— full-size gap.
- Windings have IGC-SuperPower proprietary ac loss reduction features.
- 15 turns in primary & secondary coils.
- Instrumented with heater, voltage taps and carbon resistance thermometers.
- **Fourth coil has actual 5/10-MVA conductor and winding configuration.**



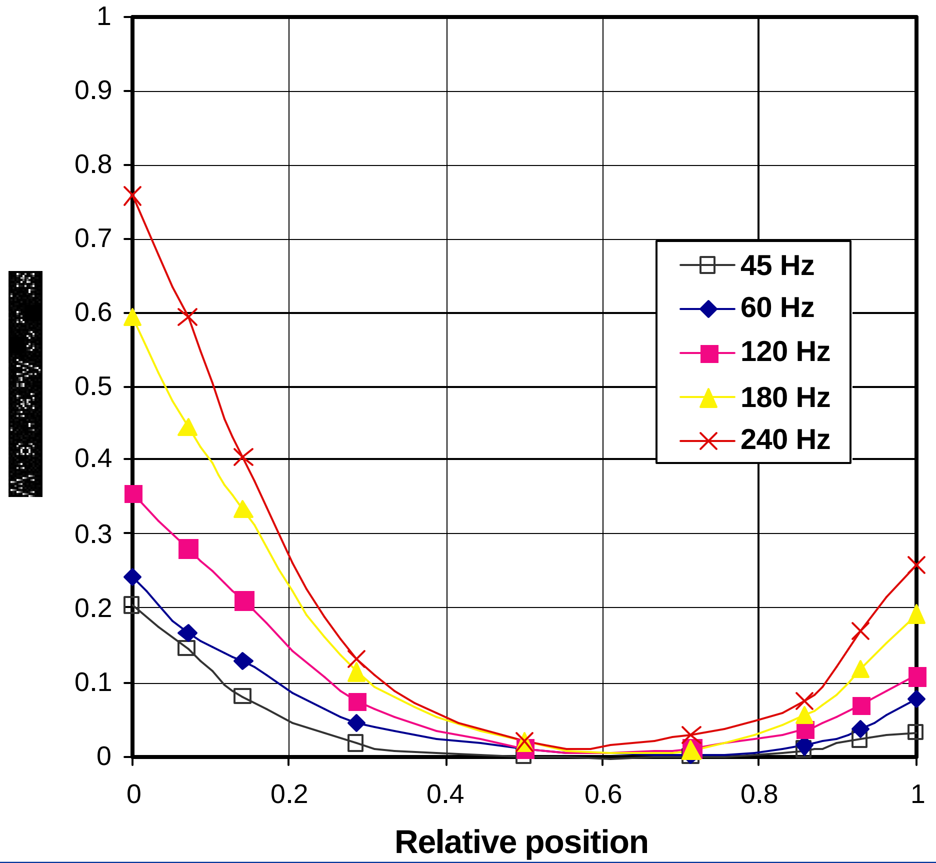
AC Loss Tests are Made Calorimetrically

- Test coil hangs in vacuum with good thermal isolation.
- Calorimetric measurement avoids the influence of the metal dewar.
- Loss sensitivity <0.1 W.
- Heating rates on thermometers are observed with 10-sec ac pulses, frequency 45-240 Hz.
- Short pulses limit T drift and give losses on individual turns (difficult with electrical measurement).
- Calibration by comparison of ac data with heating rates for known dc heat inputs to heater.

Critical current tests were performed on Sample Coil 4 at 44 K.



AC losses are roughly linear in frequency and depend strongly on position in coil.



Current = 60 A

T = 28 K

ORNL AC Loss Tests Have Validated IGC-SP's Low AC Loss Designs

- **Losses are concentrated at ends of winding, as expected.**
- **Minimum losses in central region hold for most of coil.**
- **A generally linear frequency dependence of the ac losses is observed, suggesting that hysteresis is the main loss mechanism.**
- **Measured losses in Coil Set 4 confirm anticipated losses for the 5/10 MVA Transformer.**
- **Results have facilitated economical design of the 5/10 MVA transformer for low losses and refrigeration.**
- **Design and economics for eventual 30/60 MVA and higher-MVA commercial units can be projected.**

FY 2002 Plans

- Completion and test of the 5/10-MVA cryogenic cooling system
- Participate in assembly, commissioning, and testing of the 5/10-MVA transformer

FY 2002 Performance

- ✓ Cooling system was completed and successfully tested at WES.
  - ✓ Fabrication carried out in local shops.
  - ✓ Survived all shipping loads w/o damage.
  - ✓ Operated automatically without supervision.
  - ✓ Acceptable temperature differentials to the cryocoolers were maintained.
  - ✓ Operated well with both one & two coolers.
  - ✓ Transition from normal to overload operation carried out smoothly.
- ✓ Consulted on all design and assembly issues as they arose.
  - ✓ Several visits to WES and IGC-SP sites.
  - ✓ Final assembly & testing later in 2002.

FY 2002 Plans

- Carry out high-voltage insulation tests.
- Carry out critical current and ac loss tests on YBCO.
- Conduct fault current tests on sample coils from IGC-SP
- New tasks were taken on.

FY 2002 Performance

- ✓ Extensive data on several materials confirmed Weibull breakdown statistics; PD data shows effect of voids; high-voltage cylindrical sample constructed.
- ✓ Short samples of YBCO received from IGC-SP- tests in progress. 4th Sample Coil tested further in cryo-cooled test rig. More detailed loss profiles, Ic data, and variable frequency measurements obtained.
- ● Deferred pending receipt of coils. IGC-SP calculations show that fault tests may not be needed.
- ✓ Coil set MLI designed; core cooling calculations were made.

ORNL's FY 2003 Plans Include:

- Participate in final assembly & testing of 5/10-MVA unit.
- Refine cryogenic and high voltage insulation system designs for commercial production 30-MVA transformers.
- Carry out ac loss and critical current tests on further sample coils for the 30-MVA transformer.
- Continue high-voltage insulation tests, with focus on 550-kV BIL applications for 30-MVA transformers.
- Investigate fault-current-limiting transformer designs.
- Carry out any other required materials testing as necessary and appropriate for ORNL facilities.

Research Integration

- ORNL/WES/IGC-SP/RG&E team possesses strong complementary abilities in research, engineering, manufacturing, & utility operation.
  - Consultants— RPI, Advanced Energy analysis, Applied Cryogenics Technology
- All partners are now working on final fabrication and installation for the 5/10-MVA transformer— 3 major team meetings at WES and IGC-SP; ORNL made 2 other individual visits.
- Many standard components and outside shops are being used for fabrication of 5/10-MVA unit.

Research Integration— II

- Partners freely trade tasks and loan equipment to best take advantage of capabilities at each location.
  - ORNL performed MLI design for IGC-SP and core cooling calcs for WES.
  - IGC-SP did resonance and stress analysis on ORNL cooling module.
  - Final coil assembly location was shifted from IGC-SP to WES plant, for more integrated & flexible assembly; also to mitigate floor loading issues at the IGC-SP location.
  - WES loaned PD detector to IGC-SP, and tan-delta bridge to ORNL.

Joint Presentations and Publications

- Presentations:
  - January, 2002— IEEE PES Winter Power Meeting
  - December, 2001— 10th US-Japan Workshop on HTS
  - August, 2002— Applied Superconductivity Conference
  - October, 2002— Conf. On Electrical Insulation & Dielectric Phenomena
- Joint Technical Papers in:
  - IEEE Trans. PES
  - Physica C
  - IEEE Trans. Appl. Superconductivity
  - IEEE Trans. On Dielectrics & Electrical Insulation
- ORNL Web Site—
  - www.ornl.gov/HTSC/htsc.html

ORNL Continues to Support the Team in Long-Term HTS Transformer Development.

5/10-MVA Transformer at WES Plant

Mike Walker, IGC-SP

The whole team wishes the best to Mike Walker in his retirement.

Bill Schwenterly Marty Lubell