

# Flexible Cryostats for Superconducting Cables: Reliability and Lifetime Issues

Mike Gouge, ORNL

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# Utility Perspective

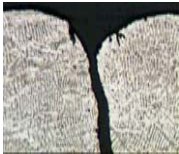
- Utility perspective: “bury and forget” cable/cryostat for 10-20 years.
- From conventional DC cable brochure:



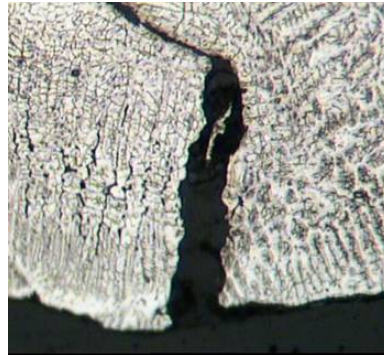
HVDC Light (ABB) - Invisible power transmission

# Cryostat Reliability Issues

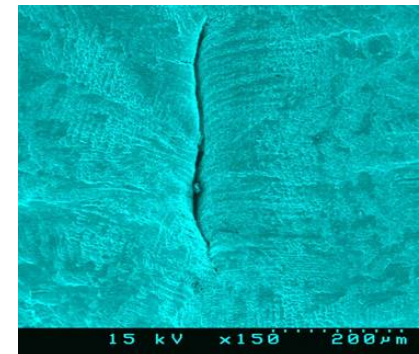
- Issue 1: loss of vacuum integrity during or just after manufacture
  - before or after initial cool-down
  - due to incorrect or poor quality materials and/or weld process control
  - example: *Pirelli Cable Project*. In 2 of 3 electrical phases:
    - Several micro cracks detected in inner corrugated tube(s)
    - All microcracks oriented parallel to the tube longitudinal axis and inside a corrugation groove near the weld line.
    - Micro cracks initiated from outer surface.
    - Remaining phase had a leak that could be compensated by pumping (not desirable as the pump becomes a critical system component)
    - No corporate experience with flexible cryostats (as opposed to flexible tubes operating at ambient temperature)



Crack detail on outer surface



Crack detail on inner surface



SEM of different crack

# Issue 1 - Pirelli Conclusions

(Jim Curley, Pirelli, 2003 DOE Peer Review)

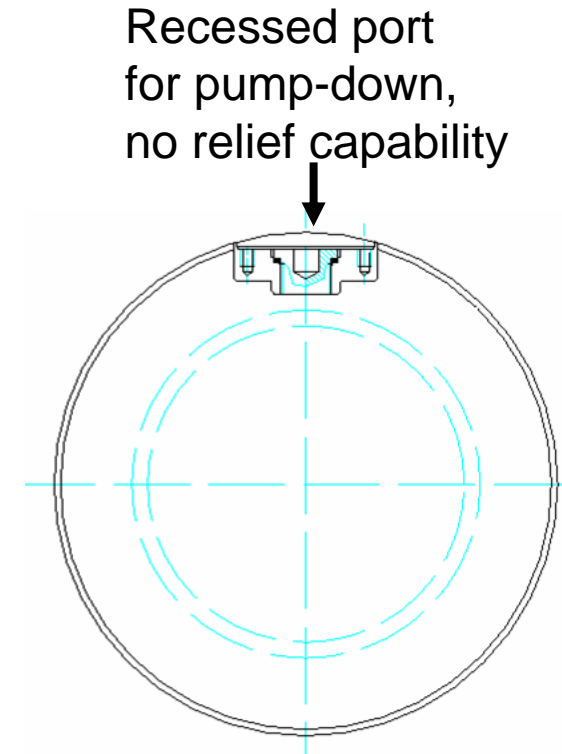
## • Conclusions

- SEM analysis suggests defects formed during the solidification process.
- Material characteristics contributed to defect origins rather than solely welding process anomalies.
- Hypothesis that excessive gaseous content ( $H_2$ ) may have contributed to defects.
- Resulted in *hydrogen embrittlement*; in combination with cold working in the corrugation process had a significant role in the creation of local weak spots.
- Weak spots may have turned into complete fractures upon further mechanical stress of installation.

This type of early vacuum integrity failure can be avoided by fully qualified manufacturing processes (materials and welds), quality control and warm and cold testing. Examples of successful cryostats are 30-m HTS cable at Southwire, 66 kV TEPCO/SEI cable and 77 kV, 500-m Super-ACE cable (Japan).

# Issue 2: Installation

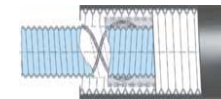
- Cable Cryostat Installation
  - Damage on installation of cryostat in duct –
    - recessed pump-out ports every 100-m and burst disks on ends only to minimize damage during pulling of cryostat into duct
  - Damage during pulling of cable in cryostat
    - If cable not made in parallel with cryostat
  - Concern in both cases: generation of small, (cold) leak from rough handling, friction
  - In principle, cryostat can be tested before cable is energized
    - internal pressure test at 10-20 bar and vacuum jacket test to verify  $10^{-5}$ - $10^{-6}$  torr).
    - But access may be difficult for long runs



Provided by  
Nexans-Cryoflex

# Issue 3: Degradation in service

- Reliability proportional to  $1/\text{length}$ 
  - One manufacturer's warranty on 100-m flexible cryostats is 2 years
    - Assume 2 year warranty = 1% failure risk over design life
    - A four km cable would have 40 of these sections; for example  $(0.99)^{40} \sim 67\%$  overall reliability: not good enough: need 99.9 %
  - Is a 10-20 year “bury and forget” lifetime achievable (hydrogen out-gassing)?
- Lightning impact (previous talk)
  - hits on buswork and adjacent ground strikes
  - voltage gradient inner/outer cryostat and exterior strike damage
  - Prof. Chowdhuri's talk this session



Cryoflex transfer lines from Nexans

# Cryostat Configuration Options

- Constraints:
  - Need pump-out port every ~100-m for initial bake-out/evacuation
  - Need over-pressure protection on each discrete vacuum section
  - Loss of a single 100-m section will shutdown cable as increase in heat load of order kW at 77 K cannot be accommodated by cryogenic system (as well as skewed cable temperatures)
- Option 1: Discrete 100-m vacuum sections along cable runs
  - Pros: easier to test at factory, easier to locate leak in service (if you have access to 100-m sections)
  - Cons: Single failure may take cable out of service; cannot pump on ends if underground 100-m section has leak
- Option 2: 100-m sections tied together in a single vacuum volume
  - Pros: Over-pressure protection easier (devices at one or both ends), can monitor entire vacuum region, can pump on ends if underground 100-m section has leak (but may be ineffective)
  - Cons: Single failure takes cable out of service,

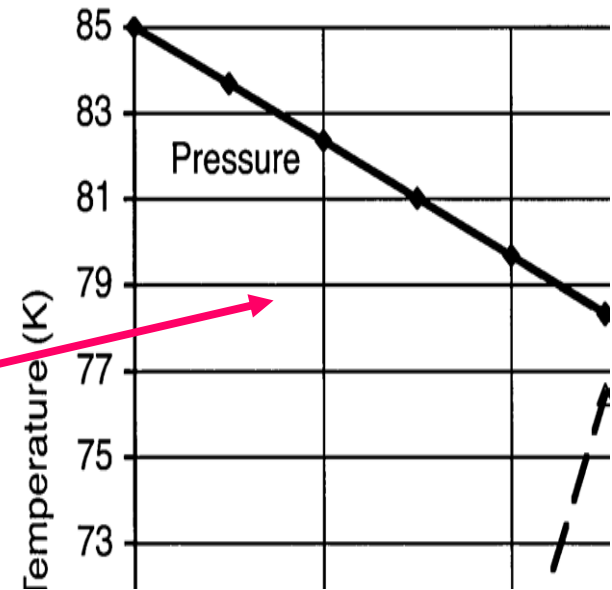


Fig. 6. HTS conductor temperature and liquid nitrogen pressure distributions for a 1000-m-long HTS CD cable system. The inlet liquid nitrogen flow, pressure, and temperature are 200 g/s, 10 bar, and 65 K, respectively. The dashed curves include the damaged cryostat section.

# Getters for passive pumping (1)

- SAES Getters suggests a getter solution:
  - LOTHAR (*Liquid Oxygen Tank Hydrogen Advanced Remover*) is a new getter for the adsorption of hydrogen from the evacuated jacket of cryogenic pipes.
- Its composition ( $\text{Co}_3\text{O}_4 + \text{PdO}$ ) makes it safe as well as a cost-effective alternative to the standard palladium oxide.
  - A complete solution offered by SAES getters for vacuum cryostats with MLI is to combine this getter with a high surface version of  $\text{CaO}_2$  for removal of residual water and CO.
- The above getter materials can be supplied in a suitable container (metal box with mesh or similar) for a specific mounting option.
  - Best mounting position is to attach the getter container to the outer (warmer) corrugated tube.
- The ideal positioning of getter material is to distribute it along the 100-m cryostat sections (for instance a getter container each 10 m).
  - it could be acceptable to position it at each end of the 100-m sections.
  - conductance limitations are not a serious issue in this application given the long times involved in sorption dynamics

*Input by Livio Rosai, SAES*

# Getters for passive pumping (2)

- The outgassing behavior of cryostat materials can be predicted using literature data or by actual laboratory tests. The total expected amount of gas released during cryostat lifetime is obtained by integration of the formula:

$$Q(t) = Q_0 t^{-a} \text{ where } Q_0 \text{ is the outgassing rate after 1 hour.}$$

- The data for each gas, and for each material used inside the cryostat is extrapolated to 20 years by fitting of the outgassing rate curve of the first 24-100 hours that determines the specific value of the parameters  $Q_0$  and  $a$ .
  - Data obtained in past tests indicate that a quantity of the above getter material around 300 grams each 100 meters should be sufficient for 20+ years lifetime
- Past tests on materials used in cryogenic cables have also shown that the getter material is not only necessary for taking care of the gas released inside the vacuum enclosure during the lifetime but that it can be an useful contributor in optimizing the processing time.
  - Of course the getter cannot substitute for the initial pumpdown with mechanical pumps, but can work in parallel with them in the last phases of the process, acting as an "in-situ" pump.

*Input by Livio Rosai, SAES*

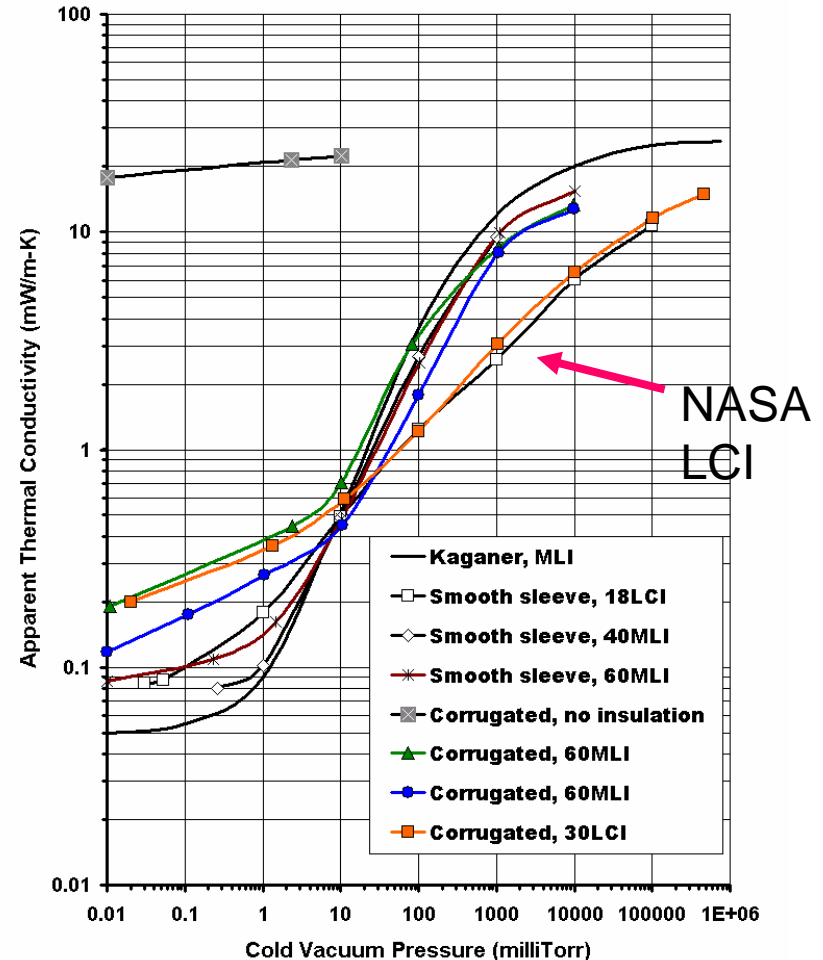
# Options for leak or saturated getter in service

- If the getter is well dimensioned it should last for the lifetime of the cryostat.
- It is not practical to replace getters when the cable is cold:
  - Cold replacement would require a vacuum lock-out chamber that is only feasible and practical on each end of the cable which for long (multiple 100-m) cryostats is a small fraction of the total installed getters.
  - Warm replacement requires several weeks for warm-up, getter installation, baking and pump-down and cool-down).
- Option to use mechanical pumps on each end when getters are saturated (need internal vacuum  $< 10^{-4}$  torr) may not be practical due to complexity and high cost.
  - Ineffective in mid section for long cable runs

*Input by Livio Rosai, SAES*

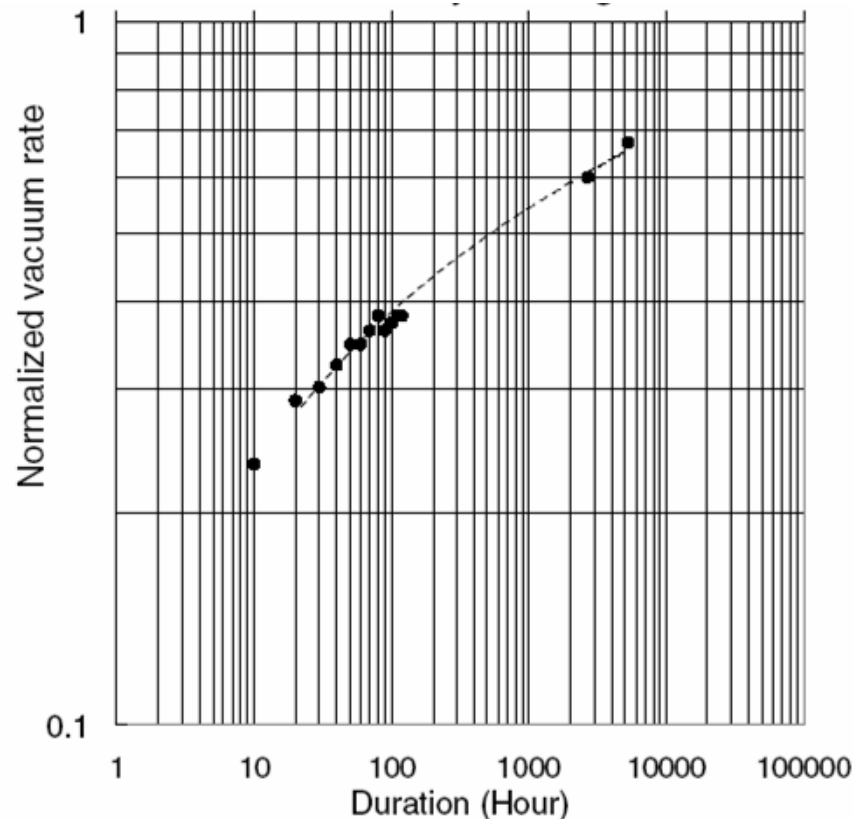
# How can R&D improve situation?

- Improved getters for 10-20 service lifetime (SAES input)
- Low outgassing internal supports and MLI
- New material that has 1/3 the thermal conductivity of standard MLI for degraded vacuum of 1 torr
  - developed by NASA KSC
  - Layered composite (LCI) performs better than standard multi-layer insulation systems if vacuum degrades.
- But no response to cryostat R&D in 2002 Cryogenics Initiative RFP and 2006 SBIRs!



2001 Peer Review

# Test a cryostat for extended periods



- Albany cable project is monitoring the 350-m return cryostat for long-term vacuum maintenance
  - leak rate  $< 10^{-10}$  Pa-m<sup>3</sup>/s
  - inner wall is not cold like it would be in service

# Cryostat Cost Considerations

- Cable now \$6,000/m, future \$500/m with tape \$10/kA-m
  - Assume 3 phases in one cryostat, 3 kA phase current, run at 50% of  $I_c$ , cold dielectric with HTS shield
- Cryostat now \$ \$650/m, near-term \$500/m, future \$300-\$400/m
  - At \$10/kA-m tape cost, the cryostat is almost as much as the cable cost per meter!!!
- Vacuum pumping \$10K/100 m = \$100/m
  - If vacuum pumping is included the cryostat cost and cable cost are about the same!
  - Long life (passive) getters less expensive
  - Power, enclosure and maintenance for pumps problematic

# General Design Guidelines

- Since reliability  $\sim 1/\text{length}$  and a single phase failure will shutdown other 2 phases:
  - put 3 phases in one cryostat instead of 1 phase per cryostat
    - Examples: Albany and Columbus cable projects, TEPCO in Japan
  - LN counterflow is more reliable than separate return cryostat
- Since running with one 100-m section with poor vacuum may not be possible (cable temperature profile and increased heat load)
  - Use common vacuum for multiple 100-m sections
    - Simplifies over-pressure relief and vacuum monitoring (only at ends): LIPA
- Burst disks more reliable than relief valves
  - But more difficult to recover from overpressure event or leak
  - Use tee section with 3-way valve and 2 burst disks so recovery is simplified
- Invest on front end in long life getters as getter replacement or mechanical pumping every 100-m may not be practical.
  - Pumping only at ends not effective for common vacuum length  $> 300$  m
  - Pumping in middle requires blanked-off pumping port with snorkel valve every 100-m and local power for pumps.
- A major leak in middle of cable run will overwhelm getters/pumps
  - How likely is this event?
  - Not much data on reliability of long flexible cryostat sections for extended times
  - Need “elephant graveyard” of cable cryostats from completed HTS demos to monitor vacuum over time (but inner cryostat will be warm).

# Extra slides

# Exterior lightning damage-1

- Underground cable tests at Camp Blanding, FL (Philip Barker and Tom Short, PTI)
  - Rocket-triggered lightning tests on underground cable systems.
  - Lightning strikes were triggered to earth directly above various 15-kV class distribution cables to investigate surges that could be introduced into the cables. PTI tested
    - an unjacketed, bare-neutral, direct-buried cable;
    - a jacketed direct-buried cable and
    - a jacketed cable in PVC conduit.
- All three cable types showed significant damage at strike point, with damage ranging from a minor puncture of the cable jacket and a few melted neutral wires, to extensive puncturing of the jacket and the melting of nearly all of the neutral wires, which occurred when an unjacketed cable was hit.
- In the case of the installation in PVC conduit, the side walls of the conduit were completely destroyed and the stroke then hit the concentric neutral wires.
- Mechanical damage to the cable was the result of the high temperature generated by the stroke, which vaporized the material at the point of the strike because of stroke multiplicity and the long durations of current flow.
- Of the types of damage observed, the neutral damage was most significant, since a single-phase cable carries a large return current on its neutral.
- **For HTS cables a major concern is cryostat puncture**
  - But is ground strike lightning an issue in typical applications?

# Exterior lightning damage -2

- Measurements and physical examination of the cables after the tests show that for the primary cable, mechanical damage is the main threat from these kinds of strikes, not surge voltage.
- A review of the test results and lightning attraction theory shows that the incidence of damaging strikes to cables could be greater than expected and, in some cases, may rival overhead line direct strokes.
  - Calculations show for a cable located in an area with a flash density of about 10 flashes per sq km per year, (typical for FL), roughly 0.2 "lightning attachments" per km of cable per year would occur.
- Many of the tests involving strikes to the side of the cable showed that lightning usually found its way to the cable for strikes of up to about 30 ft (9 m) on either side of the cable route.
  - The total danger zone is considered to be about 60 ft (18 m) wide
  - any strike falling in this area has a likelihood of striking the cable under the soil conditions that existed in the experiment.