HTS Power Transformers

Presented to the

2004 DOE Peer Review Committee

For the WES/SP/EE/ORNL Team

By

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Washington, D.C. July 27, 2004

Project Participants

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- **SuperPower, Inc.**

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- **Energy East (new parent company of Rochester Gas & Electric):**

  Jim Marean (NYSEG)

- **Oak Ridge National Laboratory:**

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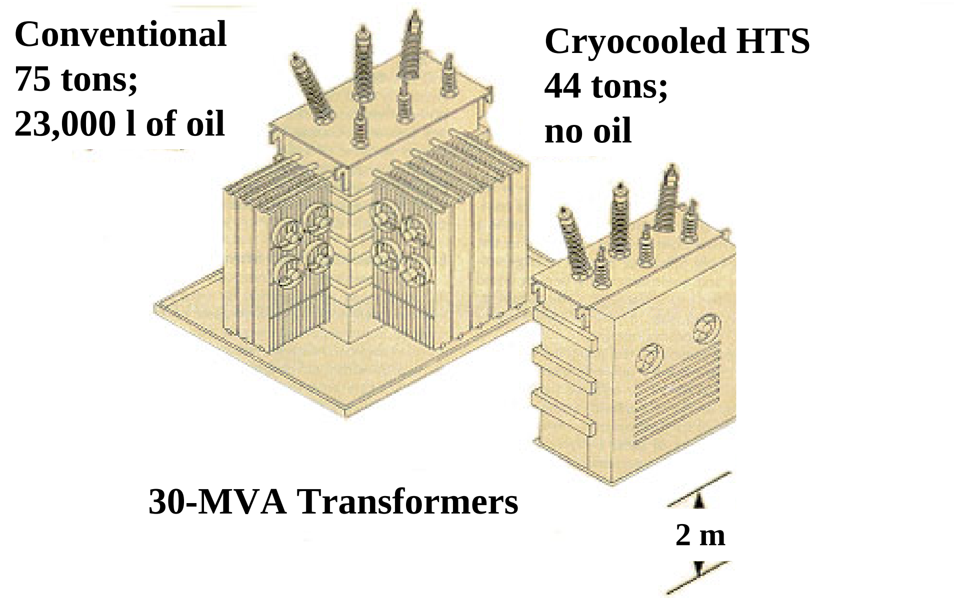
Project Purpose

- 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 concluding Phase II.

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.
- Greater security– smaller radiators; can interface directly with underground SC cable; no oil to spill or ignite, enclosed installation.



HTS Transformer Program Design Approach and Schedule

- **Cryocooled approach gives design flexibility.**
  - Allows operation from 20 K to 77 K permitting full system optimization.
  - Best available conductor at a given time can be operated at its optimum temperature.
  - Natural-convection helium circuit needs no external compressor.
  - 77-K cryocooler recondenses LN boiloff in closed cycle.
- **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 prototype transformer has been completed.**
- **Voltage and current tests have been completed on the 5/10-MVA unit.**

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 Line Current	72.5 A / 145 A	116 A / 694 A	125 A / 1255 A
Overload Ratings	N/A	2-sec 10X, 48-hr 2X	2-sec 10X, 48-hr 2X
Leakage Reactance	1.68 %	0.8 %	~ 1 %
Cooling System	Cryocooler	Cryocoolers	Cryocoolers
Instrumentation	Local	Local	Remote

- **BSCCO 2223 conductor is used in the 5/10-MVA transformer.**
- **Low-cost 2nd-generation tape required for a cost-effective 30-MVA design.**
- **BSCCO J_c too low and ac losses too high for 30-MVA unit.**
- **2nd-generation tape J_c ~10^6 A/cm^2 needed for low losses and compact size.**
- **Tape width ~ 2-3 mm needed for HV winding.**

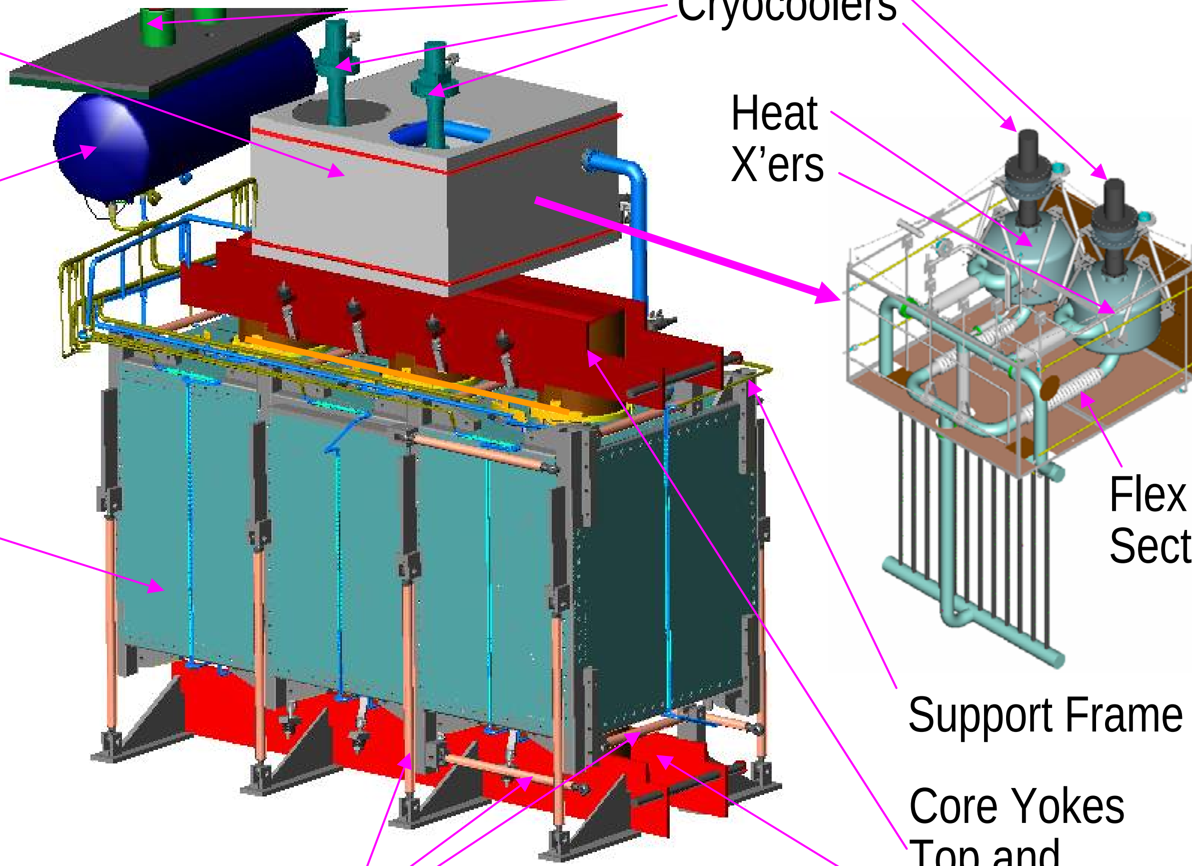
Major Components of 5/10-MVA Design

Convective He Cooling Module (ORNL)

LN2 Reservoir for cooling 80-K shields and lead intercepts (ORNL/SP)

80-K Shield (SP) surrounds coils (SP) on core

Not shown: Vacuum Tank, Bushings, RT Leads (WES)



Cryocoolers

Heat X'ers

Flex Section

Support Frame (SP)

Core Yokes Top and Bottom (WES)

Support Struts (SP)

ORNL's FY 2004 Plans Include:

(from July, 2003 Peer Review)

- **Assist in completion of tests and installation of 5/10-MVA unit on the grid.**
- **Critique and provide technical input to the 30-MVA transformer reference design.**
- **Participate in a proposed new cooperative program for further transformer development work before continuing with 30-MVA Phase 3 unit.**
  - **Cryogenic HV Dielectric materials.**
  - **YBCO properties.**
  - **Pulse tubes, tap changers, fault current limiting.**
  - **Improvements to manufacturability, marketability, match to utility requirements.**

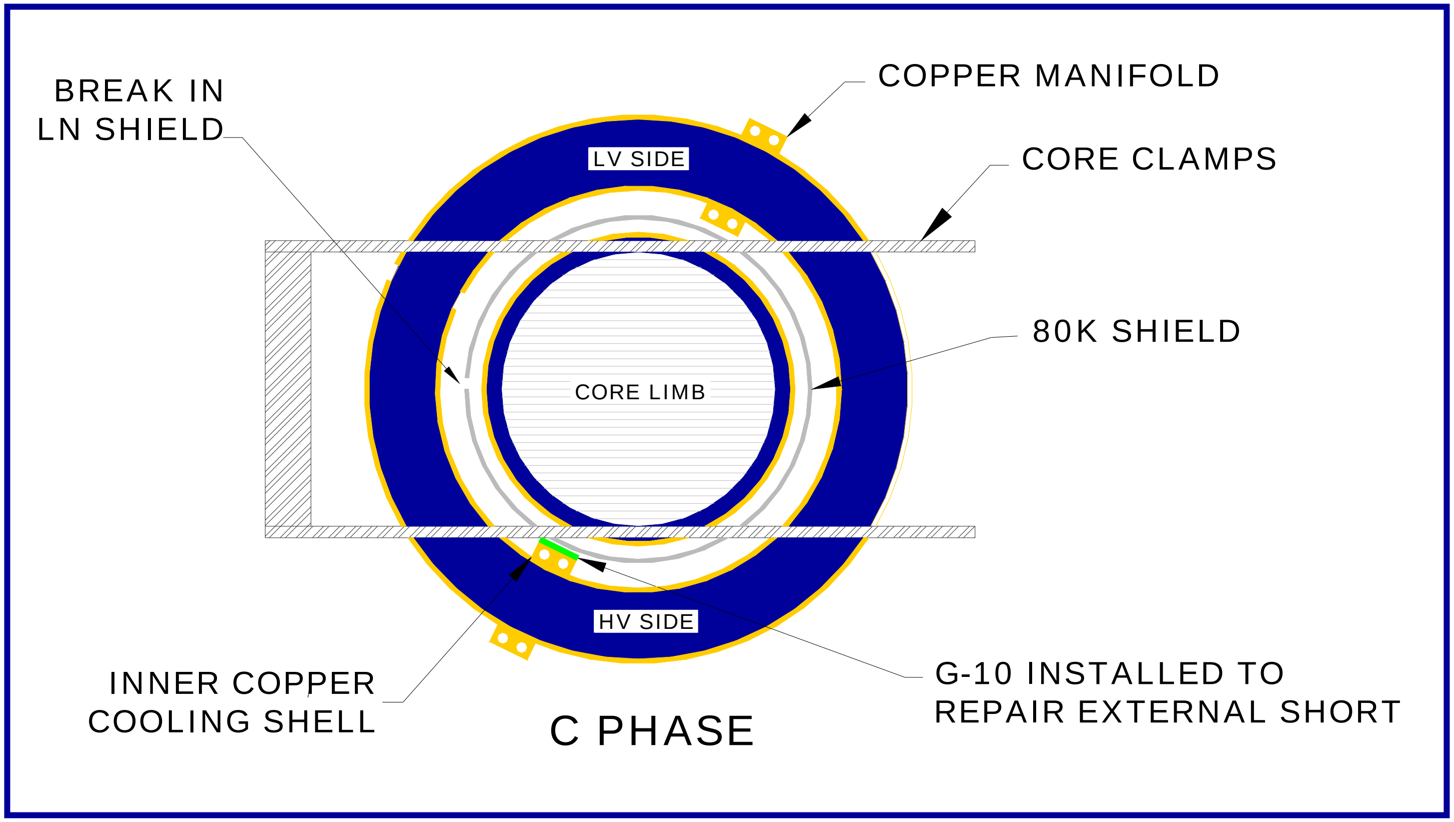
Summary of ORNL Results This Year

- **Focused on repair and testing of the 5/10-MVA transformer.**
  - **ORNL personnel made 8 extended visits to WES.**
  - **External short around "C" phase was found & repaired w/ G10 shim.**
  - **LN system leaks were found and repaired.**
  - **ORNL participated in cooldown and further testing of the transformer.**
    - **Extensive short-circuit testing up to 2X overcurrent.**
    - **High-voltage breakdowns prevented testing to full voltage.**
    - **After tests, the transformer was untanked and inspected for damage.**
    - **Coil failure prevents installation in WES substation.**
- **Many lessons were learned for application to the 30-MVA design.**
- **Dielectric tests showed unfavorable scaling of V_{br} with size.**
- **ORNL contributed to a proposal for the follow-on program.**

After the first tests in June 2003, the 5/10-MVA Unit was untanked and examined in fall 2003.

- **No physical damage to unit was observed.**
- **"C"-Phase shorted turn was found:**
  - **Sensitive gauss meter and fiber optic scope used to determine exact short location.**
  - **Touch between inner LN shield and coil cooling shell effectively caused current path through core window. G10 shim inserted.**
- **New LN system leaks were found :**
  - **LN system leak measured at 10^{-5} atm-cc/sec before cooldown.**
  - **Large leaks on ceramic electrical breaks to the LV leads, cryocooler module HX shield joint.**
  - **Repaired with Stycast epoxy.**
- **He system leaks were small and could not be localized.**

Touch at 80-K shield & copper shell caused short around "C" phase.



Preliminary Operations and Cooldown

- **All system joints were leak-checked to 10^{-9} atm-cc/sec before installation in tank.**
- **Global leak check showed that total pre-cooldown LN system leak rate had been reduced about a factor 30, to 10^{-6} atm-cc/sec.**
- **He system leakage was unchanged, also about 10^{-6} atm-cc/sec.**
  - **Pressurizing had no effect on tank vacuum with warm unit.**
- **Preliminary electrical tests at 300 K including ratio, winding resistance, capacitance, and megger to core matched for all coils– all OK.**
- **Transformer was cooled to 30 K in about 10 days.**
  - **LN flow was initially under manual control during cool down.**
  - **After LN tank was filled, all cryogenic systems ran unattended in closed cycle.**
- **Baseline vacuum 3 x 10^{-5} torr (close to N_2 vapor pressure at 30 K).**
  - **Vacuum was affected by LN and He pressures with cold unit.**

Transformer was cooled down in the WES Progress II building in about 10 days.

After cooldown, the transformer was prepared for transfer to the WES main plant.

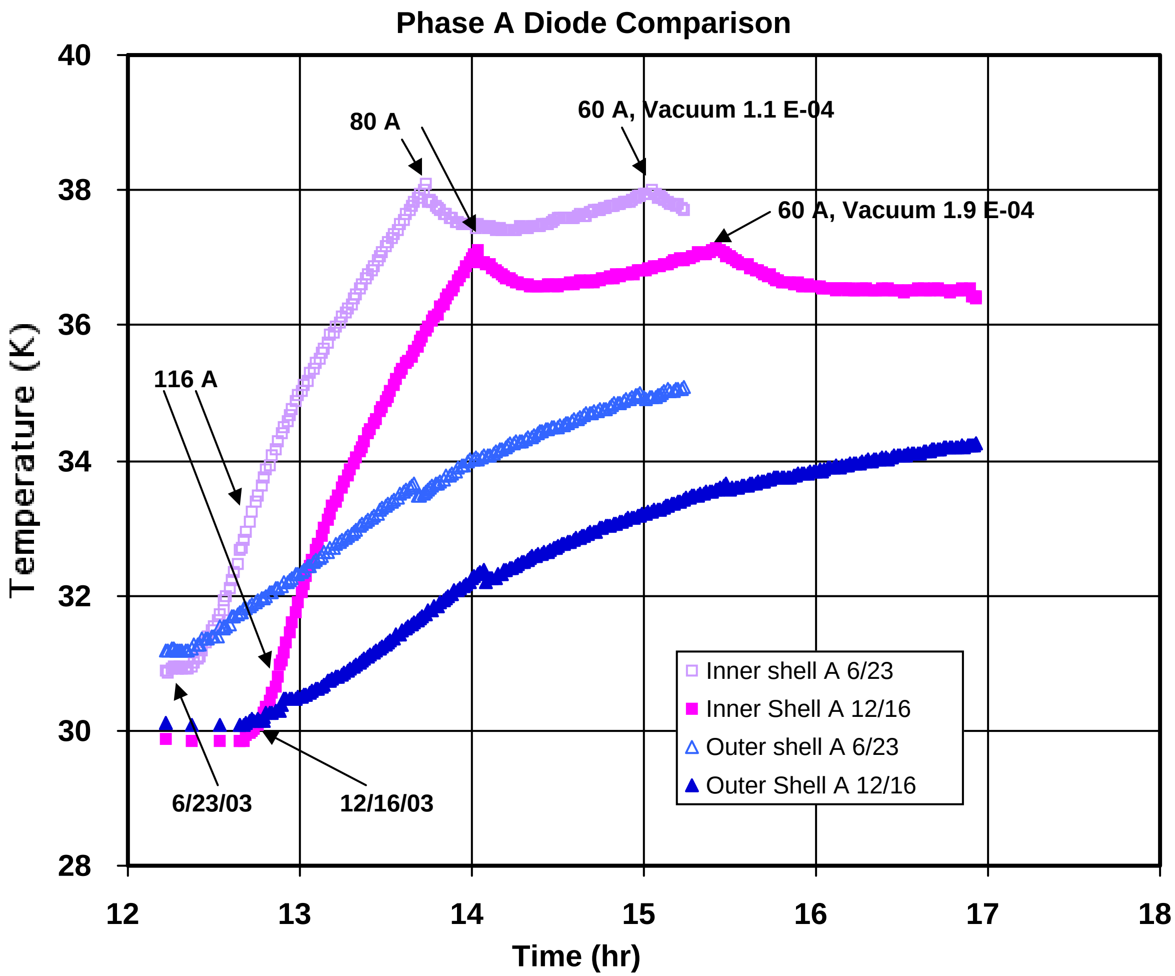
Transformer was transported cold for 0.4-km trip to Waukesha Electric main facility

5/10 MVA Unit was moved by crane to main test floor

Overview of Electrical Tests

- **Three-phase short-circuit tests were carried out with all 3 LV phases shorted together and HV phases energized.**
  - **ORNL loaned large 3-phase variac for ac current control.**
  - **Step-down transformer was added by WES to boost current.**
  - **This allowed tests at full line current of 116 A into HV winding, independent of WES test floor supplies.**
  - **Total test time was over 200 hr.**
  - **Longest continuous run was 65 hr.**
- **2X three-phase overcurrent tests were performed using auxiliary LHe cooling.**
- **High-voltage open-circuit tests were performed.**

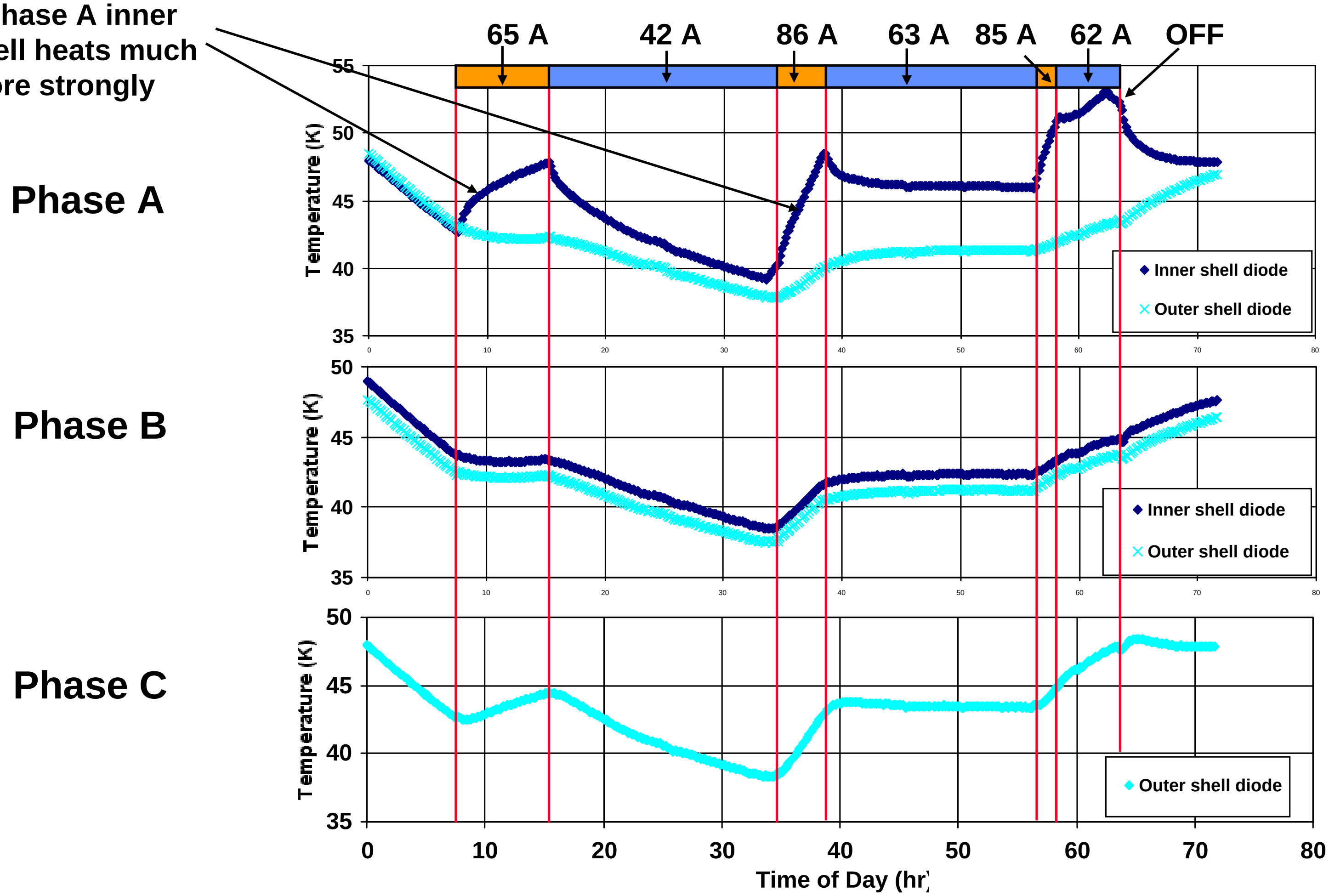
Repeat of the current-time profile for the June 03 tests showed little difference.



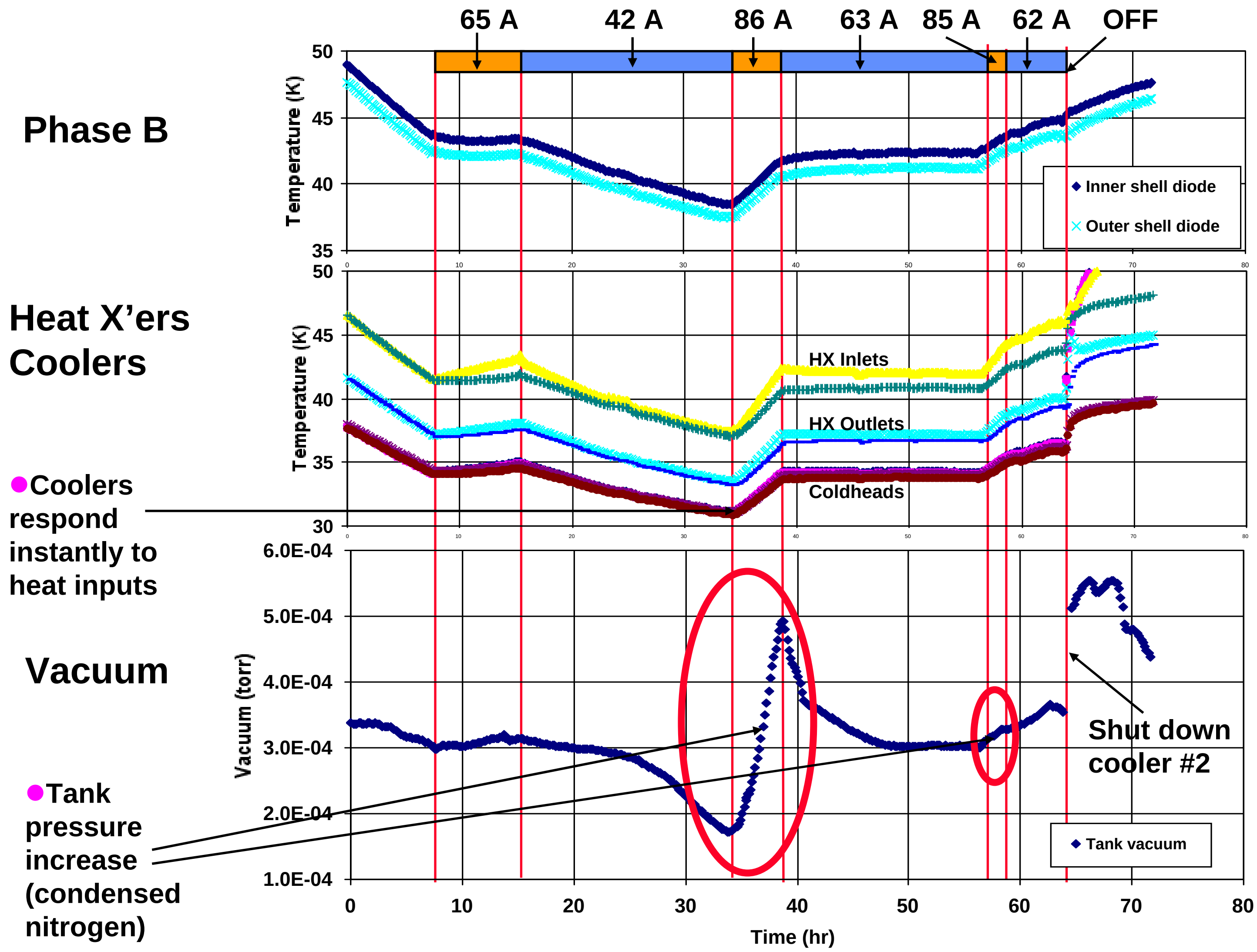
- **Currents shown are line values**
- **116 A = 1X rating**

The coils tended to warm up continuously for line currents above 65 A.

- Phase A inner shell heats much more strongly



Tank pressure increased above 65 A.



2X overcurrent tests verified mechanical strength & effect of auxiliary cooling.

- LHe from 500-L dewar circulated through coils in auxiliary circuit.
- Goal– to verify 2X overload capability.
- Current was raised in steps to 100% value and held several hours until LHe ran out.
- With another LHe dewar, current was raised in steps to 200% value of 230 A without failure.
- Coil and lead temps were running away after a few minutes, requiring shutdown.
- 60 A 3-phase current could be reapplied next morning with no problems.
- Auxiliary cooling could be used in power outage.

High voltage testing caused an HV-LV short.

- Rated line voltages are 4.2 kV for LV and 24.9 kV for HV.
- Installed PD inception voltage of coils was only ~1 kV.
- ORNL variac was used to drive a 480-V / 4160-V transformer connected to LV side.
- A snap was heard and current collapsed with LV at 1.4 kV and HV at 8.2 kV.
- Megger, ratio, capacitance, and short-circuit tests showed a shorted turn on Phase B, only 1 MΩ resistance HV-LV.
- In another single-phase HV test with Phase B shorted out, a breakdown occurred at 13 kV on HTS winding HV side.
- Afterwards, only 22 Ω was measured HV-LV.

ORNL tests for Southwire cable show that breakdown strength and PDIV decrease with stressed volume.

- **Breakdown and partial discharge inception voltage (PDIV) measured as function of stressed volume for two materials**
  - **Stycast 2850 KT (similar to FT used in 5/10-MVA with different particle size)**
  - **Araldite 5808 (unfilled)**
- **Both show similar volume dependencies.**
  - **$E = a V^{-b}$**
  - **Where the exponent “b” falls in the range 0.33-0.43**
- **Strength calculated for Stycast 2850 FT decreases from ~45 kV/mm at 1 cm^3 to <0.5 kV/mm (possibly as low as 0.1 kV/mm) at 10^6 cm^3 stressed volume.**
- **Epoxies generally lose strength for large stressed volumes.**
- **Problem is worse when defects such as bubbles are present.**
- **Scaling with volume generally not known for most materials.**

Summary of Test Results

- Cryogenic system ran well unattended and maintained the 4.5-ton cold mass in 40-K range during tests.
- Short around core on C phase was found and eliminated, but did not affect performance.
- Steady state operation achieved at 56% rated current.
- Excessive heating (mainly A-phase) and tank pressure rise observed during 1X and 2X rated current tests.
- During HV tests, breakdowns occurred at 8 kV and 13kV.
- Damage to coils prevented further testing or demonstration.
- Leakage of both LN and He into vacuum tank rose considerably during cooldown in spite of repairs.

The transformer was untanked and inspected for damage.

- No evidence of external breakdown on coils.
- A few surface cracks in Stycast epoxy were found on Phase A and B coils.
- With coils disconnected, HV-LV resistance was 360 Ω for Phase A, 18 Ω for Phase B, high for Phase C.
- A cracked ceramic break feeding LN to the LV leads was the probable source of nitrogen leakage.
- Some evidence of overheating in copper sections of the LV leads– would have increased LN heat load.
- Coils have been removed– have been shipped to SuperPower for inspection.

HTS coils could carry substantial ac currents.

- Demonstrated co-winding of up to 20 superconductors.
- Demonstrated parallel HTS windings and fault windings.
- Ran steady state, 3 phase at 63 A in short-circuit mode.
- Runs for several hours were possible at 85 A short-circuit.
- Current capacity was adequate for WES substation application.
- Reached 2x rated current for several minutes.
- Auxiliary cooling system provided extra cooling for 2X tests.
- For all 3 phases the following measured parameters were the same both warm and cold:
  - Turns ratio
  - Excitation current
  - Capacitance
  - Insulation resistance

Thermal systems worked as designed.

- **Helium gas-cooled natural circulation design worked well.**
- **Standby operation with one cryocooler was demonstrated.**
- **Successfully demonstrated the LN2 shield cooling system.**
  - **Closed-cycle system is directly relevant to LN-cooled YBCO design.**
- **Cooling shell design proven to adequately cool coils.**
- **Successfully demonstrated core cooling system on test core.**
- **Transformer successfully transitioned several thermal cycles.**
- **Two independent designs were successfully implemented for leads with low heat leak losses, one for high voltage, and the other for high current.**
- **LN and He leakage from internal circuits must be reduced.**

Vacuum vessel performed well.

- The empty 34 m^3 vacuum vessel with 27 openings reached pressure in the low 10^{-5} torr range at room temperature.
- Compact 300 l/sec turbopump maintained vacuum.
- Tank maintained vacuum with many different materials in it at room temperature in the low 10^{-4} torr and cryopumped down to low 10^{-5} torr at 30K.
- Tank design incorporated a bolt-on cover (2.5m x 3.7m) with three openings using O-ring seals that held vacuum even with repeated pressure cycling and removals.

Some parts of dielectric system performed well.

- **Used OEM insulated connectors & bushings for HV and LV connections.**
- **Demonstrated a low-heat-load high voltage mast design to connect warm high voltage leads to cold coils.**
- **Embedded fiber optic temperature sensors allowed measurements at high voltages.**
- **Coil set “B” was tested 15kV to ground at 80K (<u>but</u>– with high PD).**
- **High-voltage breakdown of coils prevented installation in substation.**

Design addressed handling and transportation stresses.

- Low heat leak internal assembly supports survived all handling and shipping loads.
- Successfully manufactured major components in three separate facilities around the country, for assembly at Waukesha.
- Transformer was transported in the cold state from one facility to another at Waukesha Electric with no problems.
- Robust design survived handling by crane and truck.
- All systems up and running 3 – 4 hours after arrival.

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FY 2004 Plans

- **Participate in repair & testing of 5/10-MVA unit.**
- **Install and run unit on the utility grid.**
- **Critique and provide technical input to the 30-MVA transformer ref. design.**
- **Participate in a new extension of the transformer SPI:**
  - **Carry out YBCO materials studies**

FY 2004 Performance

- ✓ **Transformer was repaired; short eliminated; leakage improved; short-circuit testing completed.**
- ● **HV failure prevented installation on the grid.**
- ✓ **Testing and operating experience generated list of lessons learned for 30-MVA design.**
- ● **ORNL SOW proposal for extension has been submitted to WES and is being evaluated by management.**
  - ✓ **ORNL is already studying YBCO I_c performance and overcurrent behavior.**

What's Next?

- Transformer coils have been removed from core and shipped to SuperPower for inspection.
- Internal components will be carefully inspected for failure mode.
- Design improvements are needed to further streamline manufacturability.
  - Simplify plumbing to minimize leaks. Use all-welded SS; no copper in flow circuits.
  - Improvements to MLI assembly techniques.
  - Simpler cryogenic suspension methods.
  - Develop methods for pre-testing coils at room temperature.
- The team will be meeting to discuss lessons learned and prepare a final report.
- A follow-on cooperative project is being considered to develop solutions for dielectric problems and other design issues.

Proposed 2-year FY '05 follow-on cooperative project would address:

- Cryogenic dielectric studies for 30-MVA+ design ratings
  - PD, aging, ac and impulse breakdown strength
  - Thermal properties– shock, conductivity, heat capacity
  - Partnership with a commercial cast coil manufacturer
  - Tests on full-scale dummy coils
- Investigate electrical & mechanical compatibility between all insulation system components.
- Study YBCO materials for the 30-MVA reference design
  - AC loss
  - Ic and overcurrent capability; operation in liquid nitrogen
  - Fault current limiting
- New features– pulse tube coolers, tap changers, fault current limiting.
- Simplify design for best manufacturability, marketability, reliability, cost, match to utility requirements.

Research Integration

- **ORNL/WES/IGC-SP/EE team possesses strong complementary abilities in research, engineering, manufacturing, & utility operation.**
- **All partners worked together on repair, cooldown, and testing of the 5/10-MVA transformer.**
  - **8 extended visits– ORNL to WES.**
  - **1 extended visit– WES to ORNL.**
  - **ORNL visited SP for MFCL meetings; transformer also discussed.**
- **ORNL loaned three phase variable transformer to Waukesha for high-current short circuit testing.**
- **Communication several times a week by phone, E-mail, and fax.**

Joint Presentations and Outreach

- Presentations:
  - September, 2003 - Cryogenic Engineering Conference, Anchorage
  - October, 2003 – EPRI Superconductivity workshop
  - June, 2004 - IEEE summer PES meeting, Denver
  - October, 2004 – Applied Superconductivity Conference, Jacksonville
- Joint Technical Papers in:
  - 2003 Cryogenic Engineering Conference
  - 2004 IEEE summer PES meeting
  - 2004 Applied Superconductivity Conference
- Media Coverage
  - ORNL Science and Technology Highlights (May, 2004)
- ORNL Web Site—
  - www.ornl.gov/HTSC/htsc.html

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