Design and Development of a 100MVA Generator for Commercial Entry

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DOE Peer Review,
Washington, DC
July 24, 2003

DOE Contract Objectives:

- Build and test 1.5 MVA demonstration machine for risk reduction
- Build and completely load-test a full-size 100 MVA HTS generator
- Develop designs through 250 MVA rating

Requirements for Success:

- Performance
- Cost
- Reliability

HTS Generator team and major vendors: DOE contract

GE-GR	HTS & Cryogenic Technology
GE-PGT	Generator Technology
GE-PSEC	Grid interaction studies
AEP	Generator Technology Evaluation
AMSC	HTS wire
Sumitomo H. I.	Refrigeration system

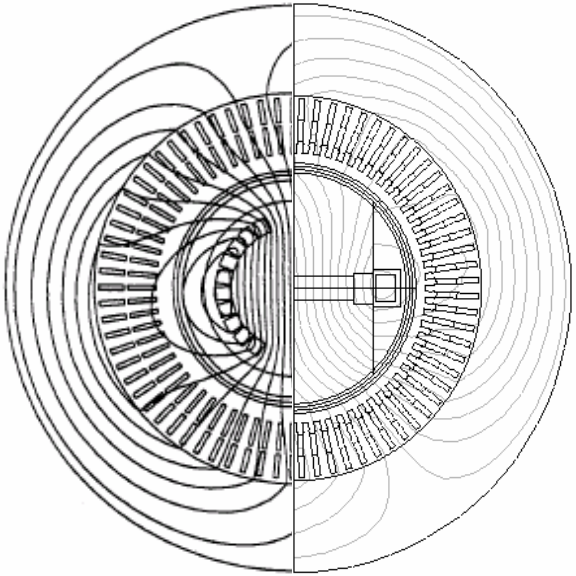
DOE National Labs: ORNL and LANL

Utility Partners Program Contribution

- Define/Validate customer CTQs
- Assess HTS technology benefits
- Perform power plant integration analysis
- Analyze commercial benefits
- Evaluate impact on T&D
- Sit on program advisory council

Superconducting Generator Approaches

Concept	Conv	Air Core	Iron Core
Magnetic field strength	Low	High	Low
Magnetic rotor forging	Yes	No	Yes
Magnetic stator teeth	Yes	No	Yes
Performance			
Efficiency	🔴	🟢	🟢
Reactive power capability	🔴	🟢	🟢
System stability	🔵	🟢	🔵
Design Considerations			
Size reduction	🔴	🟢	🔵
Minimum superconductor length	N/A	🔴	🟢
Minimum cryocooler size	N/A	🔵	🟢
Simplicity of field coil	🔴	🔴	🟢
Simplicity of stator winding	🔵	🔴	🔵
Minimized auxiliary cost	🟢	🔴	🔵
Reliability			
Cyclic capability	🔵	🟢	🟢
Rotor torque transfer	🟢	🔴	🟢
Stator torque transfer	🟢	🔴	🟢
Stator design experience	🟢	🔴	🟢
Auxiliaries	🟢	🔴	🔵



Iron Core Enables HTS Power Generation

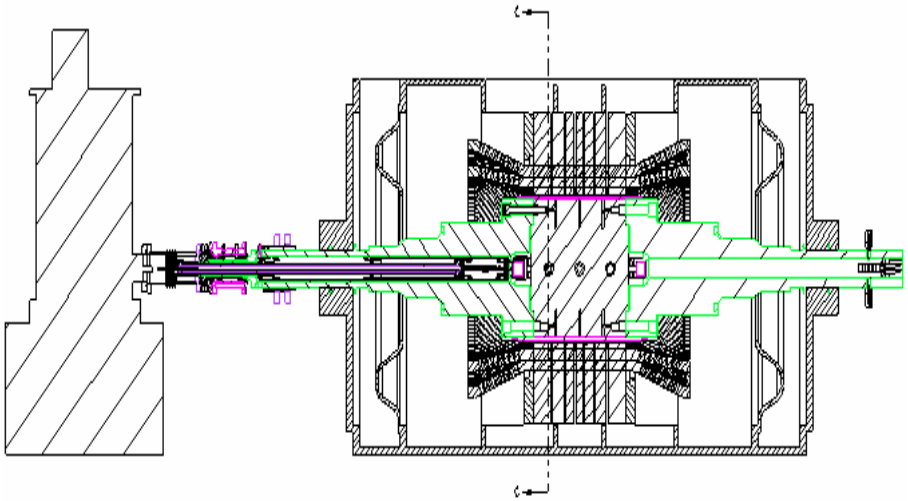
HTS Generator - Why & What (Approach)

HTS Generator characteristics:

- Easier HTS field coil design
- HTS rotor is same size as conventional rotor
- Common technology for new and retrofit units

What stays the same :

- Stator core & winding
- Frame & coolers
- Flange & bearings



Major customer benefits :

- 0.35-0.55 % efficiency gain (reduced emissions and fuel)
- Increased T&D stability (VAR capability, SCR)
- Generator uprate capability

New Components :

- Cryogenic Refrigeration
- He Transfer Coupling
- HTS Field Coil & Support
- Exciter

New approach to superconducting generator design

Major milestones: (end point: mid-05)

Item	Status
• Build and test a 1.5 MVA demonstrator machine	• Complete
• Perform 100-250 MVA conceptual designs	• partially complete (end: mid 03)
• Perform detailed design of 100 MVA HTS rotor	• In process (end of 03)
• Fabricate 100 MVA rotor	• Components in process (end of 04)
• Factory test 100 MVA rotor	• Future (end: mid 05)

Accomplishments/progress

- The 1.5 MVA demonstrator has been built and tested. Electrical and mechanical testing indicate soundness of basic design and give several valuable design improvements.
- Cryorefrigeration approach verified. Final cryorefrigeration system was specified and is in construction at vendor.
- Transfer coupling approach verified.
- Thermal system under final specification with ORNL, LANL help on emissivity, vacuum, etc.
- Help from ORNL and LANL in PD, quench, coil mechanical properties, excitation, ac loss
- HTS wire verified to meet specifications (with AMSC)
- Exciter concepts vetted.

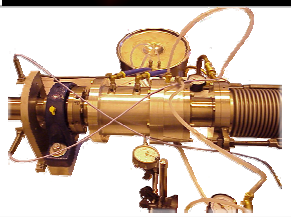
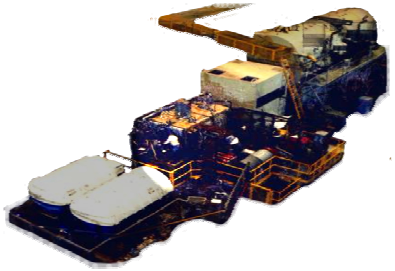
Risk Reduction

- Demonstrator machine at 1.5 MVA tests many full-size components and design ideas
- GE 6-Sigma (DFSS, DFR, RAM, FMEA, Risk Management) methods followed rigorously during program
- DOE participants (Mike Gouge, ORNL, coordinating) invited to key design meetings

2004 plans

- Complete conceptual designs through 250 MVA with business case.
- Receive, build, and test all components for 100 MVA rotor during 04 (e.g., cryorefrigerator, transfer coupling)
- Wind and test 100 MVA HTS coil.
- Select and secure final exciter.
- Complete detailed design and fabrication of 100 MVA rotor by end of 04.

Development Plan

Technology Demonstration	1.5 MVA Risk Abatement Rotor • HTS coil technology • Cryogenic system • Assembly and operation	
Component Tests	100 MVA HTS Components • Completed performance validation • Component life testing in progress	
Factory Test	100 MVA HTS Generator Prototype • Full speed and rated load operation • Cyclic duty testing • Integrated system testing	
Grid Operation	100 MVA HTS Generator At Pilot Site • Installation through rotor exchange • Validation of operation on the grid • On-line monitoring	

Move HTS Technology From Promise To Product

High Temperature Superconducting Generator

2003 Annual Peer Review

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

July 23-25, 2003
Washington, DC

ORNL Project Participants

- Jonathan Demko
- Robert Duckworth
- Alvin Ellis
- Mike Gouge
- Randy James

Winston Lue
Isidor Sauers
Bill Schwenterly
Marcus Young

Presentation Outline

- **FY 2003 Milestones**
- **FY 2003 Results**
  - **Emissivity Tests**
  - **Quench and Stability**
  - **Partial Discharge**
- **FY 2004 Plans**
- **Research Integration**
- **Summary**

FY 2003 Milestones

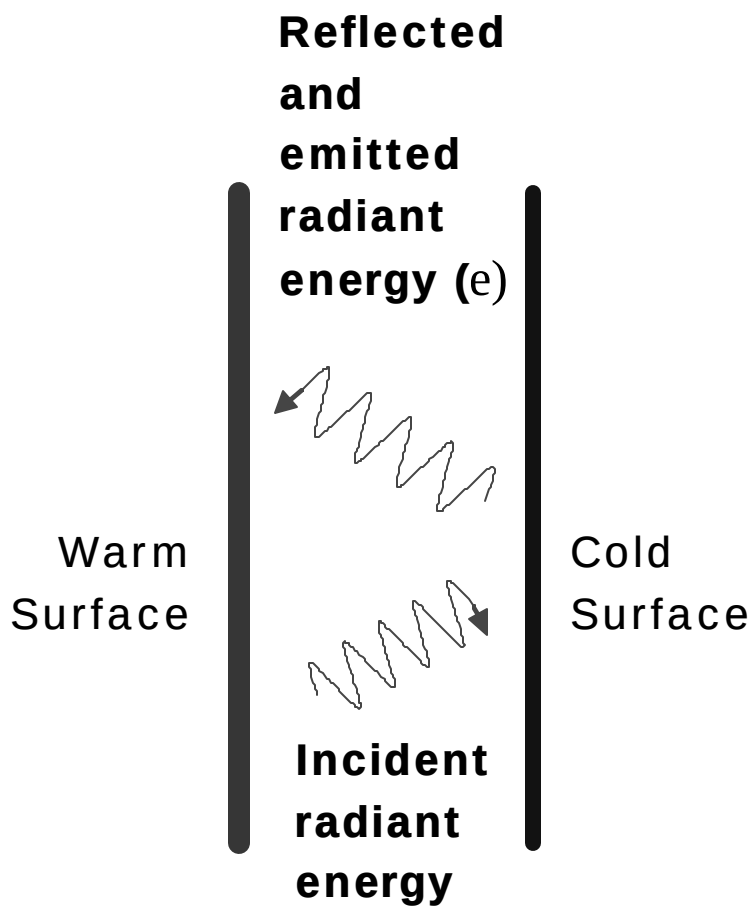
Task	Status
• **Emissivity experiments**	
– Design and construction of Test Apparatus	• Completed May 2003
– Calibration and measurement of test samples	• In progress (July 2003)
– Measurements of effects of surface contamination	• September 2003
• **Stability and Quench Studies**	
– Retrofit test facility to handle higher operating currents (300 A ® 750 A)	• Completed July 2003
– Measurement of flux flow resistivity as function of temperature and magnetic field	• August 2003
– Measure different quench dynamics to validate generator model	• September 2003
• **Dielectric Testing**	
– Testing of model tape and coil geometry	• In progress (October 2003)
• **Material properties measurements**	
– Mechanical composite testing	• Completed June 2003
– Thermal property measurements	• October/November 2003

FY 2003 Results

- **Emissivity test rig:**
  - **The heat meter and warm surface source were designed and fabricated.**
  - **After some initial calibration of the heat meter, some design modifications were made and initial tests were made on a copper plate**
  - **Contamination source fabricated.**
- **Quench protection modifications to existing test apparatus are being made to accommodate overcurrent testing of BSCCO-2223 tapes down to 20 K.**
  - **Existing equipment, that is capable of 330 A current pulses, is being modified to be capable of taking 1000 A current pulses.**
- **Dielectric testing:**
  - **Setting up to test single tape and coil samples provided to ORNL by GE for measurement of partial discharge.**
- **Mechanical Properties**
  - **A novel resonant ultrasound spectroscopy (RUS) technique was applied to measure the mechanical properties of HTS prototype coils.**
  - **The material was not appropriate for this technique.**
  - **Other means under investigation.**

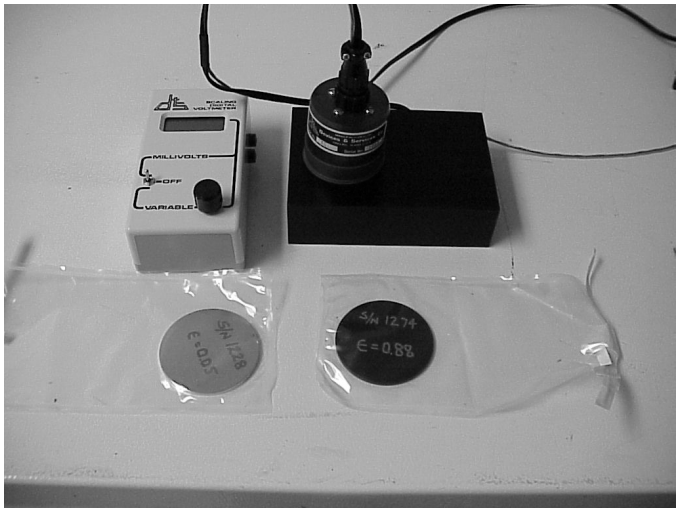
Low emissivity surfaces reduce thermal radiation heat transfer on the HTS generator

- **Emissivity measurements made for selected surfaces**
  - **Estimate the contribution of thermal shields to rotor cryogenic heat loads due to either water or air contamination**
  - **Measurement of baseline emissivity required to determine the influence of shield material and contaminate volume**
- **Measurements of emissivity depend on temperature and surface condition**
  - **Room Temperature (GE)**
  - **Cryogenic Temperatures (ORNL)**
    - **20 K to 70 K**



Room temperature emissivity measurements performed by GE

- **Done on several different materials including silver plated copper**



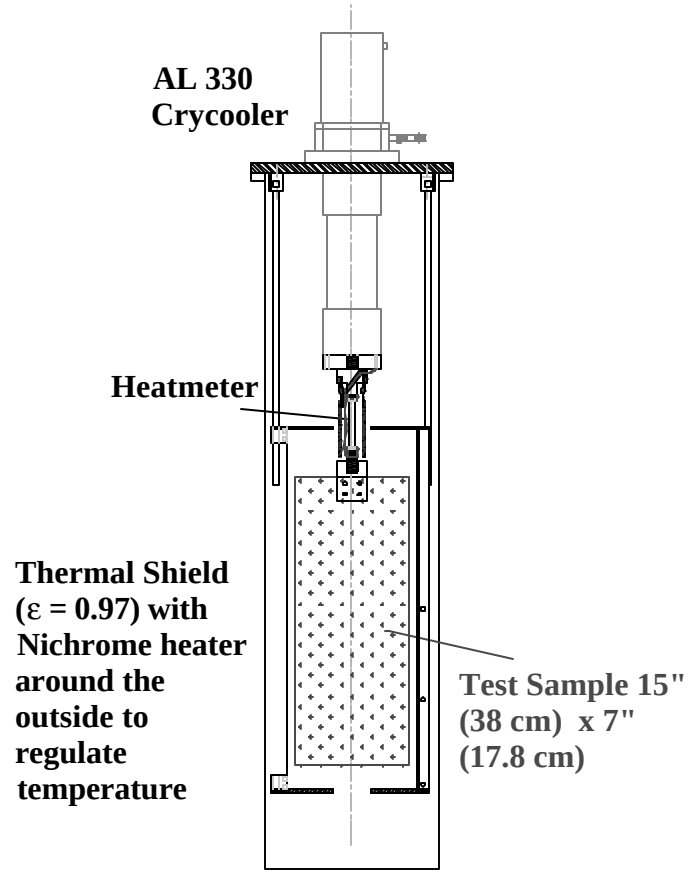
MATERIAL	CONDITION	Test Temp (K)	e
silver plated copper	.002 thk, over plate OFHC	298	0.02
304 stainless steel plate	.125 thk 304 SS , as rolled	298	0.20
Aluminum (6061-t6)	.125 thk, as rolled	298	0.07
Stainless steel shim stock	.010 , thk	298	0.14
Aluminized mylar	one layer, 5 mill	298	0.04
Sil. Brush Plating on steel	(thin layer,.0001, rough)	298	0.04

Emissivity measurements test apparatus is based on energy balance of sample.

- **Cryogenic Experimental Setup**
  - **Measures the hemispherical emissivities of samples in range of 20 K to 70 K through estimate of heat load**
  - **Utilizes variable temperature effective blackbody radiation shield**
  - **Accuracy to +/- 0.005**

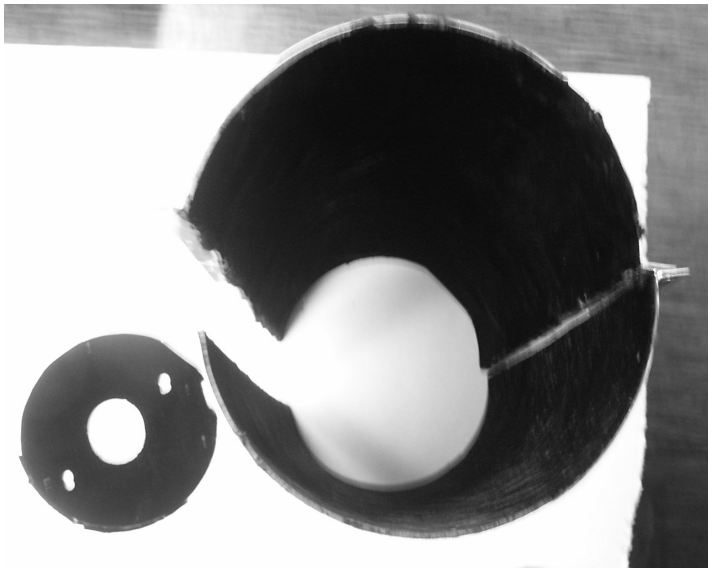
$$Q_{tot} = Q_{back} + Q_{rad}$$

$$Q_{rad} = \frac{A_{sample} s \left(T_{shield}{}^{4} - T_{sample}{}^{4} \right)}{\left(\frac{1}{e_{sample}} - 1 + \frac{A_{sample}}{A_{shield}} \left(\frac{1}{e_{shield}} - 1 \right) \right)}$$

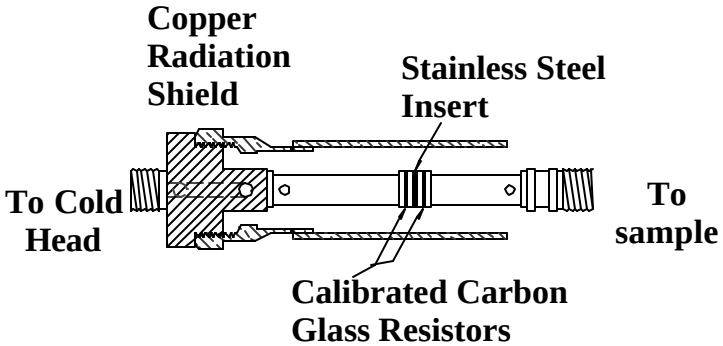


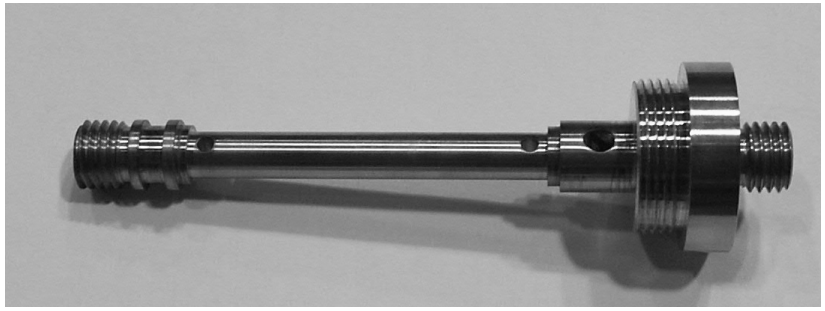
Emissivity measurement system components were designed and fabricated

- **Thermal Radiation Shield**
  - **Aluminum covered with vacuum black felt to create black body surface (e ~ 0.97)**

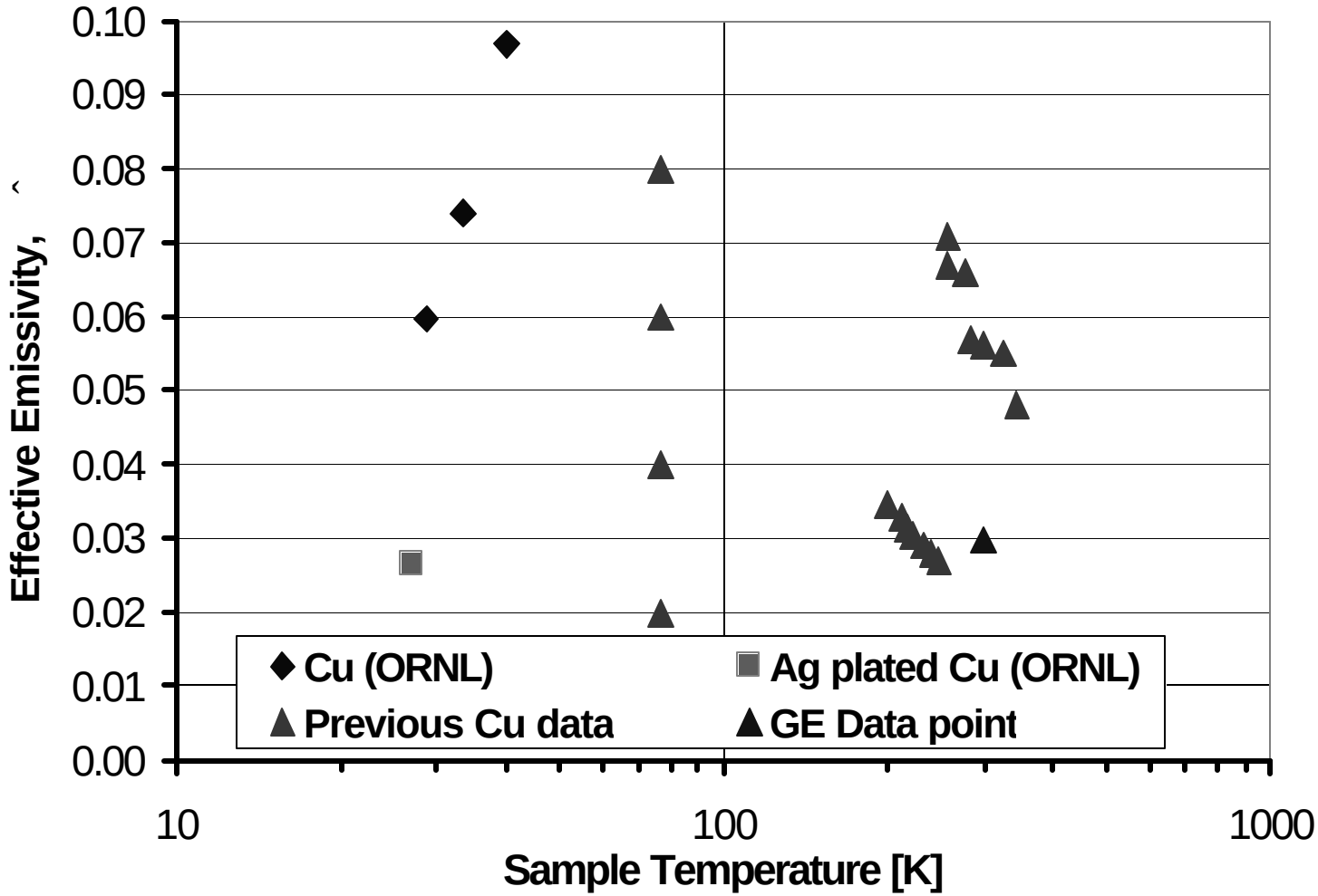


- **Heatmeter**
  - **Design and calibrated to approximately 1 W per DT of 1 K.**



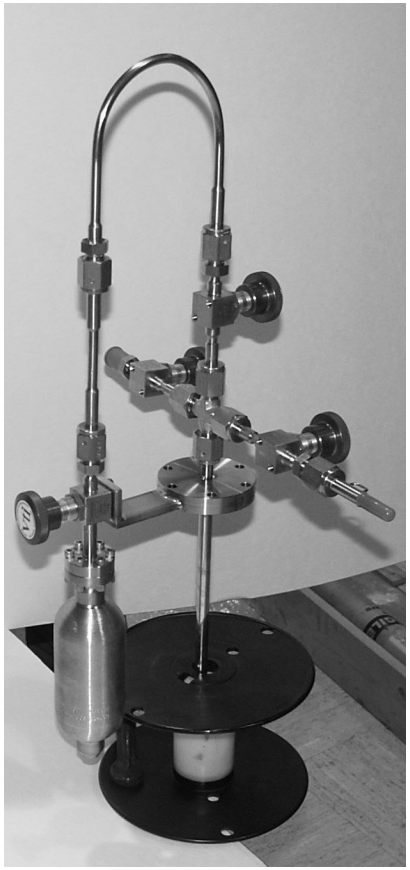


Emissivity measurements depend on surface condition.



Apparatus built for introducing surface contaminants for emissivity measurements

- **Air/Water Contamination**
  - **To be completed by the end of FY 03**

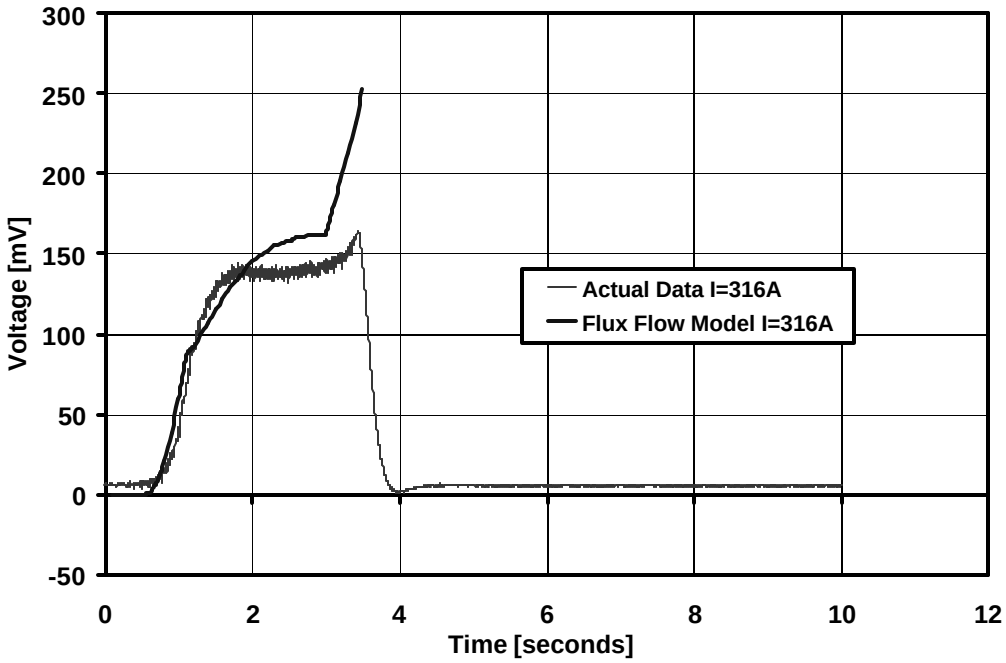


Quench and Stability Studies Using Cryocoolers.

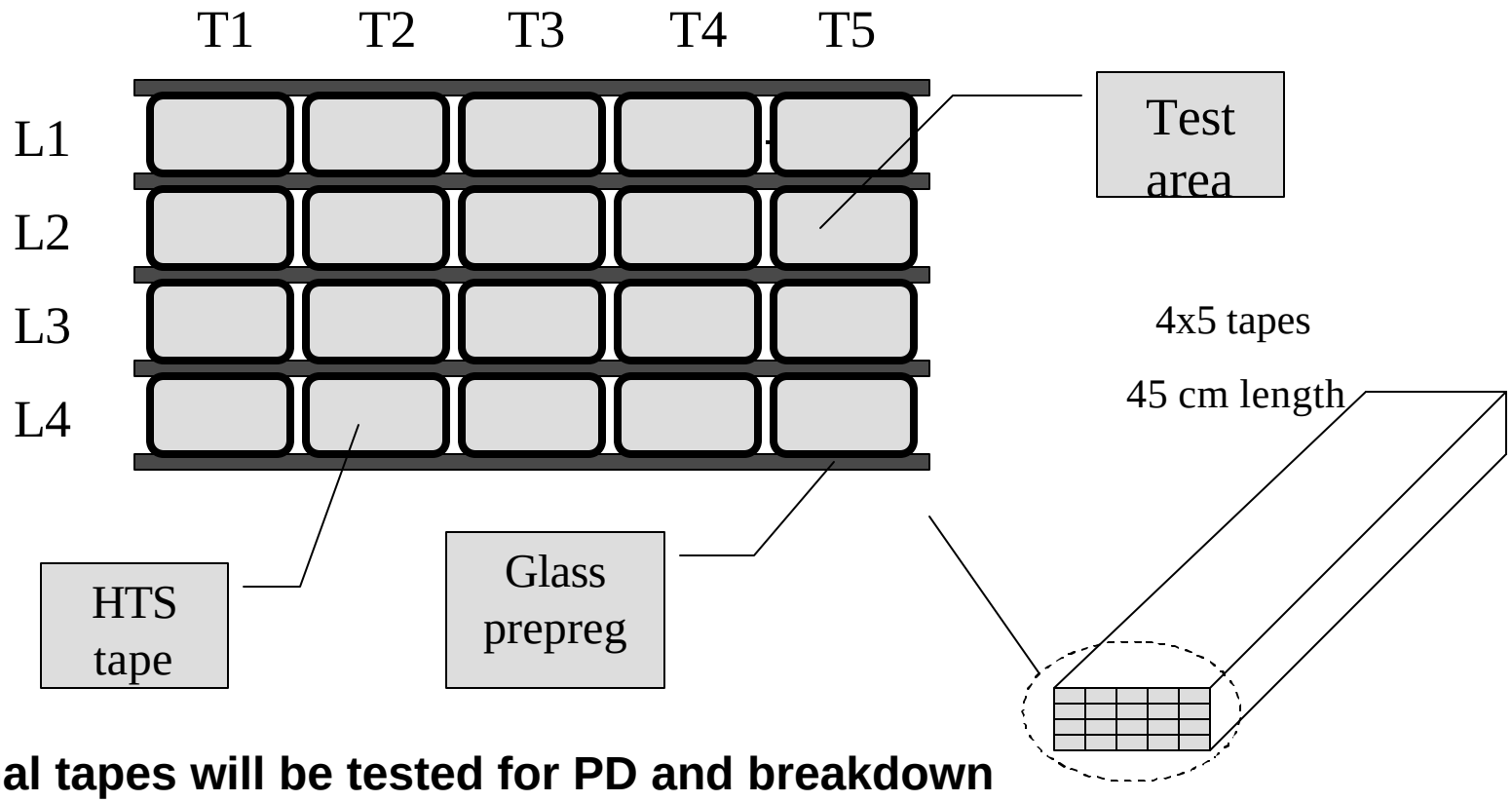
- **Modify existing HTS test apparatus to test single tape and coils at elevated fields**
  - **Will increase maximum operating current from 330 A to 1000 A.**
- **Measure flux-flow resistivity and matrix resistivity between 20 K and 100 K and at fields up to 3 T**
- **Burn out experiment with different conductive cooling links to analyze with model to be used to size and predict performance of GE rotor coils**

Quench and Stability Study of Burn-Out of BSCCO Tape in Liquid Nitrogen Bath

- **An overcurrent was applied to BSCCO tape in a liquid nitrogen bath.**
  - **I=316 A > I_c=116 A**
- **Voltage response was measured. Runaway occurred after around 3 seconds.**
- **Numerical model developed that compares favorably.**
  - **Uses flux flow resistivity model.**



Internal tape testing for PD and breakdown



Pairs of internal tapes will be tested for PD and breakdown strength at room temperature and in LN2

ORNL FY 2003 Performance

FY 2003 Plan

- This is a first year project. No plans were presented last year.

FY 2003 Performance

- ORNL designed, fabricated and assembled a test rig to measure total hemispherical emissivity of specified surfaces at 20 K;
- Conducted preliminary measurements on selected surfaces;
- Initiated modifications to an existing apparatus to support quench protection studies for HTS conductors down to 20 K;
- Initiated design and conducted preliminary experiments to measure dielectric performance and partial discharge of coil samples;
- Attempted room temperature mechanical property measurements of sample coils using the resonant ultrasonic spectroscopy (RUS) method.

ORNL FY 2004 Plans
Oct. 1, 2003 to Sept. 30, 2004

- **ORNL will work with GE to support the overall design and capabilities of the HTS generator system.**
  - **To complete measurements of the total hemispherical emissivity of specified surfaces at temperatures between 20 K – 80 K including surface contamination.**
  - **Modify existing HTS test apparatus to support quench protection studies for HTS conductors down to 20 K.**
  - **Measure dielectric performance and partial discharge of prototype coil samples.**
  - **Conduct thermal and mechanical property measurements of sample coils as required.**

Research Integration

- **Partnerships**
- **Expertise and Facilities**
  - **Efficient use of equipment and personnel between ORNL/GE.**
- **Presentations and publications during the year**
  - **A technical paper will be presented at the Cryogenic Engineering Conference in September 2003 and submitted to *Advances in Cryogenic Engineering,* 2004.**
- **Web Sites**
  - **ORNL Superconductivity Web Site includes Annual Reports, Peer Review presentations and other project information**
    - **www.ornl.gov/HTSC/htsc.html**

Summary

- **FY 2003 goals have been achieved**
  - **Emissivity test rig designed and preliminary results have been obtained.**
  - **Quench and stability test rig is being modified to accommodate higher currents.**
  - **Initial quench and stability data obtained on BSCCO tapes in liquid nitrogen.**

Design and Development of a 100 MVA HTS Generator

Los Alamos National Laboratory

Joe Waynert, Steve Ashworth, Todd Jankowski,
Coyne Prenger, Jim Stewart, Dean Peterson

Arsalan Razani, ***University of New Mexico***

Juan Campuzano, ***University of Illinois - Chicago***

CRADA with GE established August 15, 2002
FY2003 Project Funding: $430 k (DOE)
$430 k (GE in-kind)
2003 DOE Annual Peer Review
Washington, DC July 23-25, 2003

Outline

- Results of FY 2003
  - Excitation System
  - Long Term Vacuum Maintenance
  - Heat Pipes
  - AC Losses
- FY 2003 Performance
- FY 2004 Plans
- Research Integration

Generator Excitation System Results FY03

Excitation system provides dc current to rotor from ac source

Design - provided electrical design concept effective for rotors with large time constants

Experiment - proposed to demonstrate concept using 1430 MVA LANL generator which has open circuit field constant similar to superconducting rotor (large inductance, low resistance)

Task is completed

Long Term Vacuum Maintenance - 1 Motivation

HTS rotor winding at 20 - 40 K
surrounded by 300 K environment
vacuum represents main insulation

Goal: no active pumping - getters to adsorb the quantity of the particular gas species evolved over about 5 years.

Long Term Vacuum Maintenance - 2 Background

Unique outgassing and gettering properties determine vacuum life

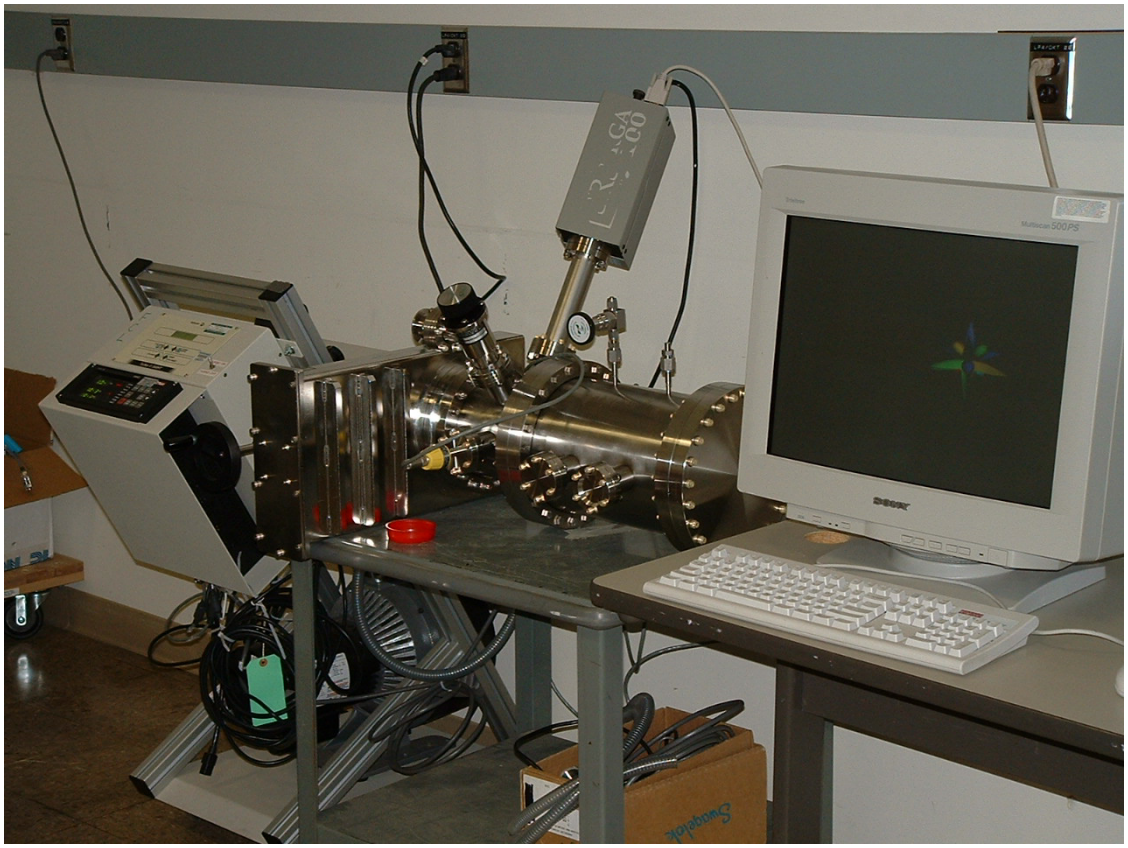
- Outgassing Properties depend on:
  - material (stainless steel, composites, aluminum, ...)
  - material preparation (machined, welded,…)
  - cleaning (materials/chemicals, methods)
  - handling
  - assembly environment
  - operating temperature
- Gettering Ability depends on:
  - getter material
  - quantity of getter
  - gas species
  - quantity of gases present
  - temperature of getter

Long Term Vacuum Maintenance - 3 Results FY03

Outgassing Measurements

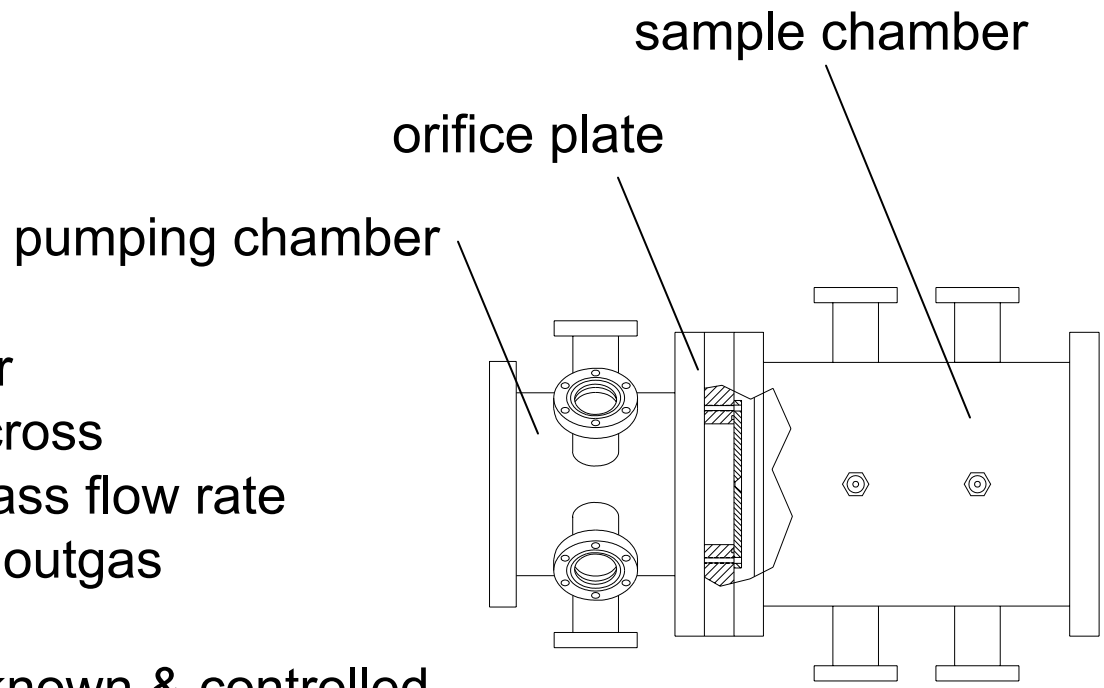
Design/fab/assemble vacuum chambers
- sample
- pump

pressure gauges
residual gas analyzer
data acquisition sys.



Long Term Vacuum Maintenance - 4 Approach

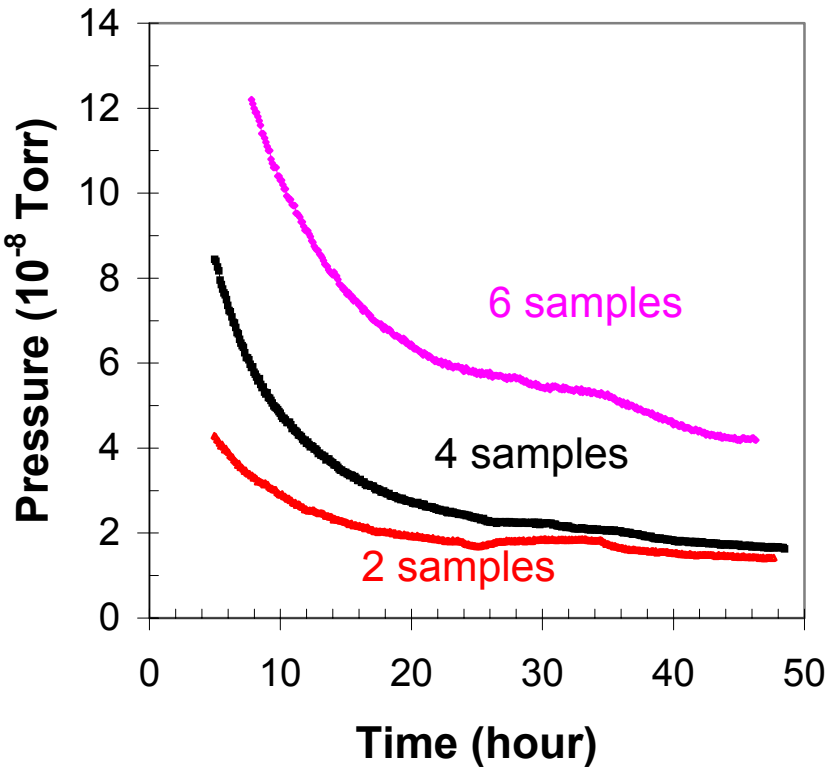
Outgassing

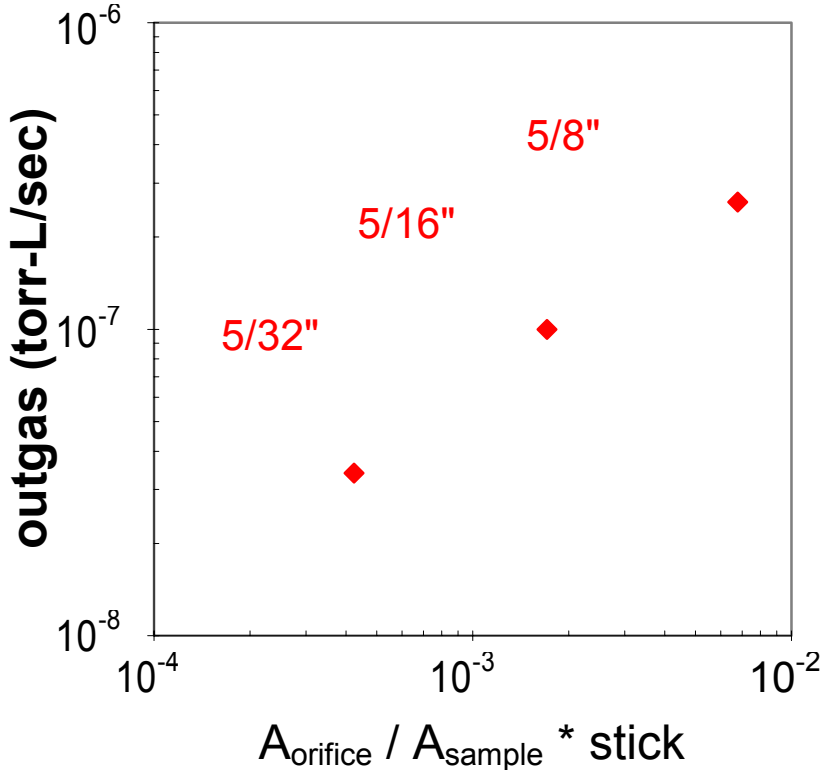


- Residual Gas Analyzer
- Pressure difference across known orifice yields mass flow rate
- Sample chamber must outgas less than sample
- Temperature must be known & controlled
- Accommodate easy sample change-out (many samples measured)
- Must account for re-adsorption:

$$\text{outgas}_{\text{actual}} / \text{outgas}_{\text{measured}} \sim 10^3$$

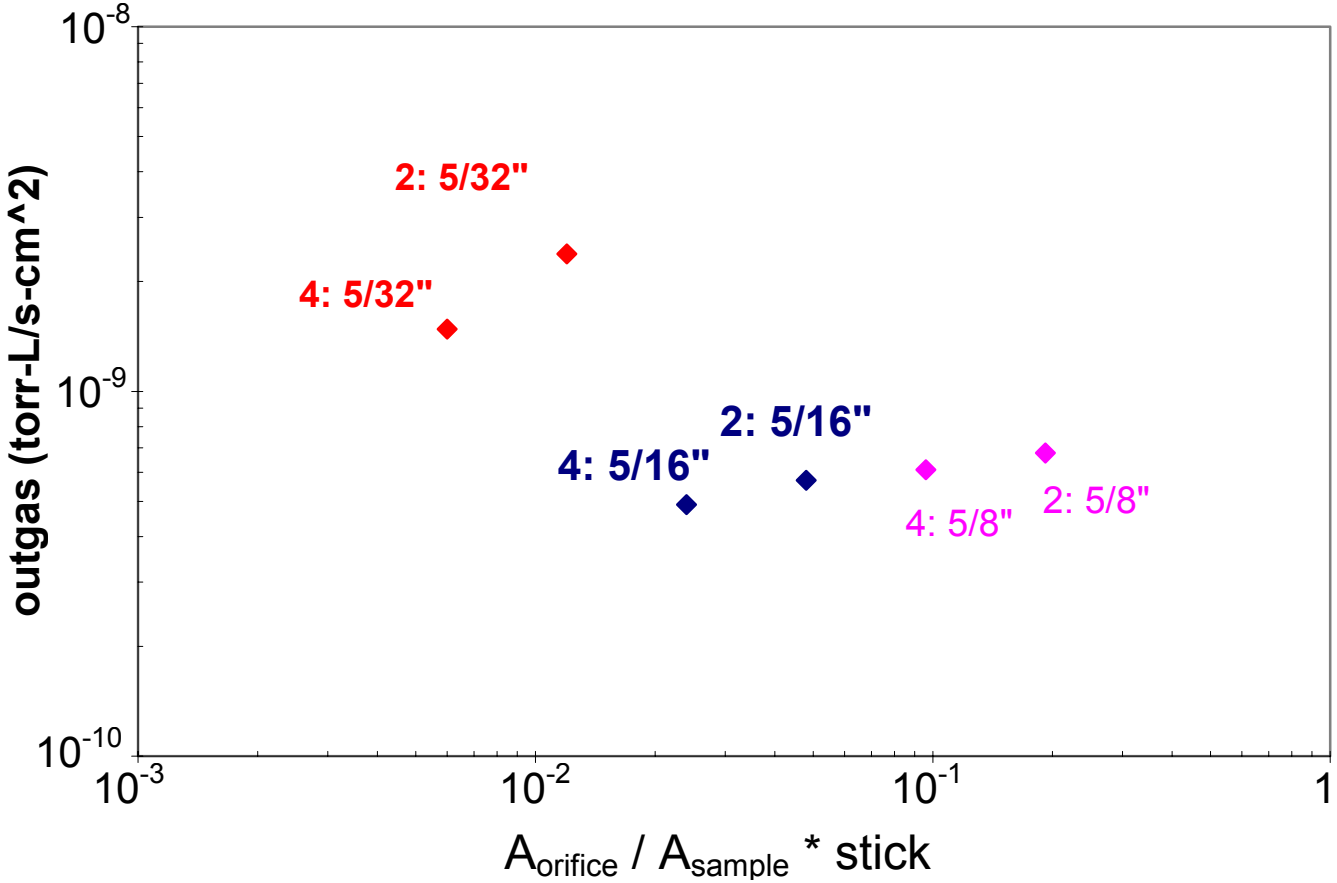
Long Term Vacuum Maintenance - 5 Results FY03





Long Term Vacuum Maintenance - 6 Results FY03

Data for *one* material

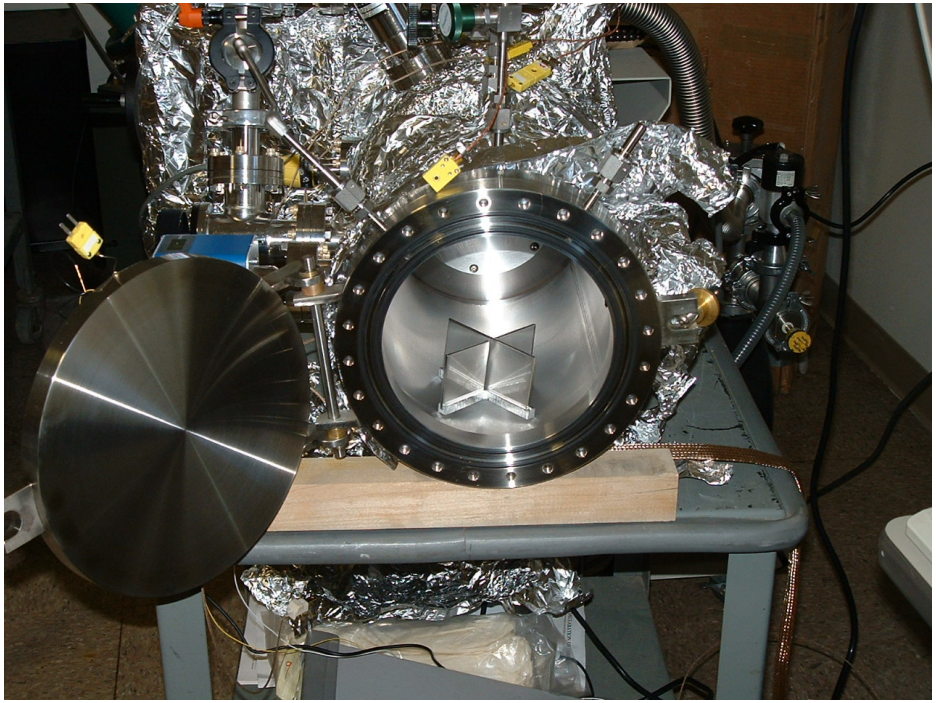


Long Term Vacuum Maintenance - 7 Results FY03

Gettering Measurements

Vacuum system modification designed

Cryocooler to be added to door

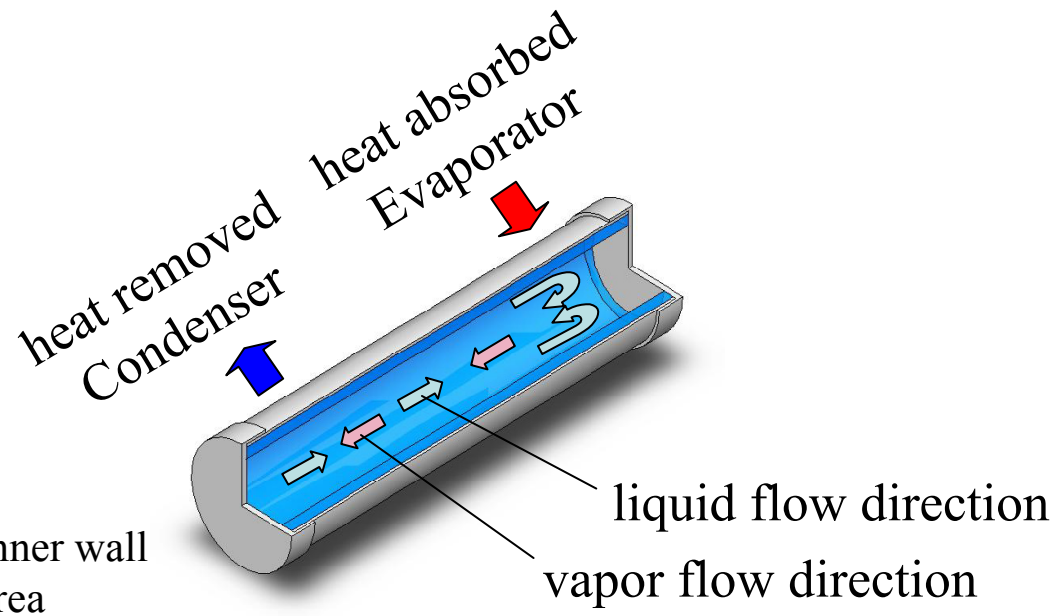


Heat Pipes - 1
Motivation

- Need an efficient method to cool and remove heat from HTS rotor and transfer the heat to cryocooler.

- Effective thermal conductivity orders of magnitude greater than copper. => ΔT required to transfer amount of heat can be small

- Severe operating conditions on rotor and heat pipe.



Liquid flows along tube inner wall
Vapor returns in central area

Heat Pipes - 2
Results FY03

- Grover (LANL) invented modern day heat pipe 1963
- Existing & validated (20 yrs) heat pipe model extended
  - included rotational aspects
  - evaluated performance capability
  - identified performance issues and limits
  - designed model validating experiments
    - based on similarity of performance via dimensional analysis
- Room temperature experiment to validate is progressing
  - apparatus and data acquisition equipment designed, costed, being procured

AC Losses
Motivation & Results FY03

- Conductor AC losses impact:
  - steady state heat loads
  - transient fault condition response
    - coil stability
    - conductor ‘protection’
  - excitation system choice
- AC loss model developed for comparison to GE data
- Results used to
  - predict heat generation in HTS rotor
  - assess losses associated with excitation system choice

FY 2003 Performance

- CRADA established August 2002
- All FY03 deliverables met:
  - ✔ ***Excitation system*** - documents proposing system design and test delivered to GE, task complete
  - ✔ ***Outgassing properties of materials*** - vacuum system design, fab'd, sample materials sent by GE being measured, data interpreted/discussed in telecons, paper to be presented at CEC
  - ✔ ***Getter system design*** - cryocooler incorporated in design, system modifications in progress, GE data and design received
  - ✔ ***Heat pipe assessment*** - model developed, three reports sent to GE, validating apparatus designed, being procured, GE performed supporting analysis
  - ✔ ***Engineering support - AC losses*** - model developed, test support provided by LANL, validating experiments being considered

FY 2004 Plans

- Specific CRADA deliverables (final reports) will be met:
  - ***Outgassing material*** characterization of all GE materials
  - ***Getter material*** evaluation based on residual gasses
  - Long term ***vacuum maintenance*** prescription based on outgassing and getter data and GE design
  - ***Rotating heat pipe*** assessment - experiment built, data will be acquired, compared to modeling, incorporation into rotor will be analyzed
  - ***AC loss*** evaluation - measurement sensors will be delivered to GE, and coil measurements will be performed on GE coil
  - ***2nd generation HTS*** conductor impact on GE rotor will be assessed

Research Integration

- Close interactions with GE, review direction, efforts, and results
- Exchange of samples, sensors, software models with GE
- Interactions with LANL experts; materials, data acquisition
- Paper on outgassing to be presented at CEC, published in Advances in Cryogenic Engineering
- Interactions with Prof. Campuzano of University of Illinois-Chicago on outgassing
- Interactions with Prof. Razani of University of New Mexico on heat pipes (PhD thesis advisor of Todd Jankowski)

Summary

- CRADA established with GE Aug 2002
- Significant support being provided to GE in high technical risk areas
- Milestones and deliverables are being met
- Challenging tasks and schedule for next year have been established