Holbrook Substation Superconductor Cable System Long Island, New York

Final Report ~ Volume 1

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LIPA Superconductor Executive Summary

Overview:

The LIPA Superconductor project broke ground on July 4, 2006, was first energized on April 22, 2008 (Earth Day) and was commissioned on June 25, 2008. Since commissioning, up until early March, 2009, there were numerous refrigeration events that impacted steady state operations. This led to the review of the alarms that were being generated and a rewrite of the program logic in order to decrease the hypersensitivity surrounding these alarms. The high temperature superconductor (HTS) cable was energized on March 5, 2009 and ran uninterrupted until a human error during a refrigeration system switchover knocked the cable out of the grid in early February 2010.

Results:

The HTS cable was in the grid uninterrupted from March 5, 2009 to February 4, 2010. Although there have been refrigeration events (propagated mainly by voltage sags/surges) during this period, the system was able to automatically switch over from the primary to the backup refrigeration system without issue as required during this period. On February 4, 2010, when switching from the backup over to the primary refrigeration system, two rather than one liquid nitrogen pumps were started inadvertently by a human error (communication) causing an overpressure in the cable cooling line. This in turn activated the pressure relief valve located in the grounding substation. The cable was automatically taken out of the grid without any damage to the components or system as a result of signals sent from the AMSC control cabinet to the LIPA substation. The cable was switched back into the grid again on March 16, 2010 without incident and has been operational since that time.

Since switching from the backup to the primary is not an automatic process, a recent improvement was added to the refrigeration operating system to allow remote commands to return the system from backup to primary cooling. This improvement makes the switching procedure quicker since travel to the site to perform this operation is no longer necessary and safer since it is now a programmed procedure versus the former written procedure that was still subject to human variation in the process.

Remaining Work:

Yearly maintenance and a bi-weekly walkthrough of the refrigeration system is the only ongoing work planned for the LIPA Superconductor in the coming year. However, Phase 2 of the project is now scheduled for the summer of 2011 when one phase of the HTS cable with be removed and replaced with a HTS cable made from second generation (2G) HTS wire. This work will be performed by the same partners involved in the initial installation and is expected to take approximately 3 months to complete. A repair of a cryostat and cable joint in an operational transmission grid will be performed on this 2G cable following the installation and successful reenergization.

Operating Experience:

A tremendous amount of operating experience has been attained since the HTS cable has been installed in the LIPA grid. Besides the knowledge gained in the operation of HTS cables and large refrigeration systems, the HTS Project Team now better understand the inner workings of an electrical distribution system and the need for a reliable cable system.

The refrigeration system performance has been continuously monitored and there have been numerous equipment problems to date. Both helium air end screw compressors failed and had to be replaced. The backup system vacuum pump was replaced before it failed. The refrigerator's turbine inlet filter is partially blocked with carbon dust from the internal absorber. Throughout all of the aforementioned maintenance and equipment repair and replacement work, the HTS cable has remained in the grid.

Both the electrical and thermal properties of the HTS cable have been continuously monitored as well. There have been no significant issues with the cable's performance since the commissioning.

Economics:

Liquid nitrogen (LN2) is the cooling medium for the HTS cable and has proven to be easy to locate and have delivered to the site. Unfortunately, in order to save on initial costs, equipment that was used on the Detroit Edison/Pirelli SPI Cable Program was incorporated into this program to allow for a greater portion of the budget to be spent on HTS wire and cable as well as the cryostat and terminations. This was an excellent decision, since the HTS cable, cryostat and terminations have performed flawlessly throughout the operational life of the HTS transmission line. However, the decision to use preexisting refrigeration equipment has had a downside. Although fitted as best as possible and having proved to operate efficiently when first installed, as time moves on, this preexisting refrigeration equipment continues to break down, causing expensive and time consuming repairs. When the primary is down and the backup refrigeration system is carrying the cooling load, a three-fold larger quantity of LN2 is required to keep the HTS cable at operational temperature.

Recommendations for Future Superconducting Projects:

Install a new next generation refrigeration system with extra cooling capacity.

Train several LIPA employees in the operation and general maintenance of the refrigeration system.

Add a battery power backup system to the refrigeration building to allow for storm ride through.

Demonstration of a Pre-Commercial Long-Length HTS Cable System Operation in the Power Transmission Network

DOE Peer Review Update
August 2- 4, 2005
Washington, DC

Agenda

• **Introduction**	**Jim Maguire, AMSC**
• **Project Overview**	**Jim Maguire, AMSC**
• **FY 2005 Results and Performance**	**Jim Maguire, AMSC**
- **System Design for LIPA Utility Grid Operation**	
- **System Contingency Planning**	
- **Program Status**	
• **Cable and Terminations**	**Frank Schmidt, Nexans**
• **Site/Installation**	**Tom Welsh, LIPA**
• **Refrigerator**	**Jim Maguire, AMSC**
• **Wire**	**Jim Maguire, AMSC**
• **FY 2006 Plans**	**Jim Maguire, AMSC**

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Project Overview

LIPA Project Overview

- Long Island Power Authority – Holbrook Substation
- Electrical Characteristics
  - Design Voltage/Current – 138kV/2400A ~ 574MVA
  - Design Fault Current – 69,000A @ 12 line cycles (200ms)
- Physical Characteristics
  - Length ~ 610m
  - HTS Conductor Length ~155km
  - Cold Dielectric Design
- Hardware Deliverables
  - Three ~610 m Long Phase Conductors
  - Six 161kV Outdoor Terminations
  - One 161kV Splice (Laboratory Test)
    - No splices for grid installation required
  - One Refrigeration System + Laboratory Pulse Tube System
- Installation/Commissioning – Fall 2006

World's First Installation of a Transmission Voltage HTS Cable

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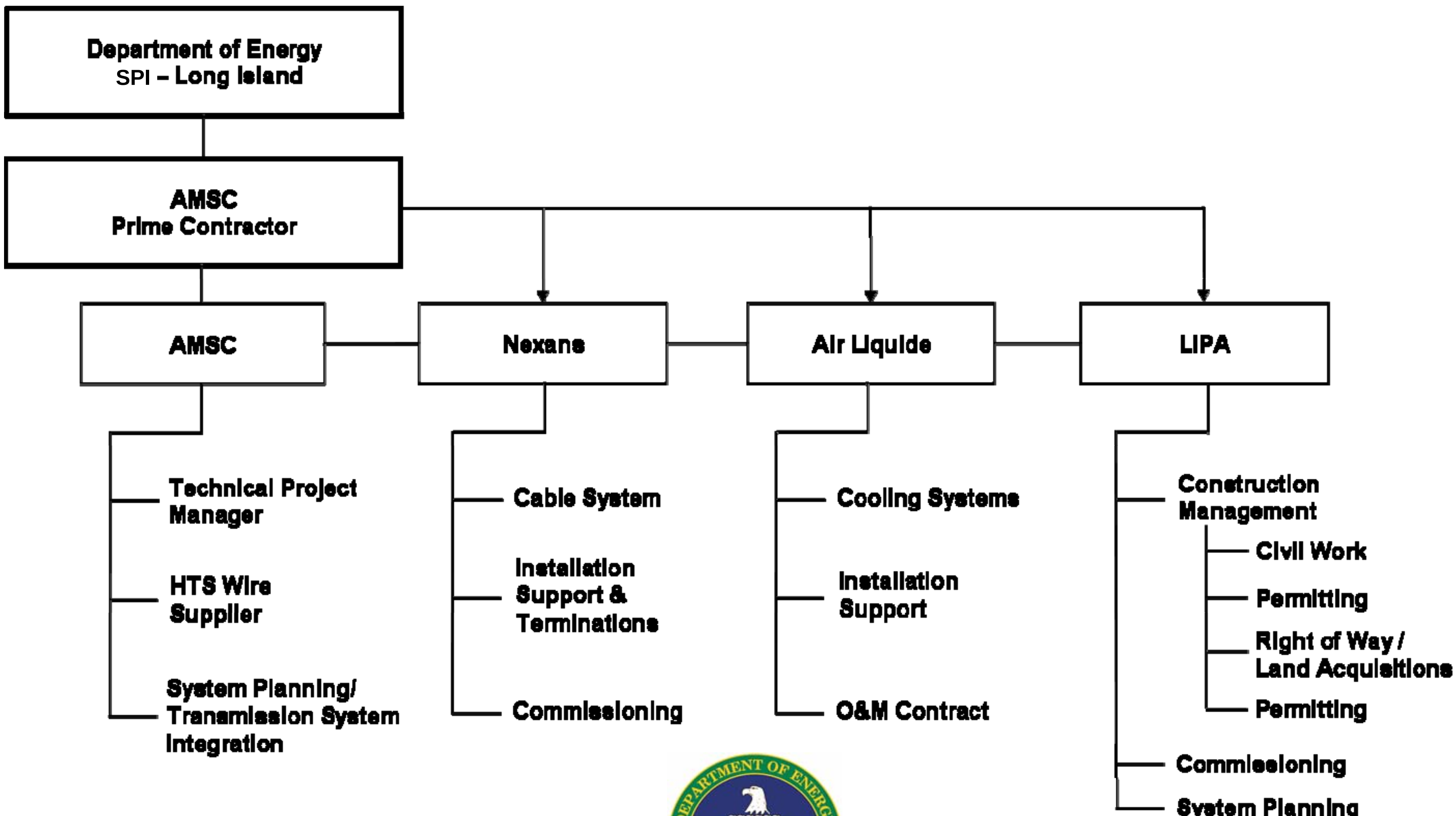
LIPA Cable Project and Project Team



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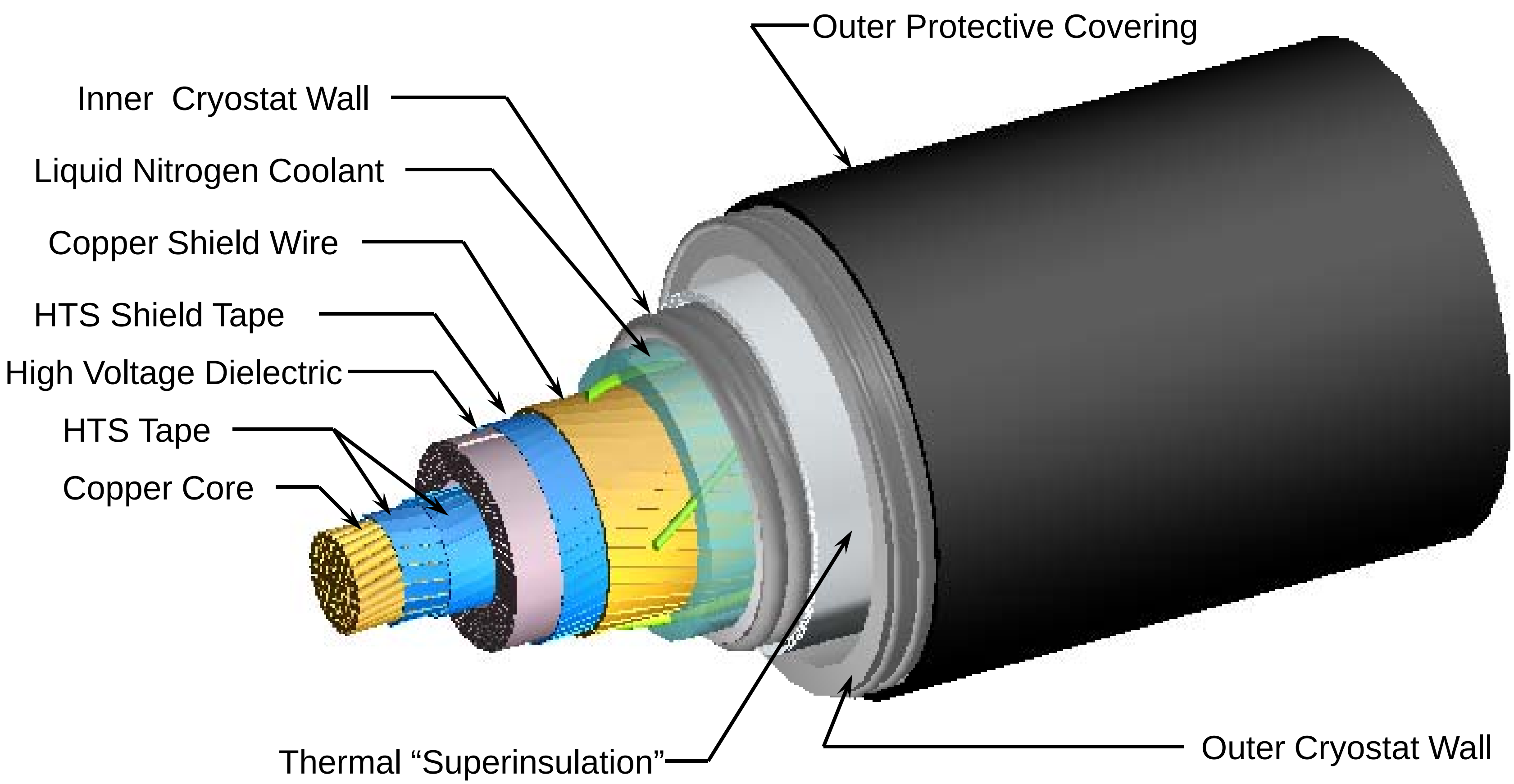
Typical Cable Cross Section



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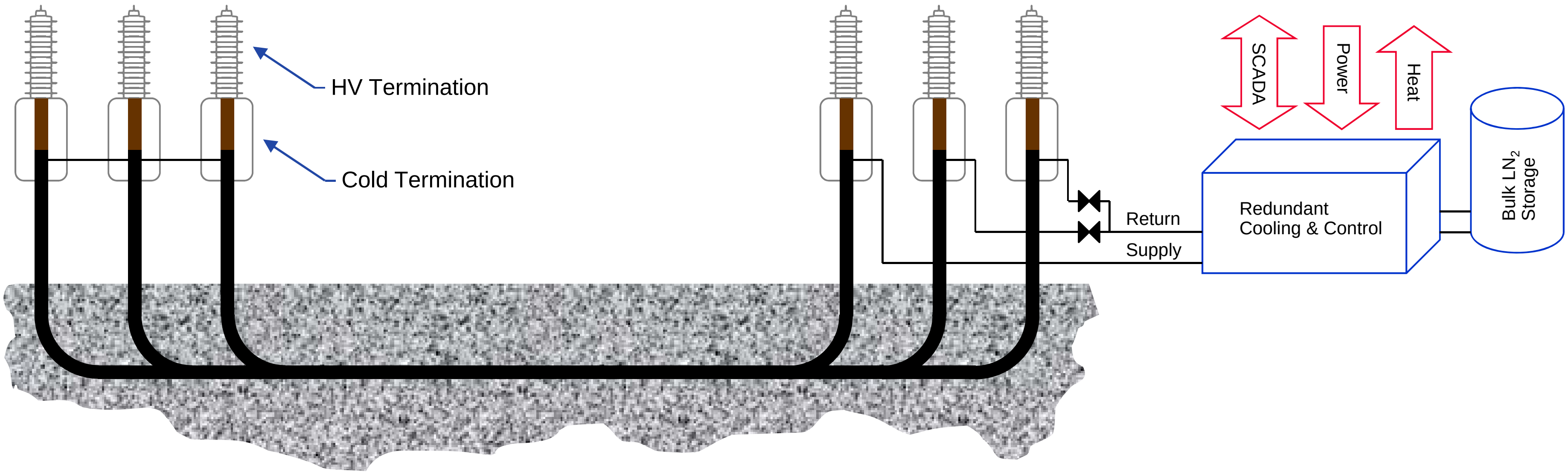
LIPA HTS Cable System



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System Design for LIPA Utility Grid Operation

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System Design Philosophy

- The LIPA Cable Project Team Has Taken the View That the Cable System Design Must Be Driven by the Operational Requirements of the LIPA Transmission System.
- There Are Several Modes of Operation Including:
  - Pre-operation Cool Down (Not Included)
  - Normal Operation
    - Steady State Operation
    - System Fault Tolerance
    - Contingency Operation
  - Post-operation Warm-up (Not Included)

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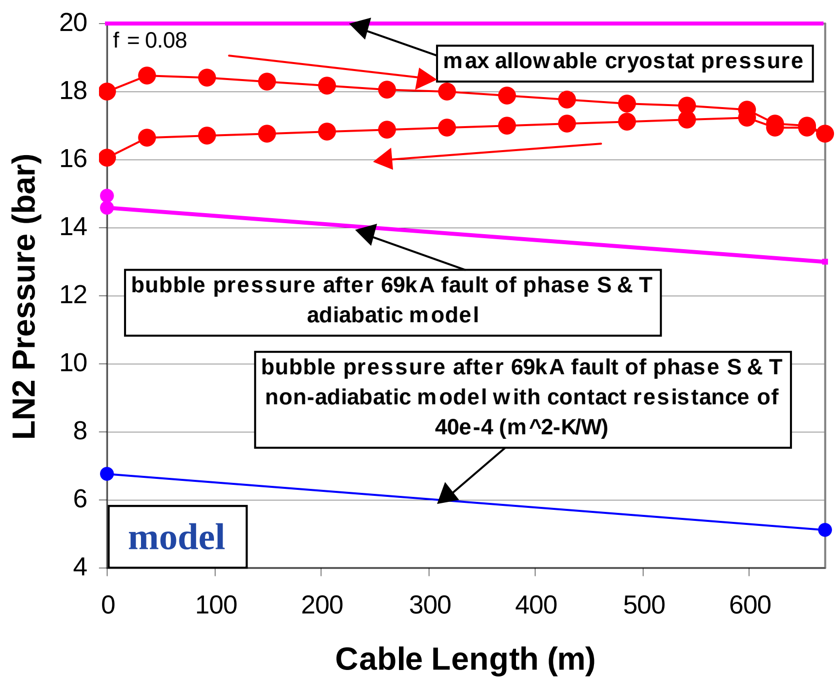
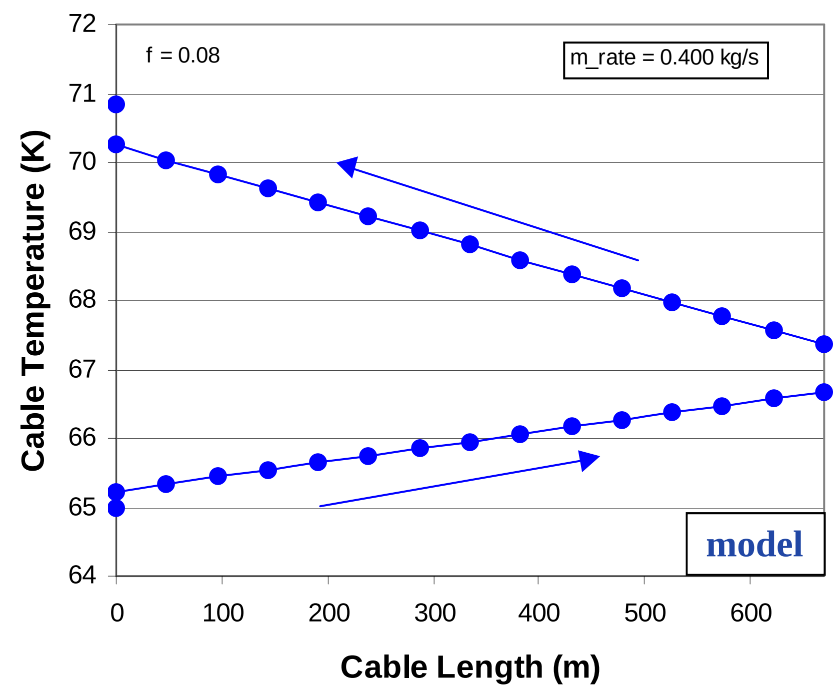
Steady State Operation with Main Refrigerator





- Friction Factor Based On Nexans Test Data
- Optimized LN2 Flow was 0.465 kg/s
- Existing Pump Recommended Flow Rate: 0.4 kg/s

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Operating Mode: Steady State with Backup System

- Backup System Refrigeration: 6.6 kW (17% Margin)
  - Existing Backup System: 4.6 kW
  - New Added LN2 Module: 2 kW
- LN2 Consumption
  - Existing Backup System: 30.4 g/s (141 L/hr)
  - New LN2 Module: 9.7 g/s (45 L/hr)
  - A 9,000 gal Tank Will be Able to Provide a 5 Day Supply

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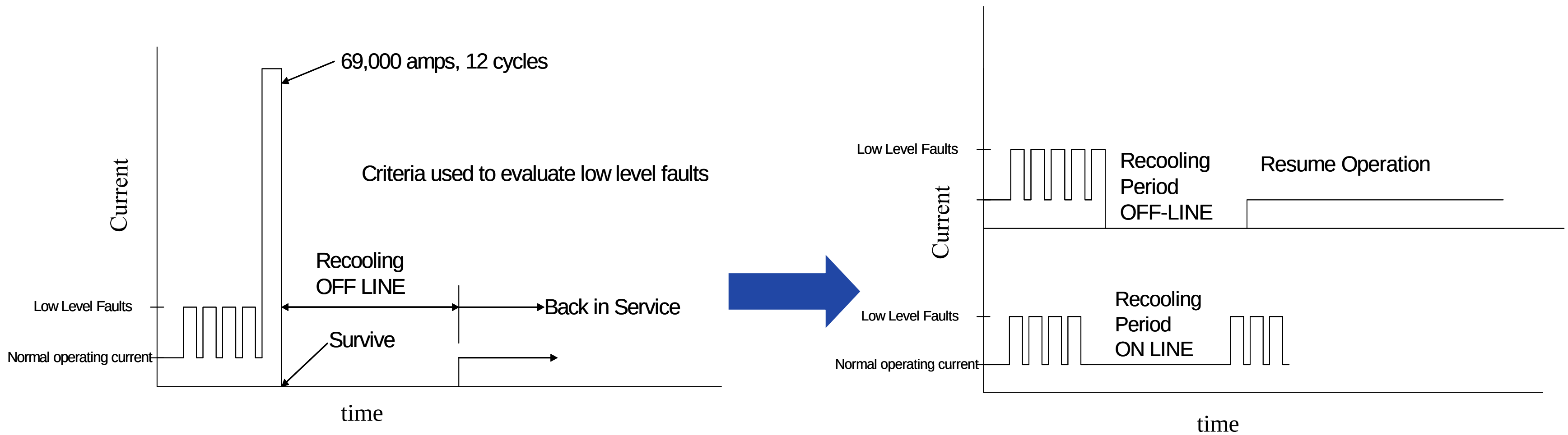
Fault Scenarios

- The Cable System Must Always Be Able to Withstand a Major Fault Without Damage, Even After Sustaining Multiple Through Fault Events Prior to the Major Fault Event
- In Cases Where Many Through Faults Occur Within a Short Time Period, the Protection System Needs to Remove the Cable From Service for a Brief Period to Maintain the Ability to Survive a Major Fault.



Impedance relay protection systems not adequate for HTS transmission cables

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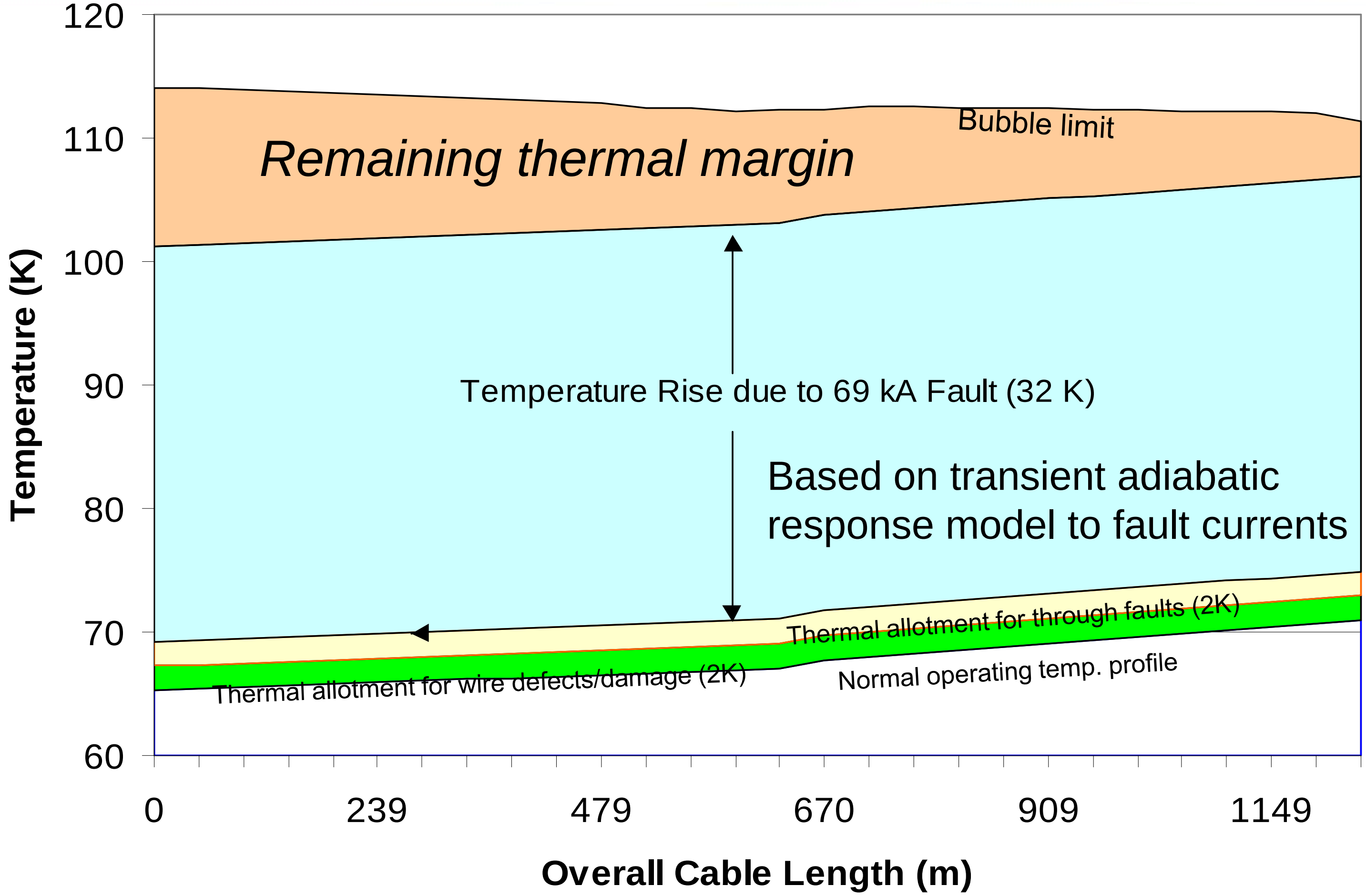
LIPA Cable Thermal Budget



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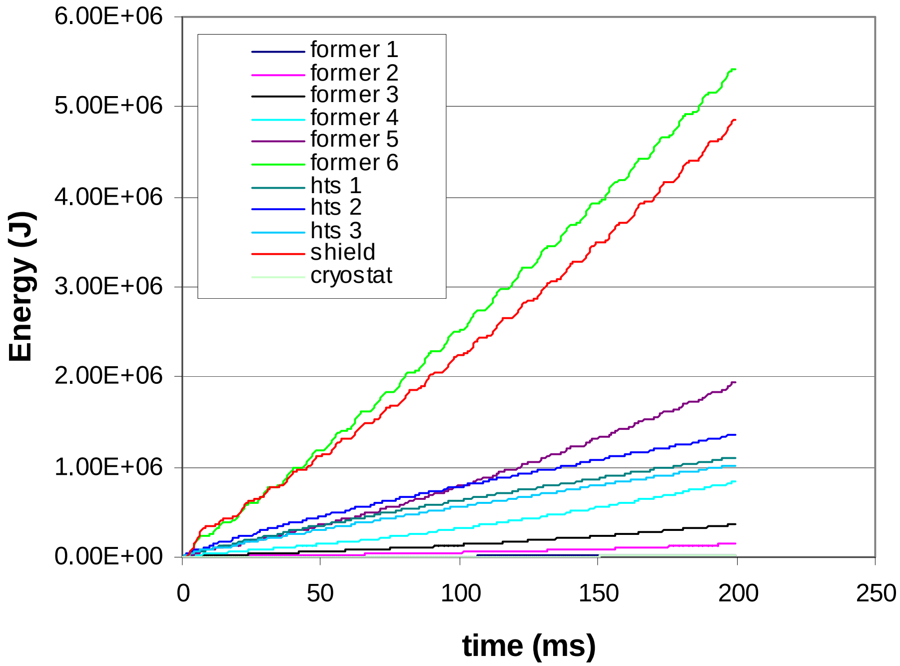
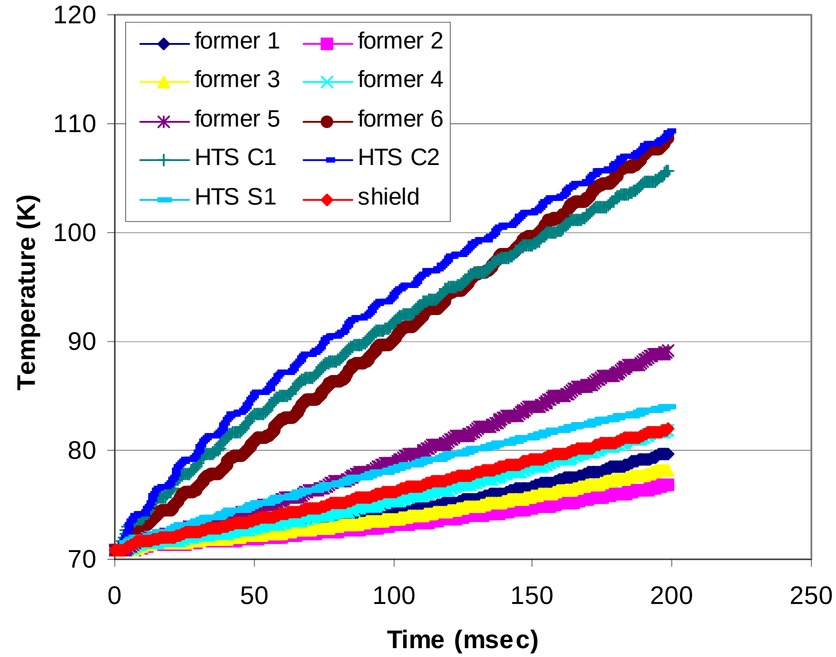
Major Fault Condition - 69kA / 200ms





- Total Dissipated Energy (3 phase): 52 MJ in 200 ms
- Temperature Rise Based On Adiabatic Model (Worst Scenario)

Cable and protection system is designed to survive 69kArms/200ms fault

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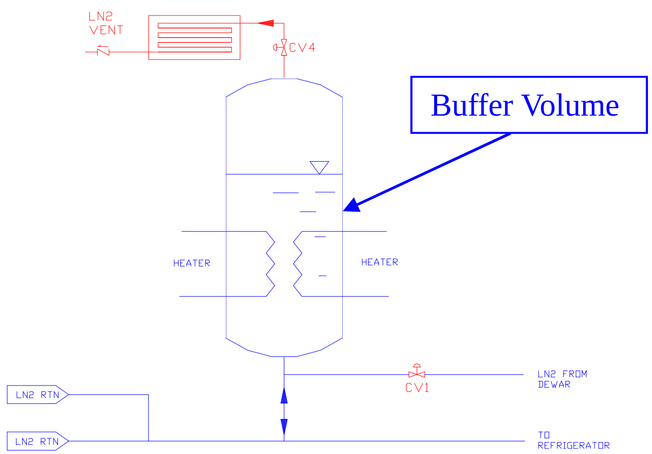
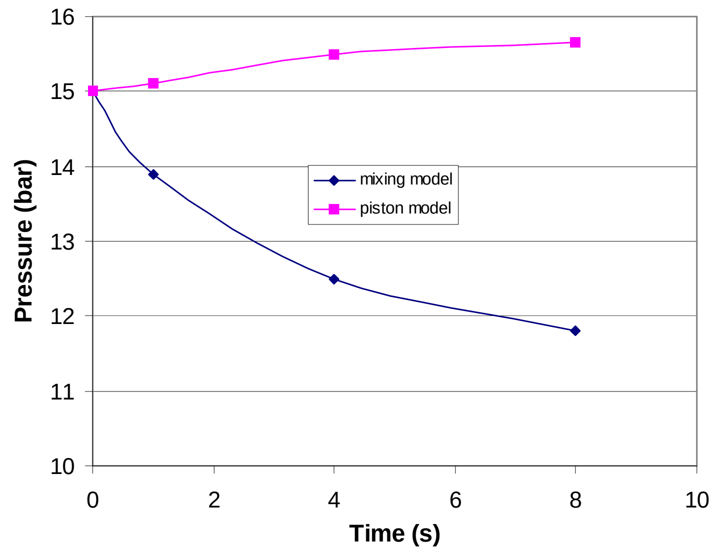
System Reaction to a Major Fault

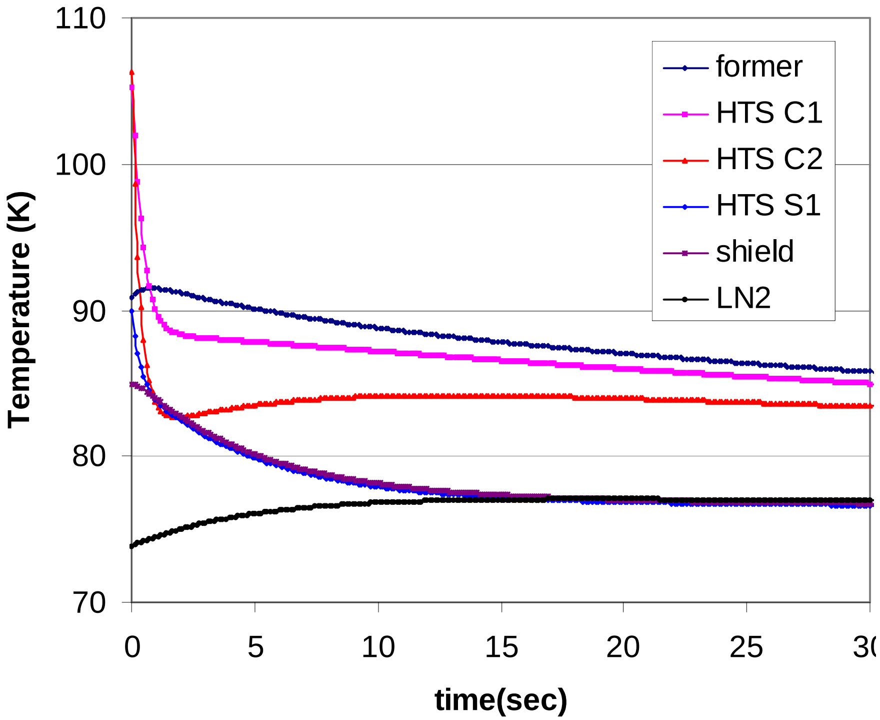


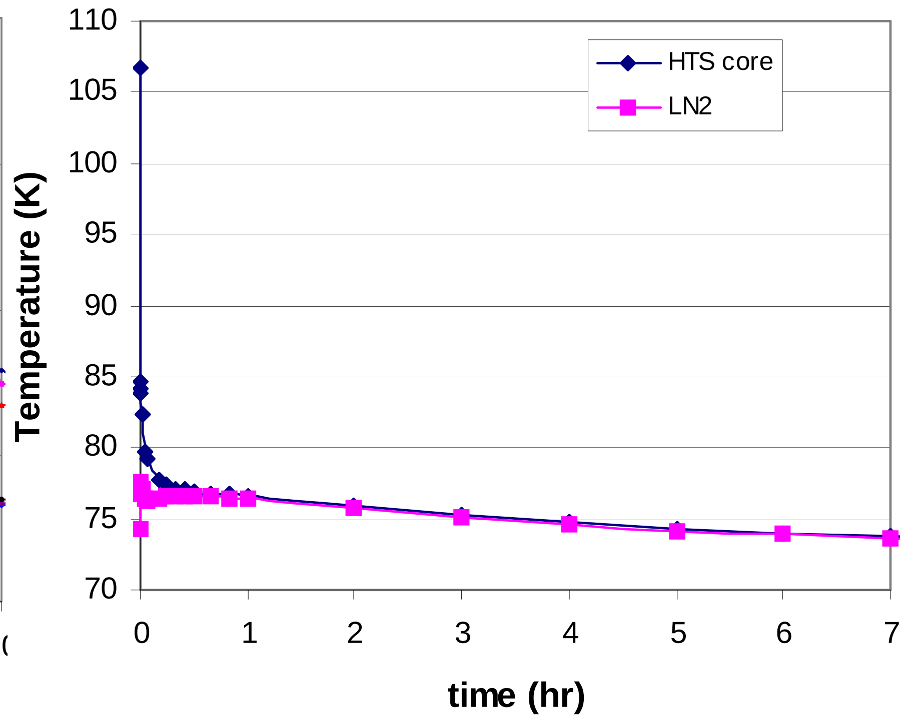


- Buffer acts to control pressure of LN2 in the cable during normal operation
- During fault conditions the buffer absorbs the volume change of LN_2 in the cable
  - Maximum coolant volume change is 80l.
  - Peak flow into the buffer is 18l/s
  - Cable system pressure will drop as subcooled fluid enters the buffer

Risk of bubble formation requires fast grounding switches to protect dielectric

Major Fault Recovery





System operators will need to recognize need for recooling before reclosure

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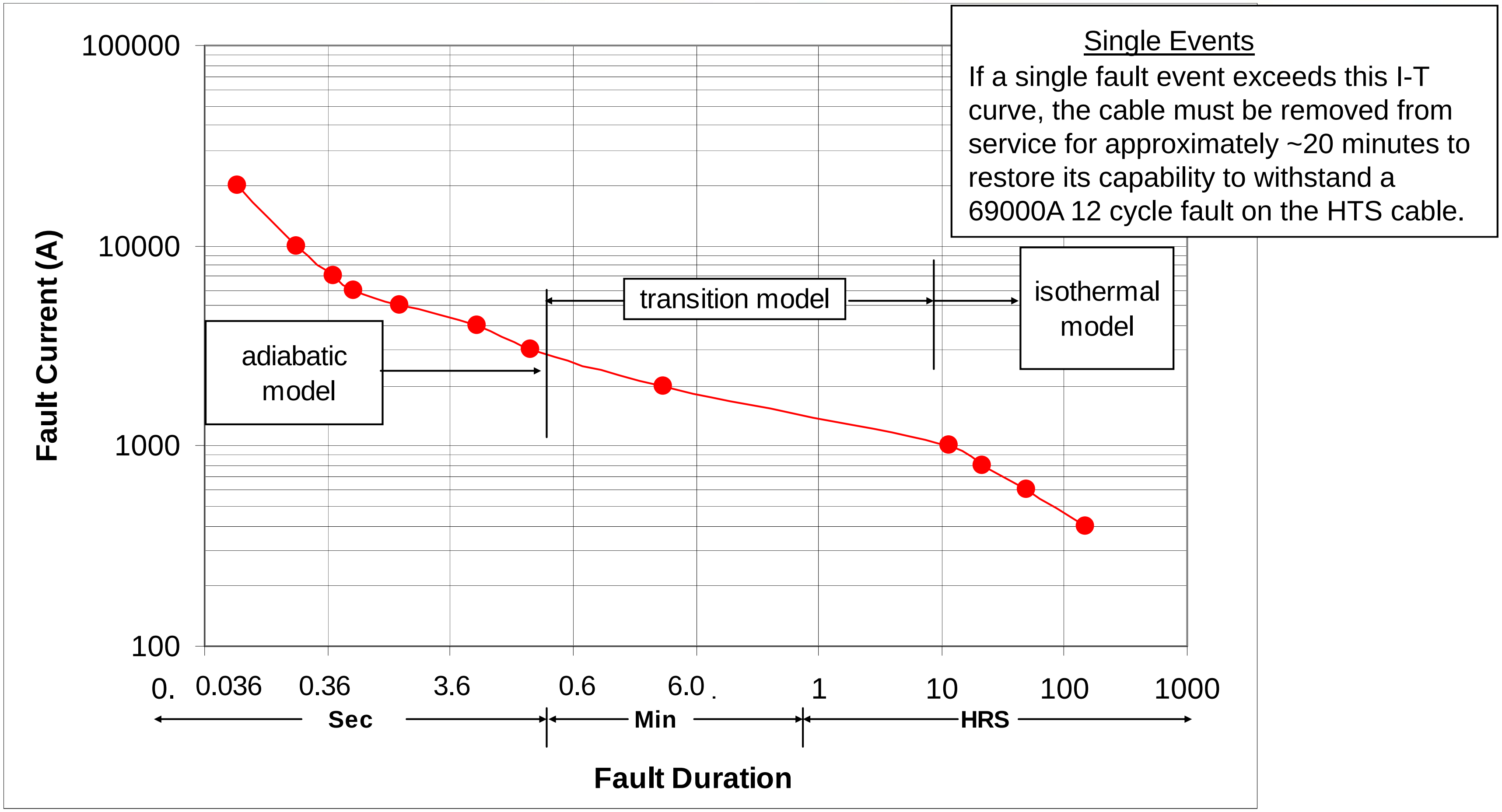
Single Through Fault Protection Scheme



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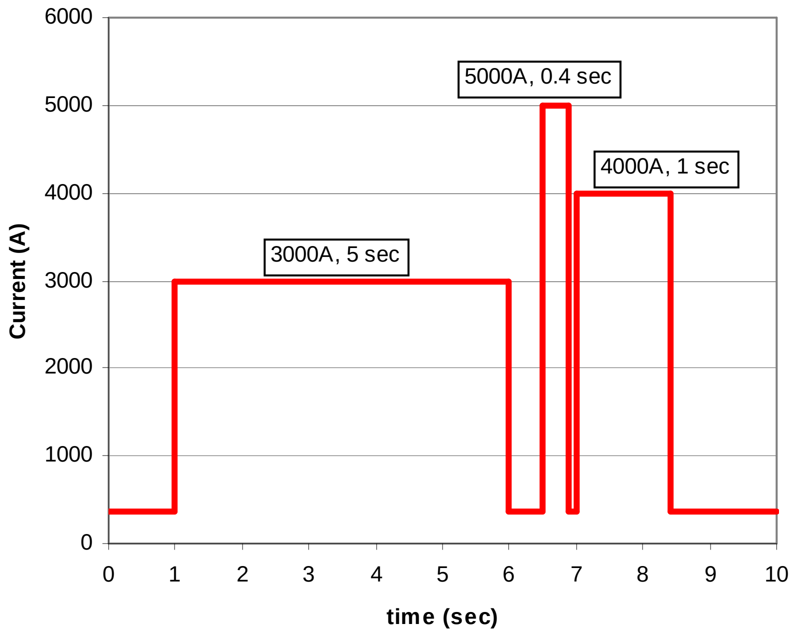
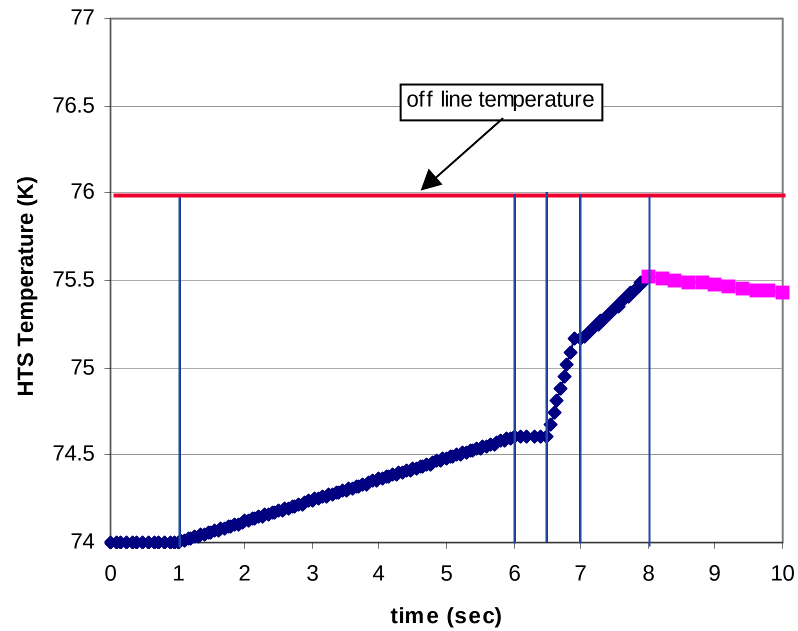
Through Fault Protection: Cable On Line After Faults





- Three Fault Events at Different Currents and Time Duration
- Final Temperature at HTS Layer Less Than the Off-Line Temperature (76K)
- Cable remains online

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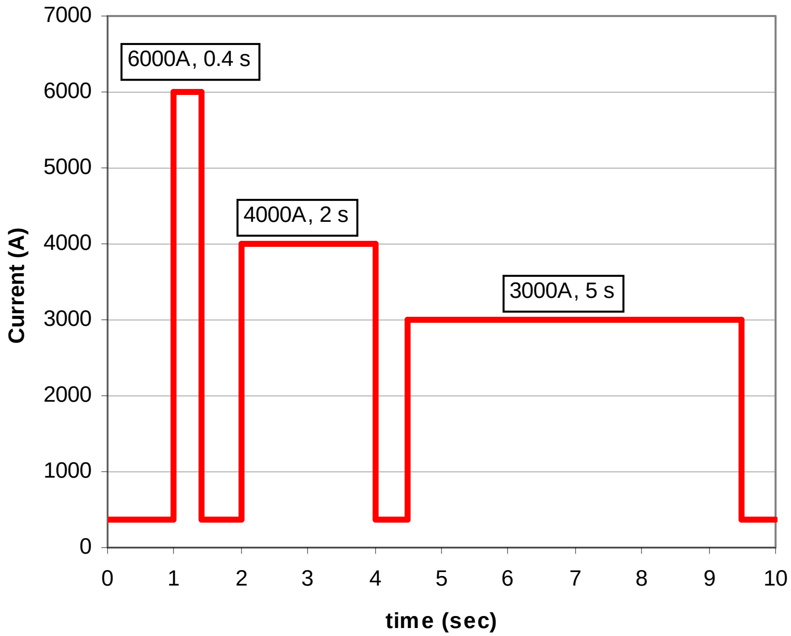
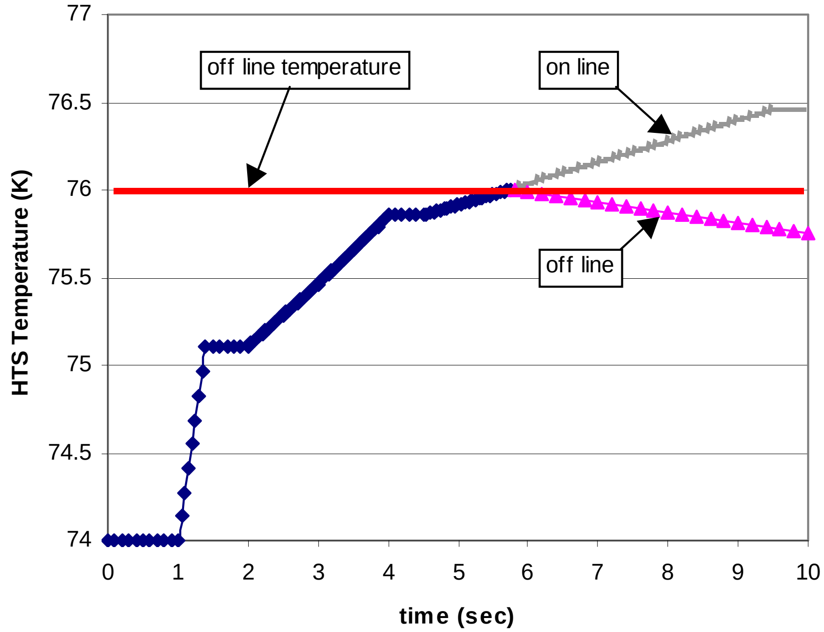
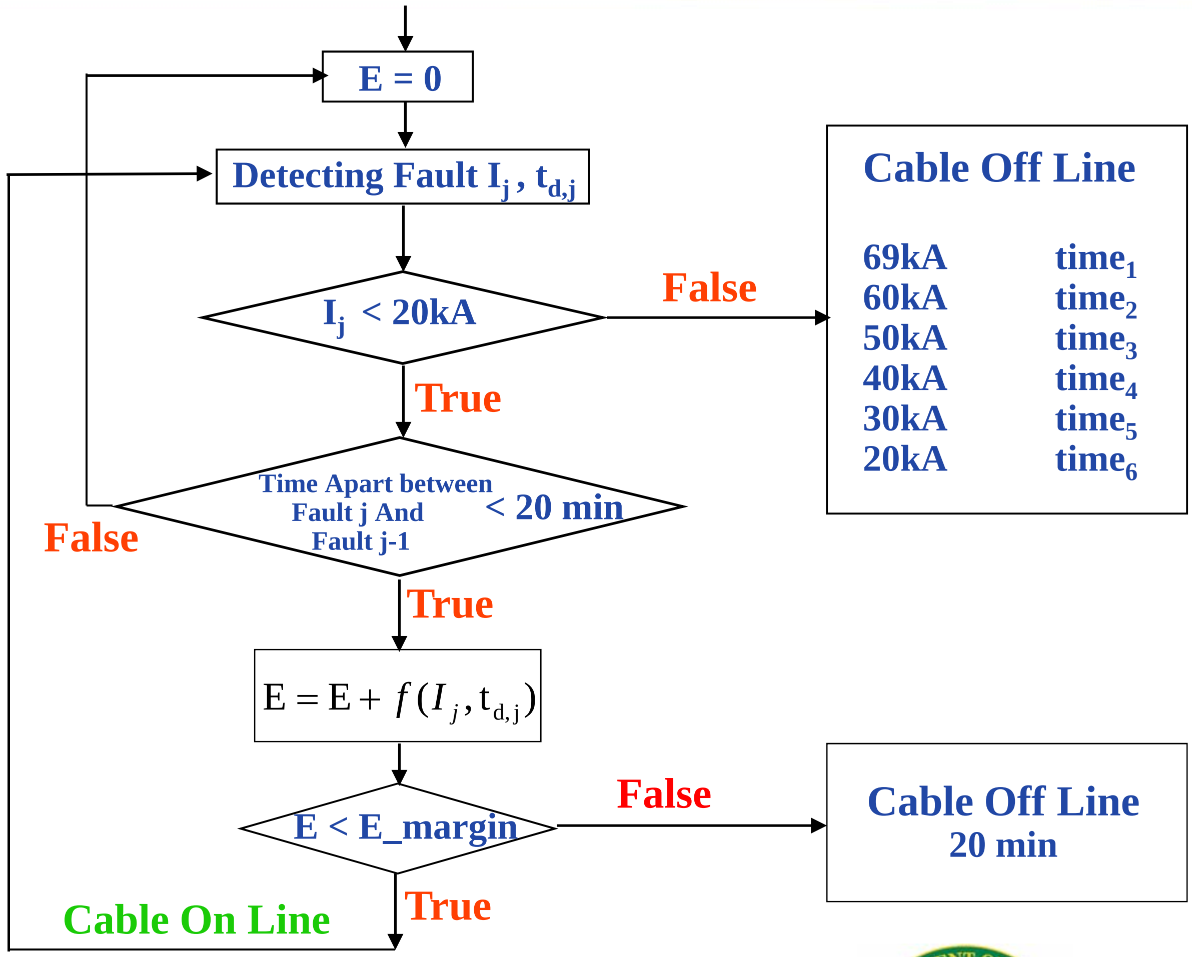
Through Fault Protection: Cable Off Line After Faults





- Three Fault Events at Different Currents and Duration
- Final Temperature at HTS Layer larger Than the Off-Line Temperature (76K)
- Cable must removed from service for ~20 minutes

HTS Cable System Fault Protection Flow Diagram



- Note
  - E: energy dumped into HTS layer 2 which determines if cable has to be placed off line
  - I_j, $t_{d,j}$: fault current and time duration of fault j.
  - $f(I_j, t_{d,j})$: function determine the energy dissipation rate at fault current I_j and time duration
  - E_margin: the allowable energy margin for through fault

* Relay: Schweitzer Electric Accelerator SEL-421

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HTS Cable System Specific Contingency Planning

- Similar to conventional fluid cooled cable systems, HTS cable systems require the consideration of various contingency conditions.
- Most contingencies will not interrupt normal cable operation through design techniques and redundancies
- The cable system has been evaluated to determine the response in the unlikely event for the following multiple failures
  - Loss of cable cryostat Vacuum
  - Loss of main and standby coolant Pumps
  - Loss of main and standby Refrigerators

System will react in a controlled manner in the event of all foreseen contingencies

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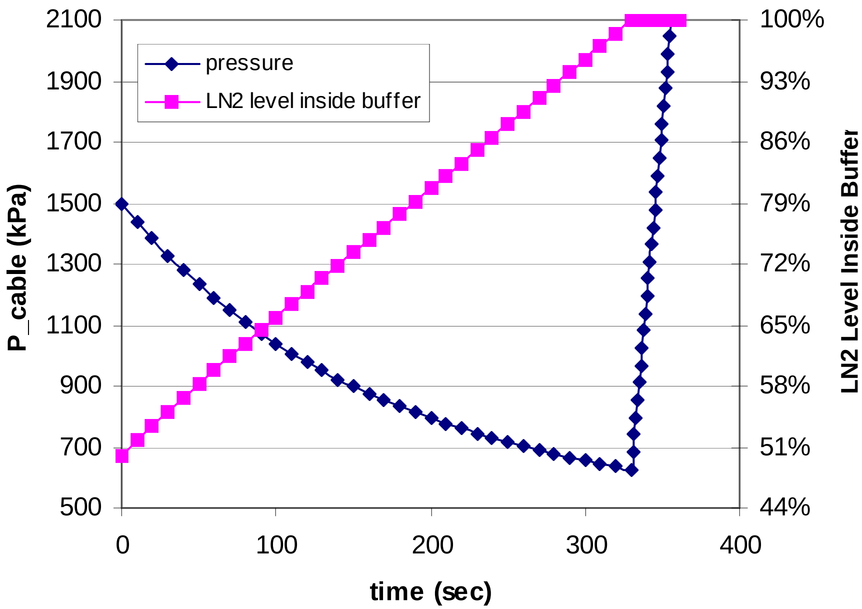
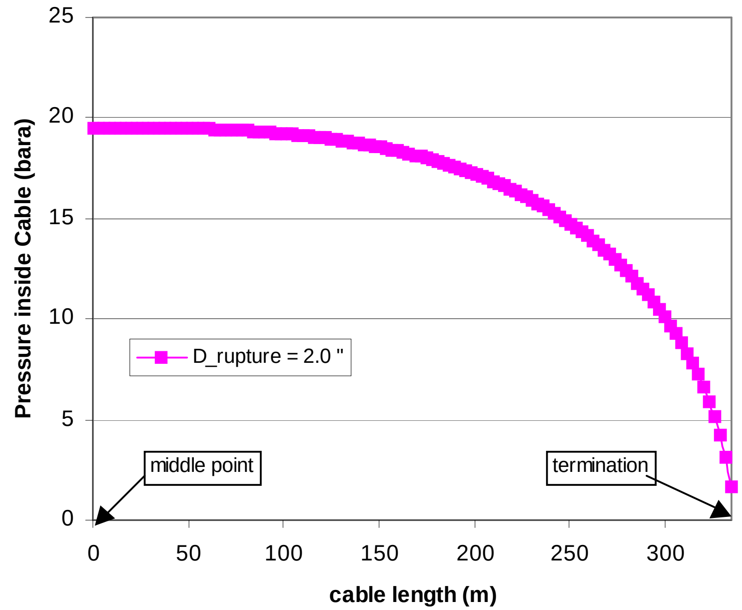
Contingency: Loss of Cable Vacuum Insulation





- CGA Standard Was Used to Determine the Heat Flux.

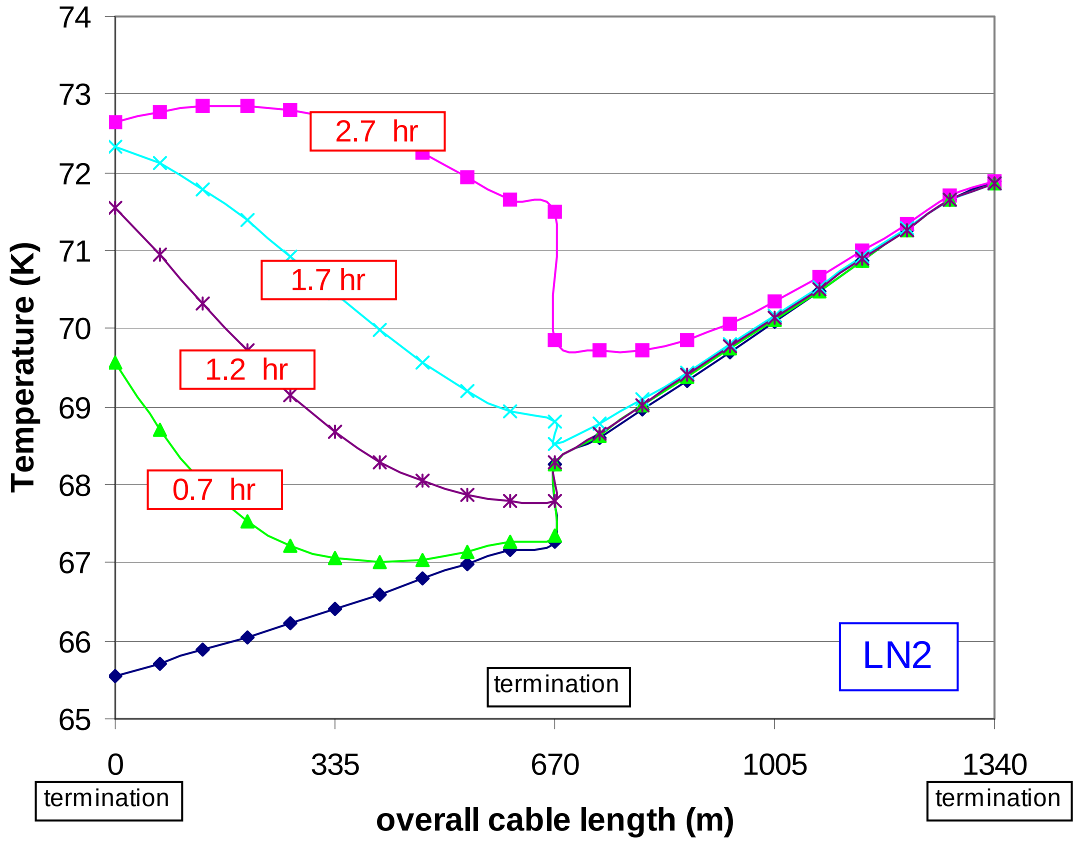
Cable pressures remain safely below burst pressure of cryostat

Contingency: Loss of Coolant Pump & Refrigerator

- Allowable Temperature Rise of HTS Layer Is 2 K In Case of a Major Fault (69kA@200ms)
- Assumptions
  - Uniform Temperature Across Cable Core and LN2. (worst case)
  - Ignore Termination LN2 Mass
- Total Energy Required To Raise 2K: 6.61 MJ
- Total Loss Into the Cable: 2.12 W/m
- Time Duration: 1.3 hr

System Operator has > 1 Hour to react to a failure of all coolant pumps

Contingency: Loss of All Refrigeration / Pump Running



System Operator has > 1 Hour to react to a failure of all refrigeration

Cable and Termination Status

Components of an HTS Cable System

- Superconducting Cable System
  - Cable
    - Cable Core
      - Cable Conductor
      - Dielectric
      - Shield
    - Cryostat
    - Termination

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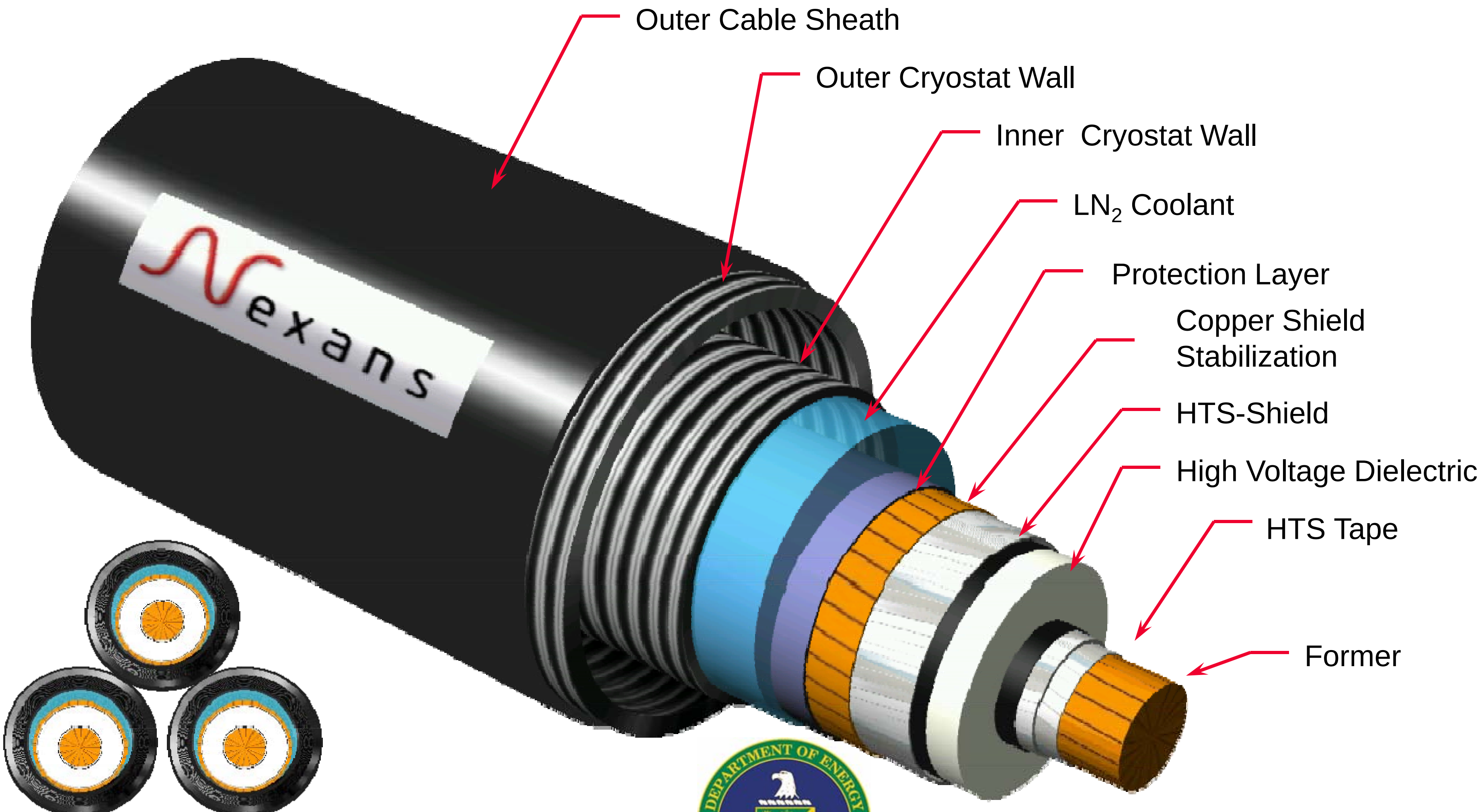
LIPA HTS Cable Concept



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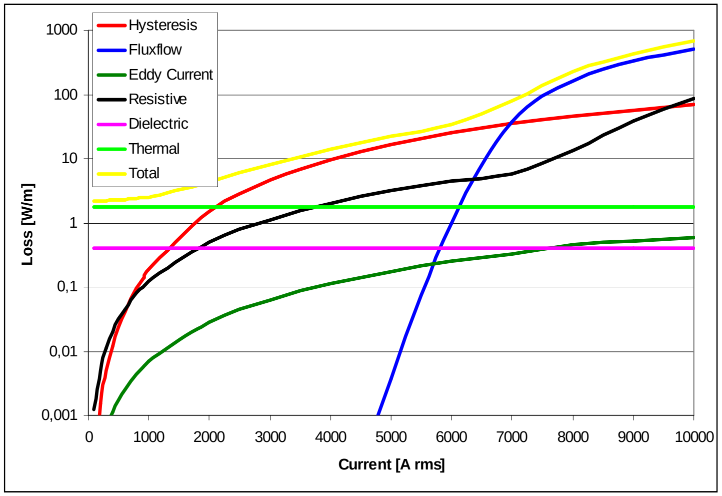
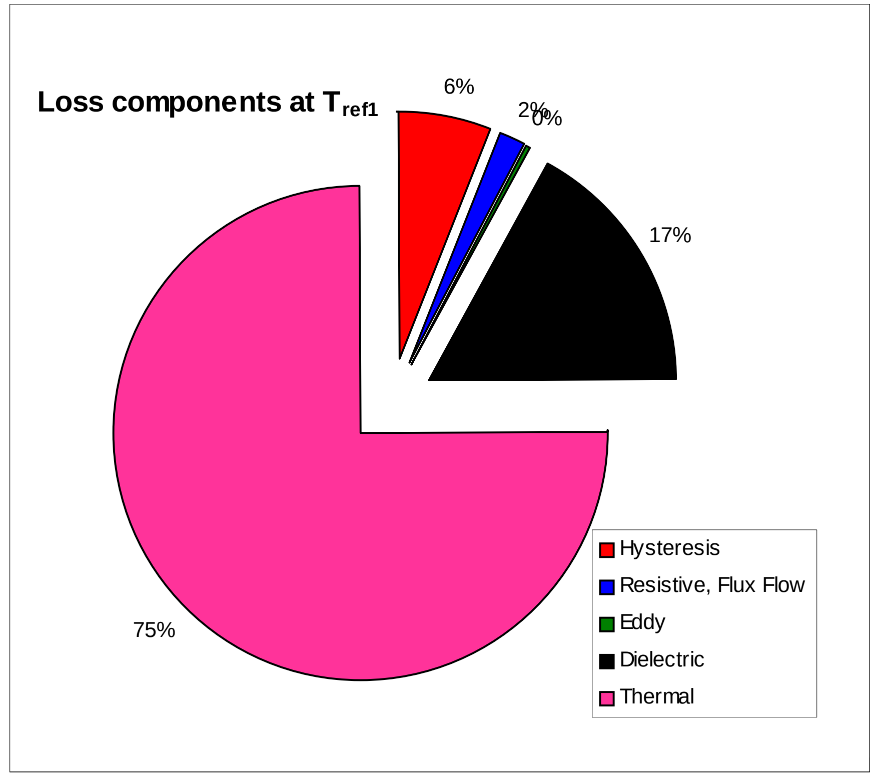
Cable: Calculated Cable Losses



- The cable losses are dominated by the cryostat thermal losses @ Phase 1 rated current emphasizing the need for accurate numbers
- AC-losses are less than 10% for the Phase 1 rated current



Cable: Thermal Contraction Solution

- Cable thermal shrinkage of app. 0.3% is expected
  - The contraction is managed in the termination by a compensation element (1.2 m at each end) requiring motion of the cable core inside the cryostat
  - The equal distribution of the motion between the two ends is achieved by a blocking point (with the cryostat) in the middle of the cable
  - The friction forces need to be taken into account during the design of this thermal shrinkage management solution

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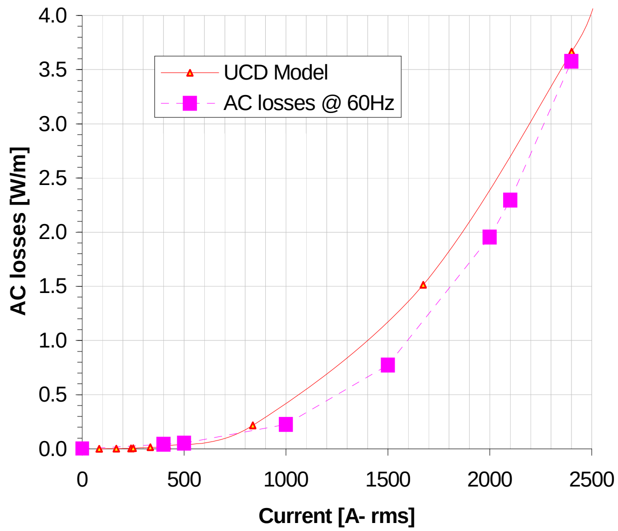
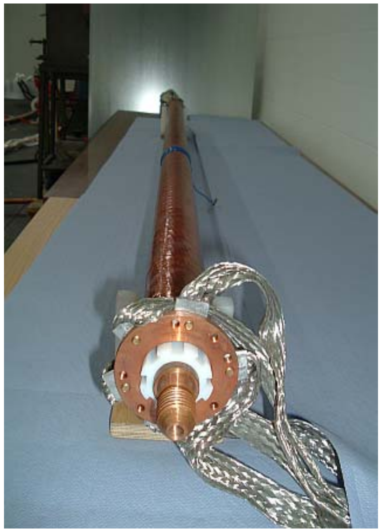
Cable: AC Losses Measurement / Short Samples





- Measurement of AC-losses to confirm the cable design was done on 2 meter samples by means of electrical measurement

- The AC losses are confirmed:
- 0.04 W/m (400 A @60Hz)
- 0.25 W/m (1000 A @60Hz)
- 3.6 W/m (2400 A @60Hz)

Measurements done validate the calculation and cable design

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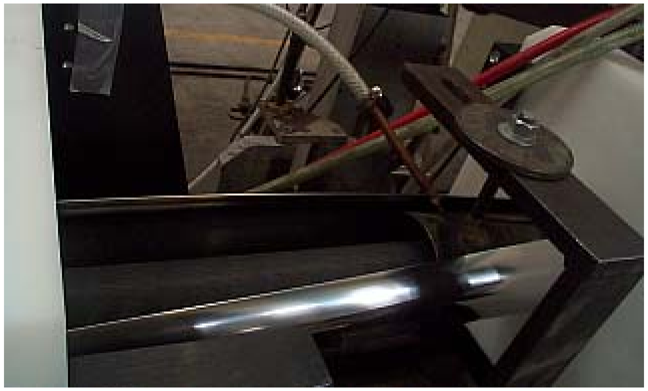
Cable: Manufacturing Process

- Cable manufacturing on existing machines
  - Adaptation of machine parts to address specific needs of HTS wire material
  - Qualification of manufacturing process under industrial conditions for long length HTS cables
    - Manufacturing of Dummy cables using Copper wire as HTS replacement
- Process verification done through
  - Superconducting tape stranding
    - Measurement of Ic and n-value to validate process
  - High voltage dielectric
    - Dry bending tests on lapped dielectric to ensure mechanical integrity of the high voltage insulation
  - Cryostat manufacturing
    - Manufacturing trial using dummy cable



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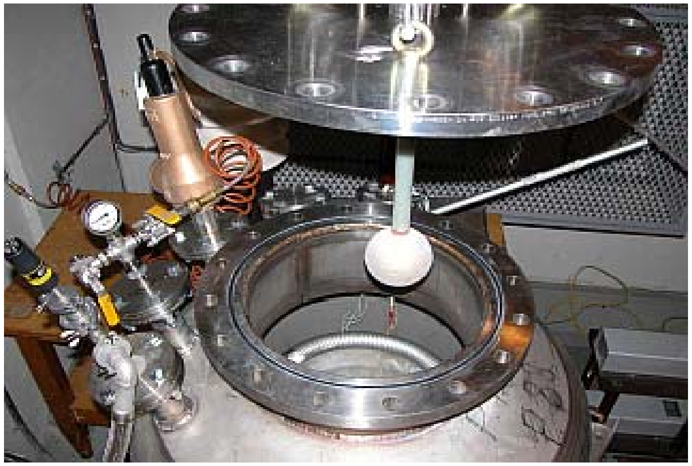
Cable Manufacturing Process - Results

- Superconductor Tape Stranding
  - Requirement: 95 % of original Ic
  - Result: no degradation in any tape after manufacturing and additional bending (>98 %)
- High Voltage Dielectric
  - Requirement: no degradation of insulating paper after large number of dry bends
  - Result: Dielectric layers in very good shape after excessive bending test
- Cryostat Manufacturing
  - Requirement: no damage of cable due to welding of stainless steel tube
  - Result: cable didn´t show any damage on sensitive outer layer

Cable: Dielectric Material Selection



- Materials Tested
  - Kraft Paper
  - PPLP
  - TYVEK
  - Nomex

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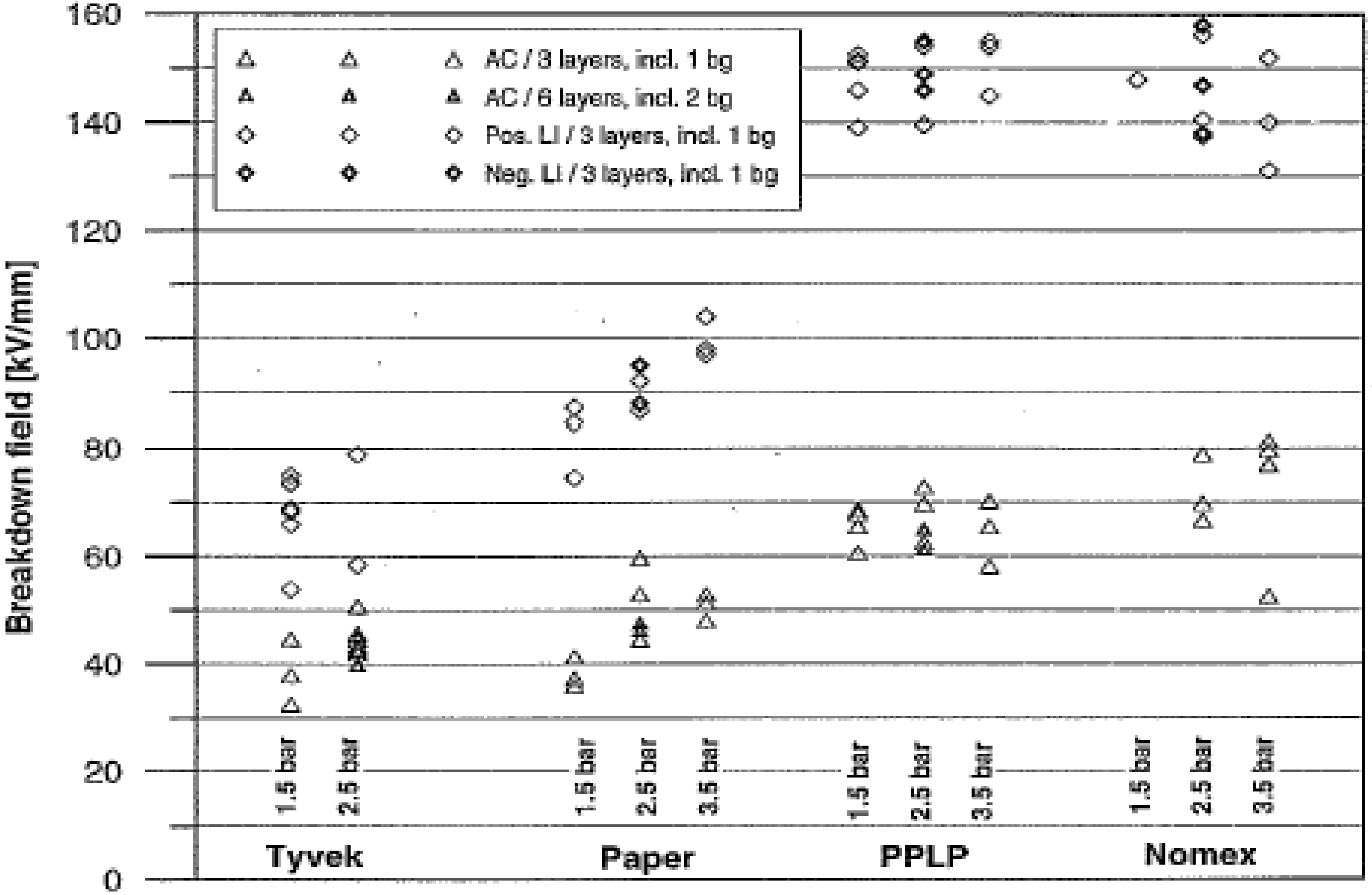
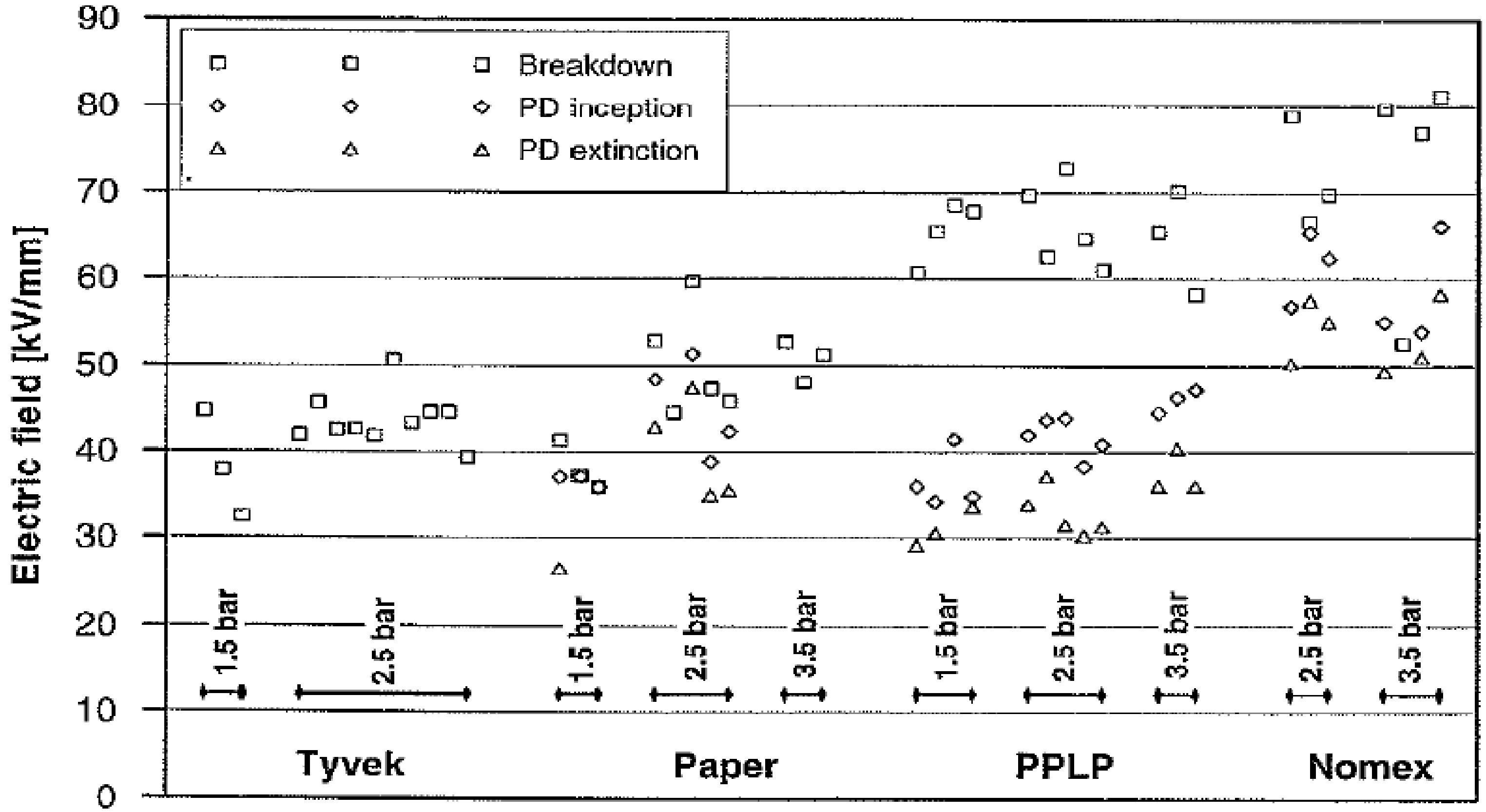
AC and LI Breakdown Field of Different Dielectric Materials



PD Inception & Extinction Field of Different Dielectric Materials



Dielectric Testing on Cable Samples

- Testing in a cable configuration
- Testing in subcooled liquid nitrogen
- Full scale geometry – no model
- Samples taken from manufacturing trials to represent industrial manufacturing conditions
- Test setup suitable for 200 kV regardless the voltage shape

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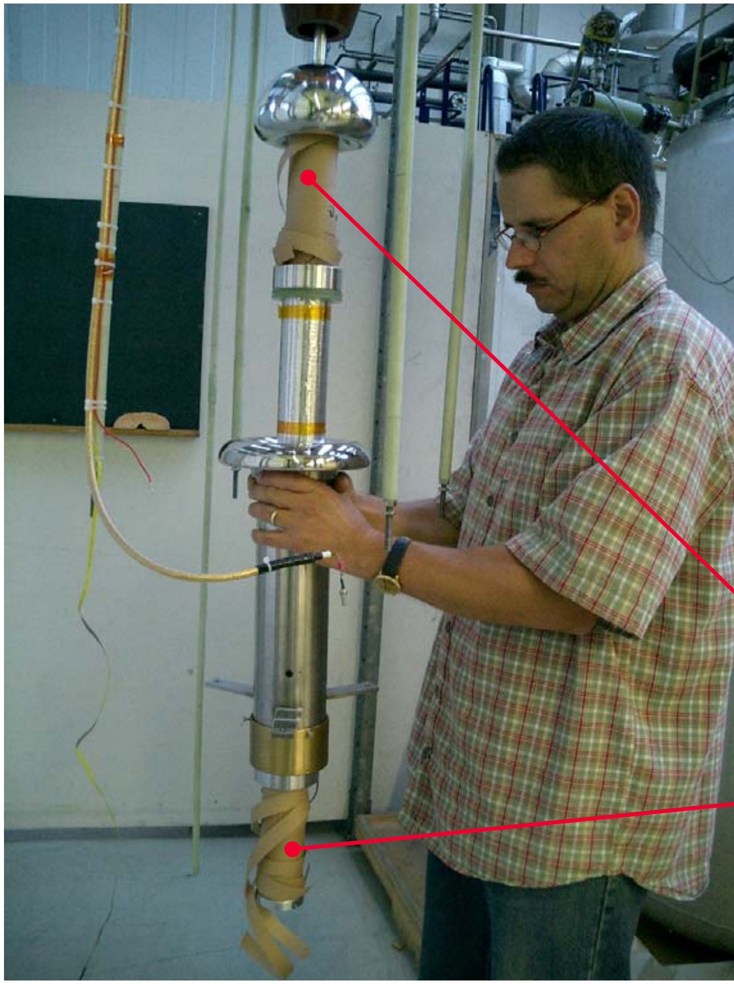
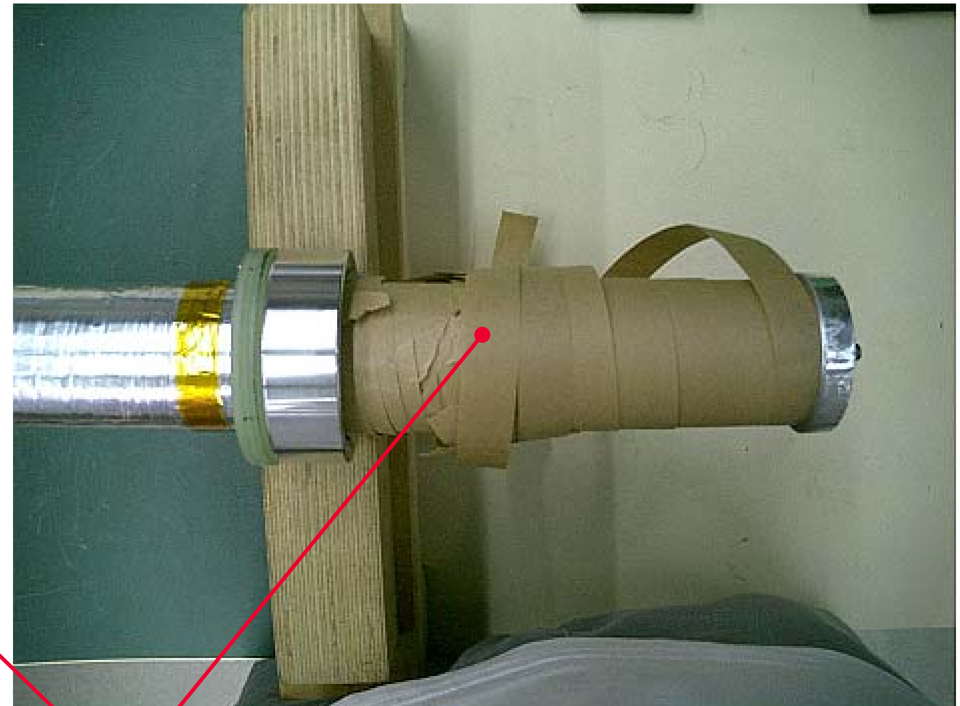
Limit of the Test Setup Dielectric Strength





Damaged Insulation

Dielectric Measurements on Cable Sample - Result

- Results of the measurements done on 1 m cable sample:
- (test conditions: 77 K, 3 bar)
- Partial Discharge Sensitivity was not always sufficient for measurement
- Samples were bent many times during the manufacturing process thus representing the final cable

	Dielectric	ε_r	tan δ	AC test	Lightning impulse test	PD
Sample 1	Paper	2,24	3,6-4,1E-3	15 min. 200 kV was OK	+/-200kV was OK	70 kV:1,3 pC 120 kV:13 pC 130 kV:22 pC
Sample 2	PPLP	2,25	1,09-1,16E-3	15 min. 200 kV was OK	+/-200kV was OK	130kV:<0,7 pC

Dielectric: Conclusion

- PPLP has been proved as a suitable high voltage dielectric in the material testing as well as the cable sample testing
- The dielectric meets the AC-withstand voltage requirement
- The LI-withstand voltage was tested in a flat sample configuration – the dielectric design takes into account reasonable margin – verification to be done in 30 m prototype test
- The cable manufacturing process does not harm the dielectric integrity
- The dielectric constant and the tan δ are in accordance with the cable design requirements

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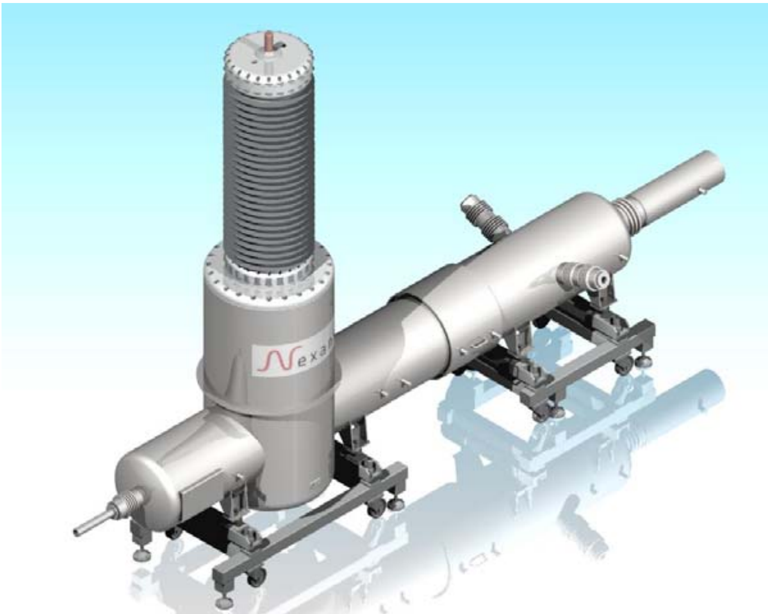
Termination: Description



Physical description

- Length: ≈ 7 m
- Height: 4.2 m
- Weight: ≈ 2100 kg
- Net capacity: ≈ 600 liters of LN_2

- Rated voltage: 161 kV
- Rated current: 2400A

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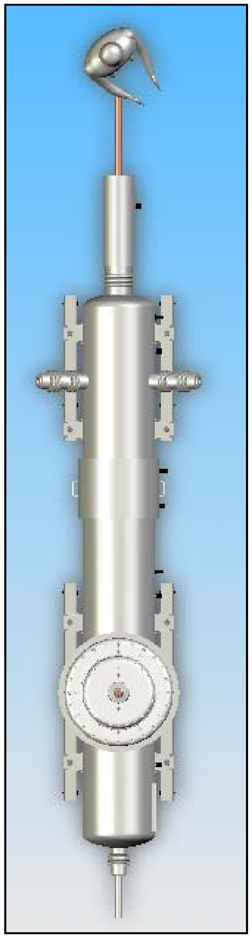
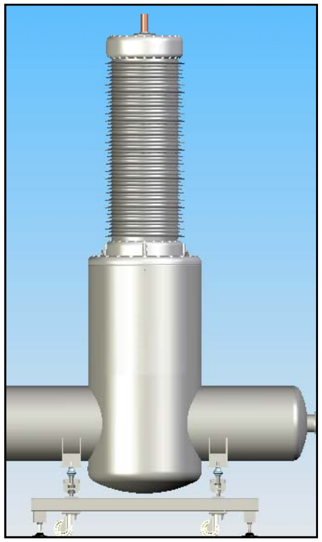
Termination: Description



- <u>Horizontal part</u>:
  - Connection of the HTS cable
  - Management of cable thermal shrinkage (>1m)



- <u>Vertical part:</u>
  - Thermal gradient 300 K-77K management with a specific bushing
  - High voltage management for network connection

Termination meets the ASME code requirements

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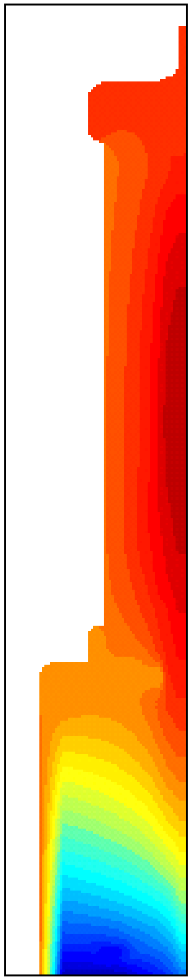
Termination: Thermal & Electrical Design

Design Optimization With Thermal Calculations



- In different working conditions:
  - No current / rated current phase 1 / full current (2400 A)
  - Extreme ambient temperature (standard, summer & winter conditions)
  - Total heat flux in LN2 < 300 W @ Tamb = 313 K ; I =2400 A
- Study of materials with different thermal behavior
- Study of termination dimensions & components shapes

Optimal thermal distribution = Best compromise between:

- ✓ Temperature compatible with HV components in outdoor sealing end
- ✓ Minimum heat flux in liquid nitrogen
- ✓ No hot spot in bushing with full current load
- ✓ Minimum vertical part height
- ✓ Material compatible with cryogenic temperature at the cold end (contact with LN2)

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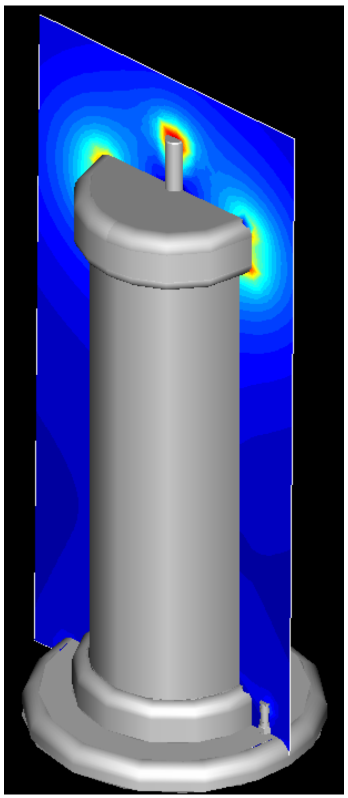
Termination: High Voltage Design

Design Optimization With Electrostatic Calculations



- **For the vertical part:**
  - Optimization of the E field deflection before the HTS cable / bushing connection (bottom of the bushing)
  - Optimization of the E field deflection before the connection to HV network (top of the bushing)

- **For the horizontal part**
  - Optimization of the E field deflection on the connection area between HTS cable and bushing

Best compromise between:

- ✓ Material electrical properties (no risk of breakdown)
- ✓ Compatibility of the HV components materials with temperature distribution
- ✓ High Voltage accessories position and geometry
- ✓ Termination dimensions for High Voltage considerations in accordance with thermal design optimization (creepage path…)

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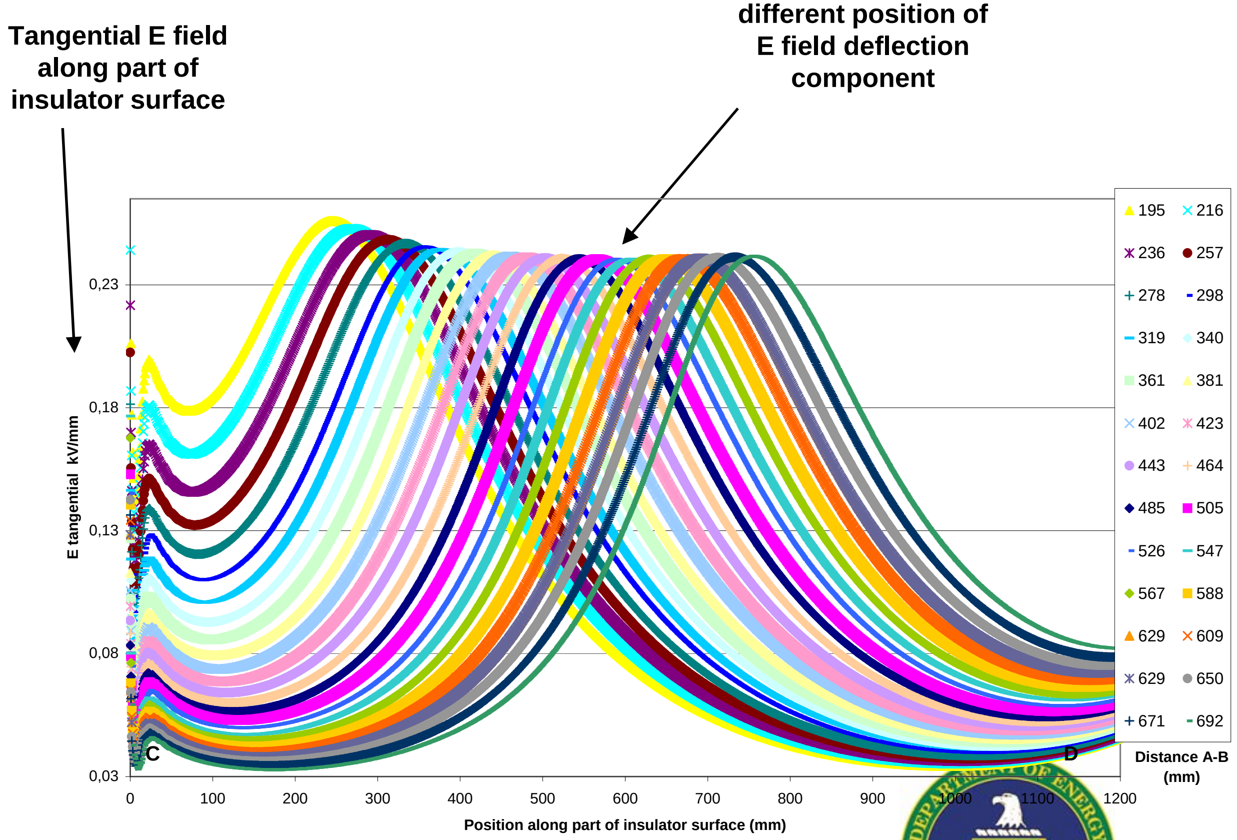
Termination: High Voltage Design

Example 1: Optimization of the field deflection component position in outdoor sealing end (Warm part of termination)



Choice of best compromise between max E field & max Leakage path length

Termination: Components Development Method

- **Test & Measurements of Components Material Properties:**
  - Especially for the 300K- 77K transition ⇨ Bushing
  - Thermal properties and evolution with cryogenic temperature were studied
  - Influence of cryogenic temperature on material Electrical properties (dielectric strength…)
  - Compatibility between two materials on interface (differential shrinkage)
- **Test of Components Prototypes**
  - AC resistance measurements on resistive parts at cryogenic conditions
  - Thermo-mechanical tests of single components
  - High Voltage tests (AC-withstand & lightning impulse) on partial assembling of the termination
- **Validation of Fully Assembled Components:**
  - Complete assembling tests of the termination with cable connection
  - Thermo-mechanical tests on assembled components
  - High voltage tests on the complete loop (termination + HTS cable)

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Termination: Components Development

- Shrinkage measurements of bushing materials properties from 300 to 77 K was done confirming design value
- Dielectric strength measurement of bushing insulating material sample at 300 & 77 K
  - In accordance with Electrostatic calculation requirements with good margin

- Mechanical measurements (tensile test) of bushing materials properties at 300 & 77K (samples)
  - Break elongation and ultimate tensile stress measurements
  - Results at cryogenic conditions combined with shrinkage measurements confirms the bushing material compatibility
    - No mechanical overload (stresses or elongation) in cold conditions
  - Compatibility valid considering static mode (cooling down achieved)
    - Conductive & insulating material have far different thermal conductivities which can have a strong influence in transient mode (during cooling down)

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Termination: Components Development

- **Thermo-mechanical tests on component prototypes:**

- Immersion in liquid nitrogen of component (bushing conductor material + insulating material)

Bushing materials choice validated

- Additional tests to check thermal behavior of the component under mechanical stresses at cryogenic temperature
  - To simulate flanging force
  - Screws torque tested up to 160 N.m

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Termination: Components Development

- **<u>High voltage test on single component prototypes:</u>**
  - **Test of a first bushing prototype alone in 2004 (not final optimized design)**
    - Only part of the termination vertical part simulated in this test
  - **AC Withstand test achieved 230 kV / 15 minutes without breakdown**
  - **Lightning impulse tests achieved up to 550 kV**
    - Test stopped due to the not optimized leakage path in LN2 for this prototype and presence of nitrogen bubble limiting the impulse withstand voltage

Bushing materials compatible with High Voltage specifications combined with cryogenic constraints

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Cable Cryostat: Description

1. Corrugated Inner Pipe
2. Spacer
3. Vacuum Space
4. Multi Layer Super Insulation
5. Corrugated outer pipe
6. PE jacketing

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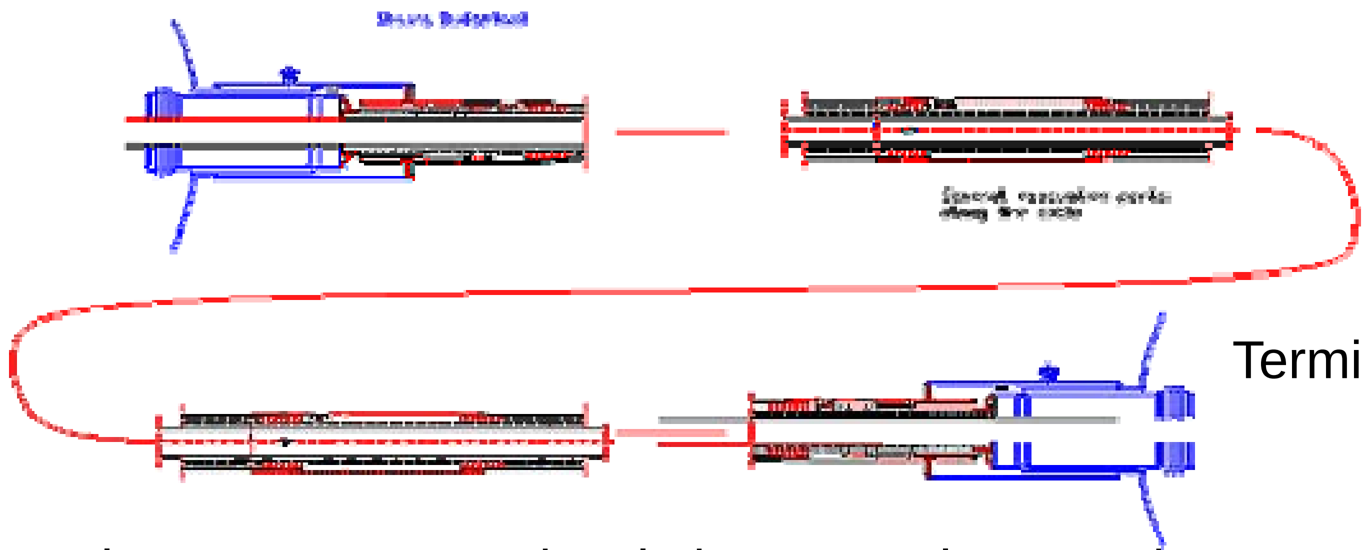
Cryostat: Design

Additional evacuation ports along the cable

Termination



Termination

- For long term vacuum insulation several evacuation ports along the cable are required.

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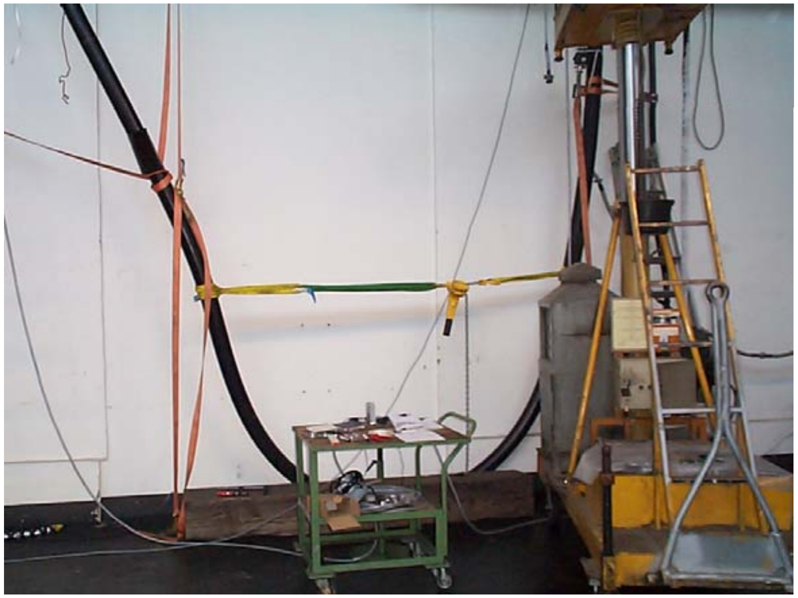
Cryostat: Heat Loss Measurement with Evaporating LN_2



- 10m CRYOFLEX 60/110 in U-bend filled with LN2
- Measurement of LN2 evaporating rate
- Measurement various radial load conditions
- Measurement under various vacuum conditions
- Heat loss for 60/110: 1.2 W/m

Calculated heat loss for LIPA Cryostat 1.6 – 1.8 W/m

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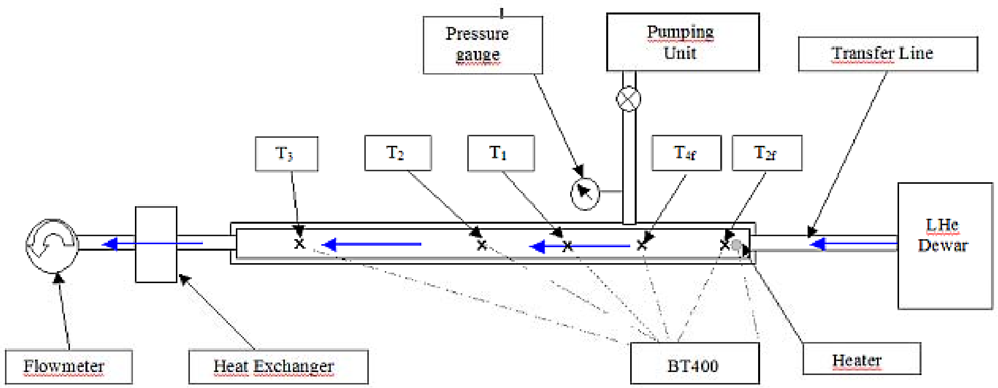
Cryostat: Measurement of Heat Loss by Cold He Gas

- Cryostat heat loss measurement was done in straight and bent conditions using gaseous helium confirming the value of 1.7 W/m
- Measurement done by Air Liquide



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ASME Code Applied on Superconducting Cable

- ASME B31.5 Refrigeration Piping and Heat Transfer Components applicable to SC-cables
- Longitudinal welding tested at each end of cable
- 5% of circumferential butt welds tested
- Cable installation tested with 110% design pressure (pneumatic test)
- Proof test according to Section VIII-Division1, UG101

The superconducting cable meets the ASME code requirements

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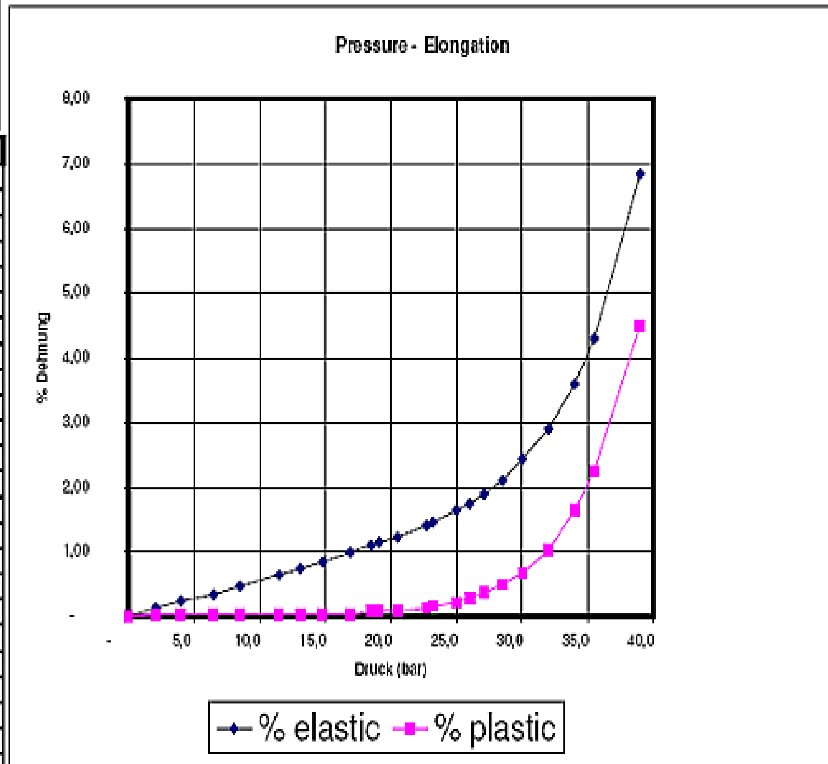
Pressure Test / Bursting Test

Elongation of pipe due to inner pressure

Wellrohr Typ 80/88 (79,5/89,1)
Wandst.: 0,8 mm
Steigung: 9,2mm
Material: 1.4401
Länge: 2010 m

bar	% elastic	% plastic
-	-	-
2,1	0,13	0,03
4,0	0,23	0,03
6,5	0,33	0,03
8,5	0,46	0,03
11,5	0,64	0,03
13,1	0,74	0,03
14,8	0,85	0,03
16,9	1,00	0,03
18,5	1,10	0,08
19,1	1,15	0,08
20,5	1,23	0,08
22,7	1,41	0,13
23,2	1,46	0,15
25,0	1,64	0,20
26,0	1,74	0,28
27,1	1,90	0,36
28,5	2,10	0,49
30,0	2,43	0,67
32,0	2,89	1,02
34,0	3,59	1,64
35,5	4,30	2,25
39,0	6,84	4,51
-	-	-



- Plastic deformation beyond 23bar
- Bursting pressure: 160bar
- Measurement done on inner cryostat pipe – outer pipe gives additional margin

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Cable System Complete Assembly

- First complete assembling achieved (beginning of 2005)
- Assembling steps & Assembling procedure validated
- Fitting of each components validated

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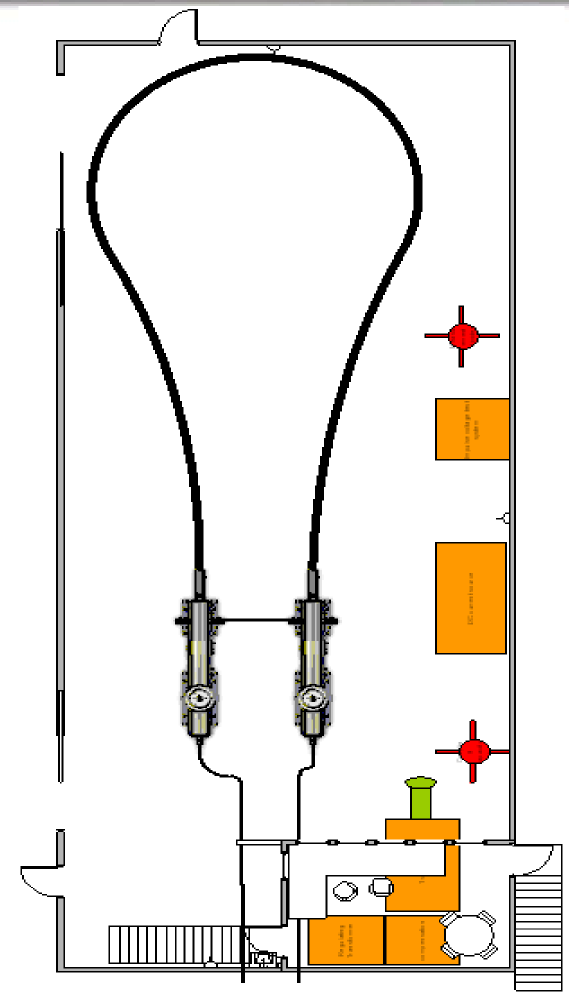
Test Field and Cable Test

- Screened Room 30 x 12 x 9 meter
- 350 kV, 2 A High Voltage Transformer
- 4000 A - AC Current source
- 1000 kV Impulse Voltage Test System
- 10 kA DC Current Source
- PD Measurement Equipment
- Tan δ Measurement Equipment
- Cooling System (~7 kW cooling power)
  - 67 K – 77 K variable inlet temperature
  - 0 – 15 bar variable pressure
  - 50 – 2000 g/s mass flow



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30 Meter Cable Test Program

- Different Kind of Tests Are Foreseen in the Test Program
  - Cable cool down behavior
  - Ic measurement
  - AC-loss measurement
  - Pressure drop measurement
  - Thermal loss measurement
  - AC-withstand voltage test
  - PD measurement
  - Tan δ and Dielectric Constant measurement
  - LI-withstand voltage test
  - Load cycle test

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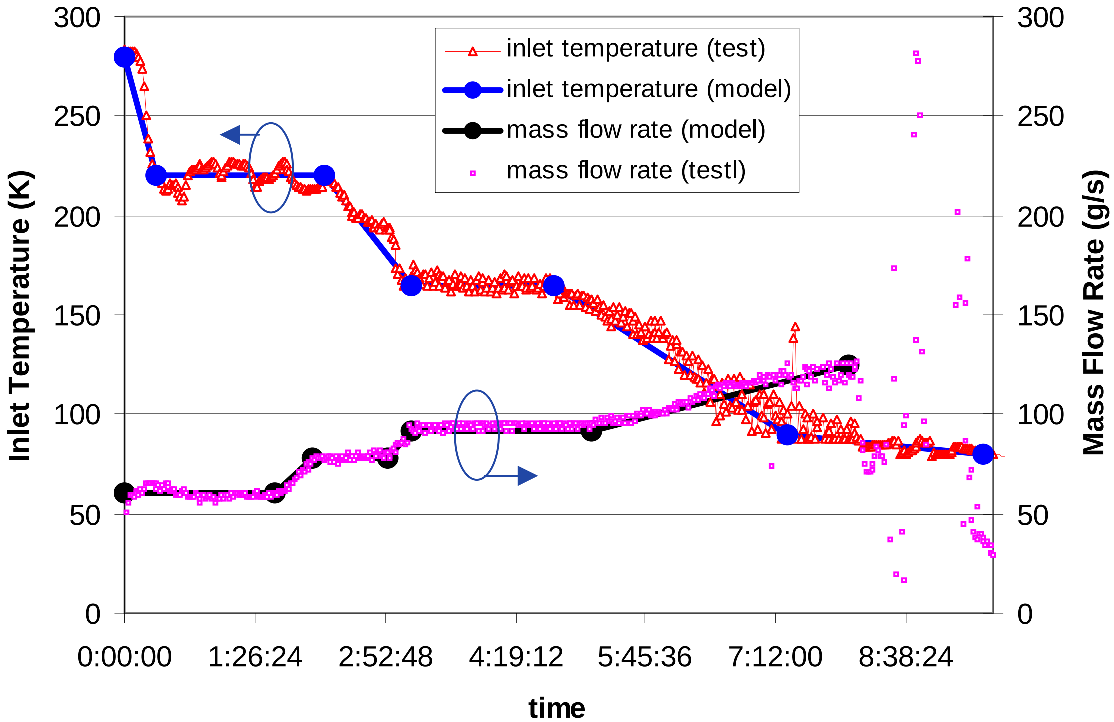
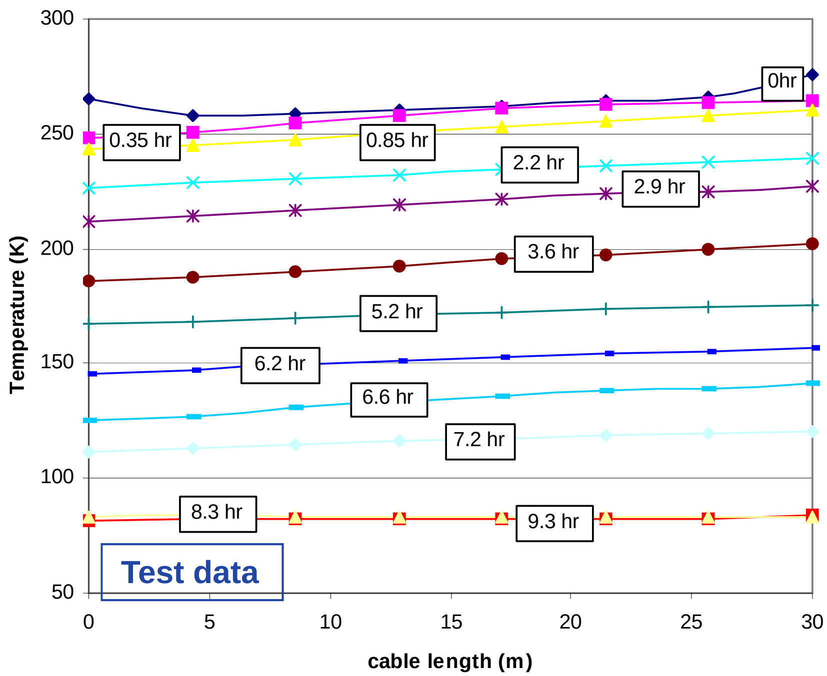
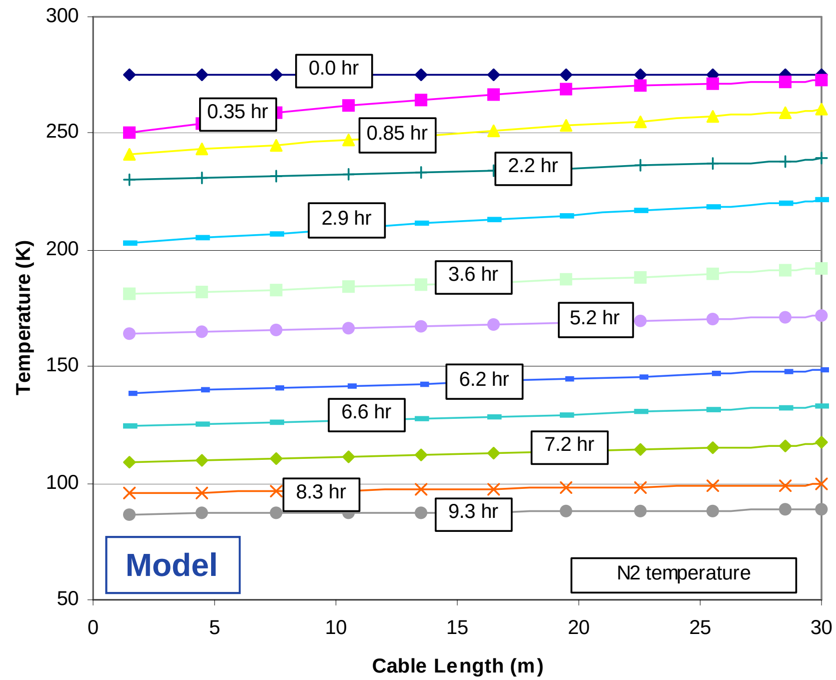
Mass Flow Rate and Inlet Temperature Profile



- Temperature Profile Used for the Modeling Represent the One Observed During the Cable Cool Down

Comparison Between Model and Test





Model prediction is slightly faster than test data bus still representing good agreement to the test data

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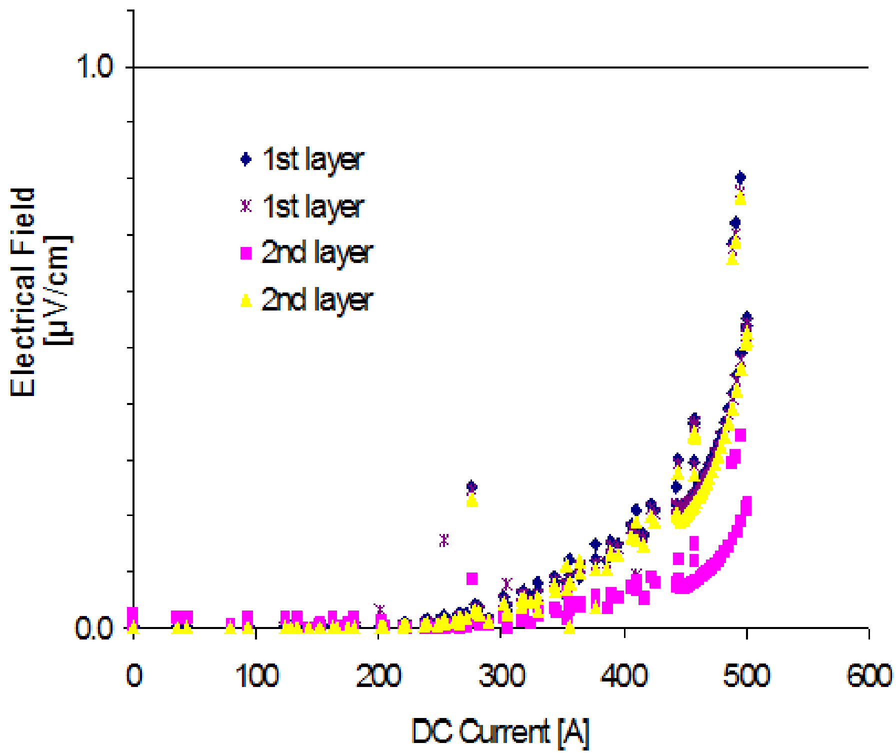
Critical Current Measurement After Installation



- Measurement on the 4 core tapes of the dummy cable at 74 K
- No noticeable degradation of the original critical current after
  - Cabling
  - Pulling in the 30 m cryostat
  - Connection to the termination

No noticeable degradation after installation

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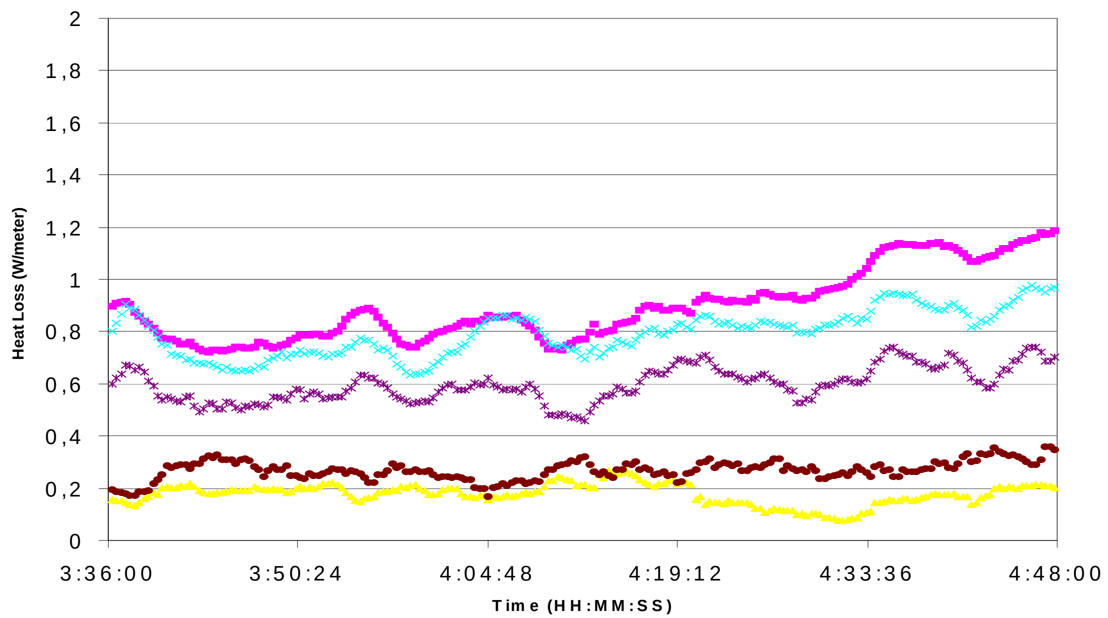
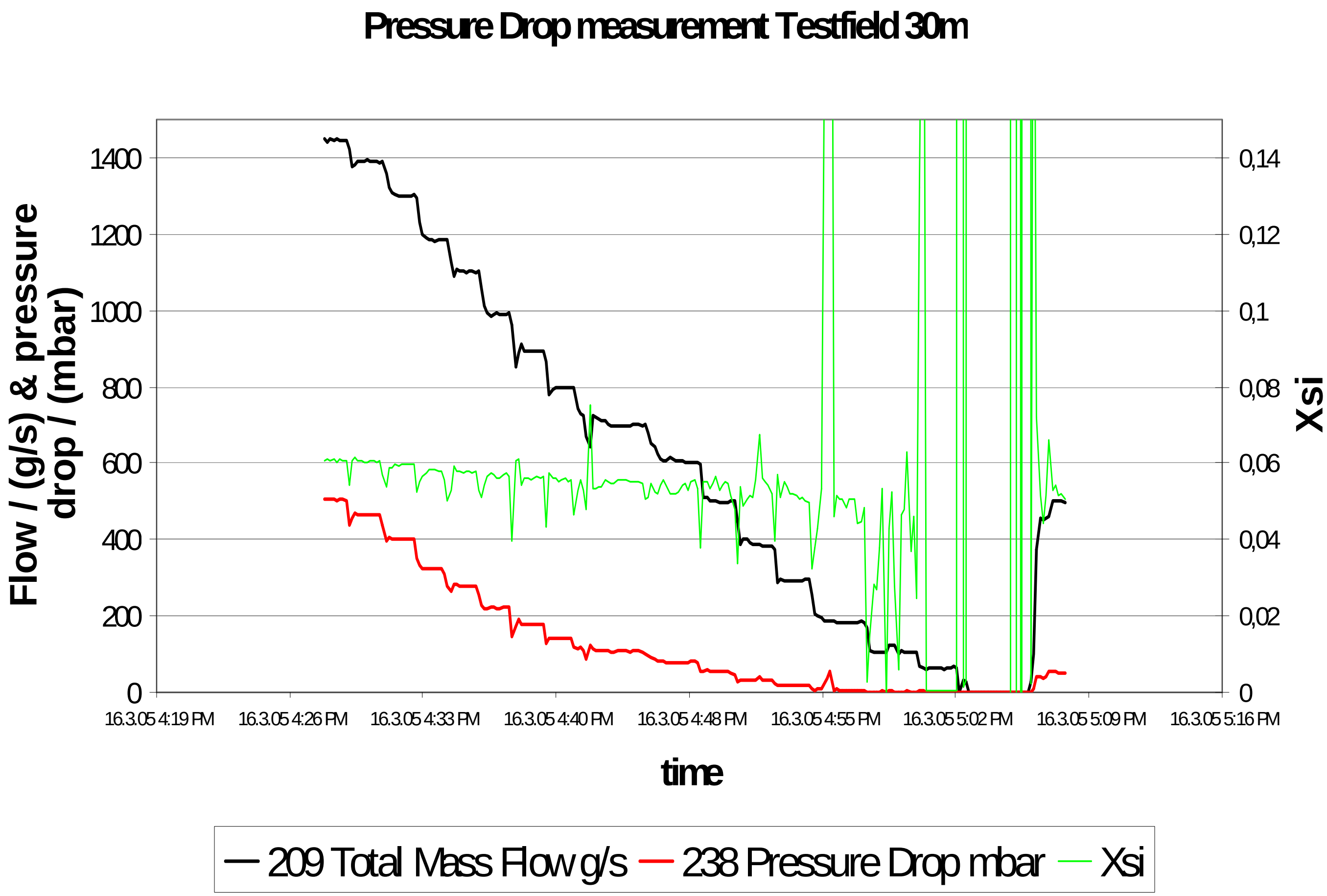
Cryostat Thermal Loss Measurement on Dummy 03



- Thermal loss measurement on 30 meter loop proved difficult due to measurement sensitivity
- Values shown present high uncertainty with regard to precision as well as thermal stability

Pressure Drop Measurement With LN2 at 30m Sample



- Measurement is confirming the value of Xsi < 0,08 determined by measurements done with water earlier in program

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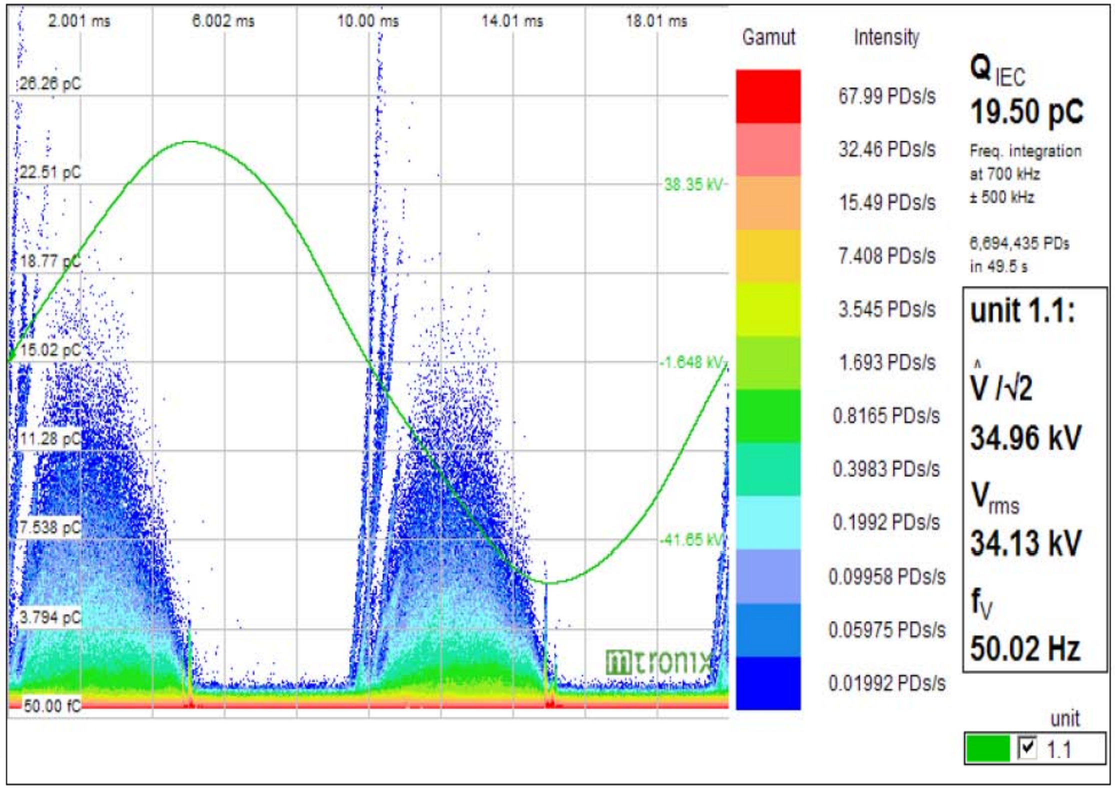
30 meter Test: Partial Discharge Measurement

- Partial Discharge was observed at rather low voltage
- Origin was identified to be in the termination bushing
- In order to identify problem voltage was increased to force dielectric breakdown



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HV Test With Complete Loop

- After several thermal cycles of the loop, HV test were performed
  - Partial Discharge remained constant
  - Voltage was increased to 75 kV where breakdown occurred
- After disassembling of the loop, the breakdown origin was identified in the bushing
- Inspection of the bushings reveals that both of them presented a thermo-mechanical failure previously to the HV test
  - The failures appear during cooling down
  - Bushings were weaken regarding high voltage due to these failures
- Additional studies were done to identified the problem origin
  - Focused on the complete assembling of termination & loop as no problem were encountered for single component test

Test of Assembled Termination (Loop)

- Thermo-mechanical tests on final terminations design (assembled terminations):
  - **Final bushing design**
  - **Complete termination cryostat**
  - **Incremental tests performed for each assembling step of the vertical part:**
    - Check of bushing integrity after cooling down with flanging step only
    - Check of bushing integrity after cooling down with flanging step only + assembling of support disc of the termination
    - …
  - **Slow cooling rate**
    - to avoid influence of this parameter and be as near as possible to static mode
  - **Bushing / top cap connection not tested**
    - design improvement identified to increase safety margin
    - development ongoing to increase flexibility of this connection (facilitate shrinkage)

No crack or damage of the bushing after the test
Termination design & assembly not the origin of the problem

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Test of Assembled Termination (Loop)

- <u>Cooling rate study:</u>
  - Cooling rate could have a strong influence in transient mode (T gradient due to different thermal conductivity behavior between material)
  - Analysis of cooling down recorded data:
    - Cooling down which has created a crack
    - Cooling down used for thermo-mechanical test (no crack)
    - Study on cable side & on bushing surface side
  - <u>Results:</u>
    - Cooling down which create cracks
      - Bushing not thermalize when LN2 reach bushing conductor
      - Important flow when LN2 reach bushing conductor (500-600 g/s)

      ➔high thermal gradient in bushing + high cooling rate when contact with LN2
    - Slow cooling rate for thermo-mechanical tests (no crack)
      - Bushing cooled down much slower before LN2 reach LN2 conductor (better thermal distribution)
      - Temperature gradient was smaller during this cool down
      - Flow when LN2 reach bushing conductor: 40-60 g/s

      ➔lower thermal gradient in bushing + lower cooling rate when contact with LN2

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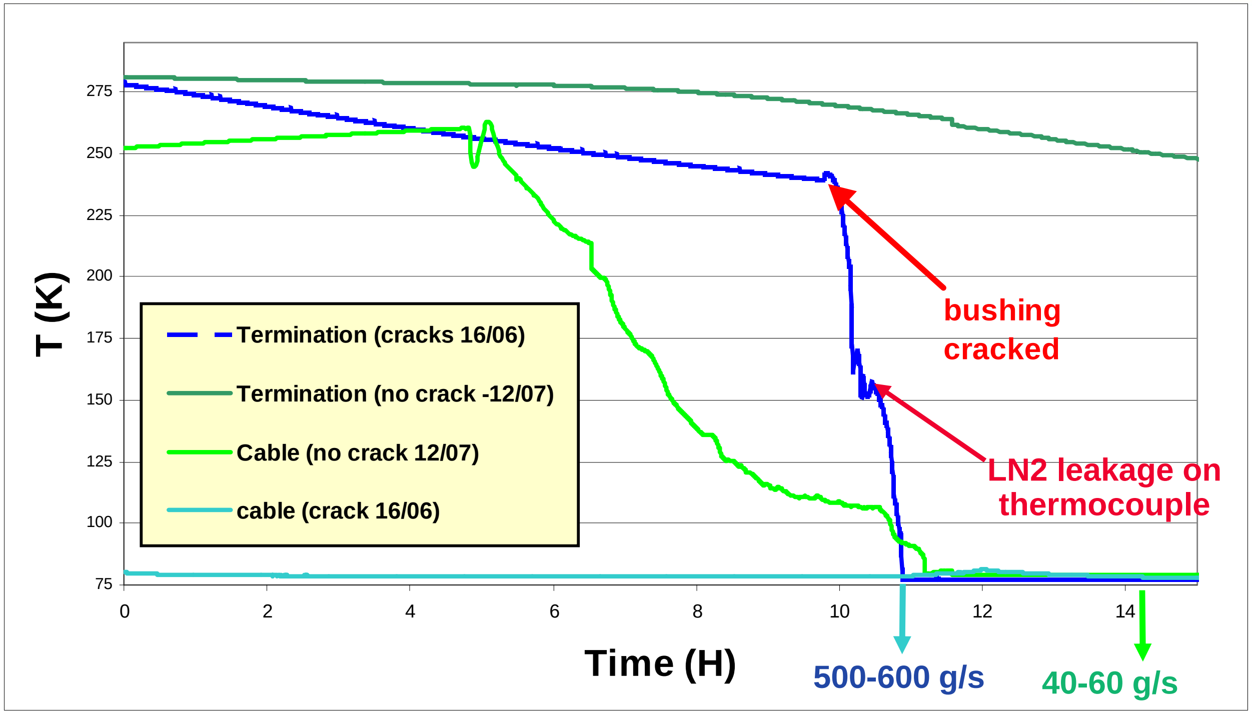
Test of assembled termination (loop)



Cooling rate twice more on bushing surface when crack observed

Cooling rate at conductor / insulating material is several times higher due to material thermal conductivity

Note: termination = T measured on bottom bushing outer surface (no LN2 contact – important insulating material thickness

Cooling rate leads to thermomechanical failure of the termination bushing

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Further Steps Defined for Cable Test

Next step: New complete installation in August and September 2005

- Slower cooling rate during the loop cooling down
  - ✓ Major parameter
- New bushing with updated shape to improve the thermal gradient
  - ✓ Increasing of safety factor with reducing thermal gradient & increasing mechanical resistance of bushing
- Including the new bushing / top cap connection (more flexible) to limit shrinkage stresses
  - ✓ Increasing of safety factor with increasing connection flexibility (facilitate shrinkage)

Further testing to finally verify cable system design and start cable manufacturing

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Site and Installation Status

Holbrook Area Transmission System

- Port Jefferson Power Station (*north*)
  - 2 ~ 138 kV wires
  - 2 ~ 69 kV wires
- Shoreham
  - 2 ~ 138 kV wires
- Spine ~ West
  - 2 ~ 138 kV wires
  - 3 ~ 69 kV wires
- Spine ~ East
  - 2 ~ 138 kV wires
  - 3 ~ 69 kV wires

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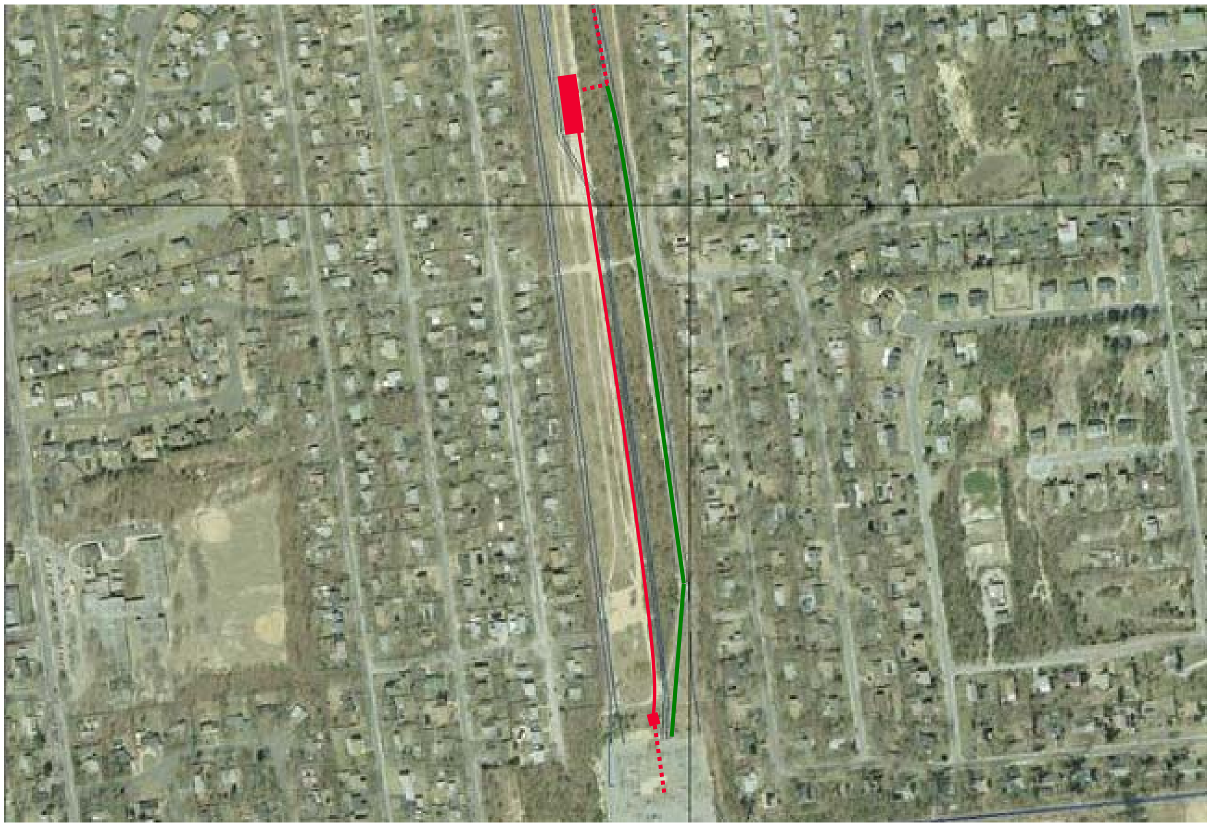
Holbrook Cable Location



- Underground di-electric cable from the 138 kV bus to the south termination
- South Termination
- 610 meters of superconducting cable in three separate conduits laid in a trench
- Northern termination located in switching station
- Switching station provides connection back to 138 kV overhead

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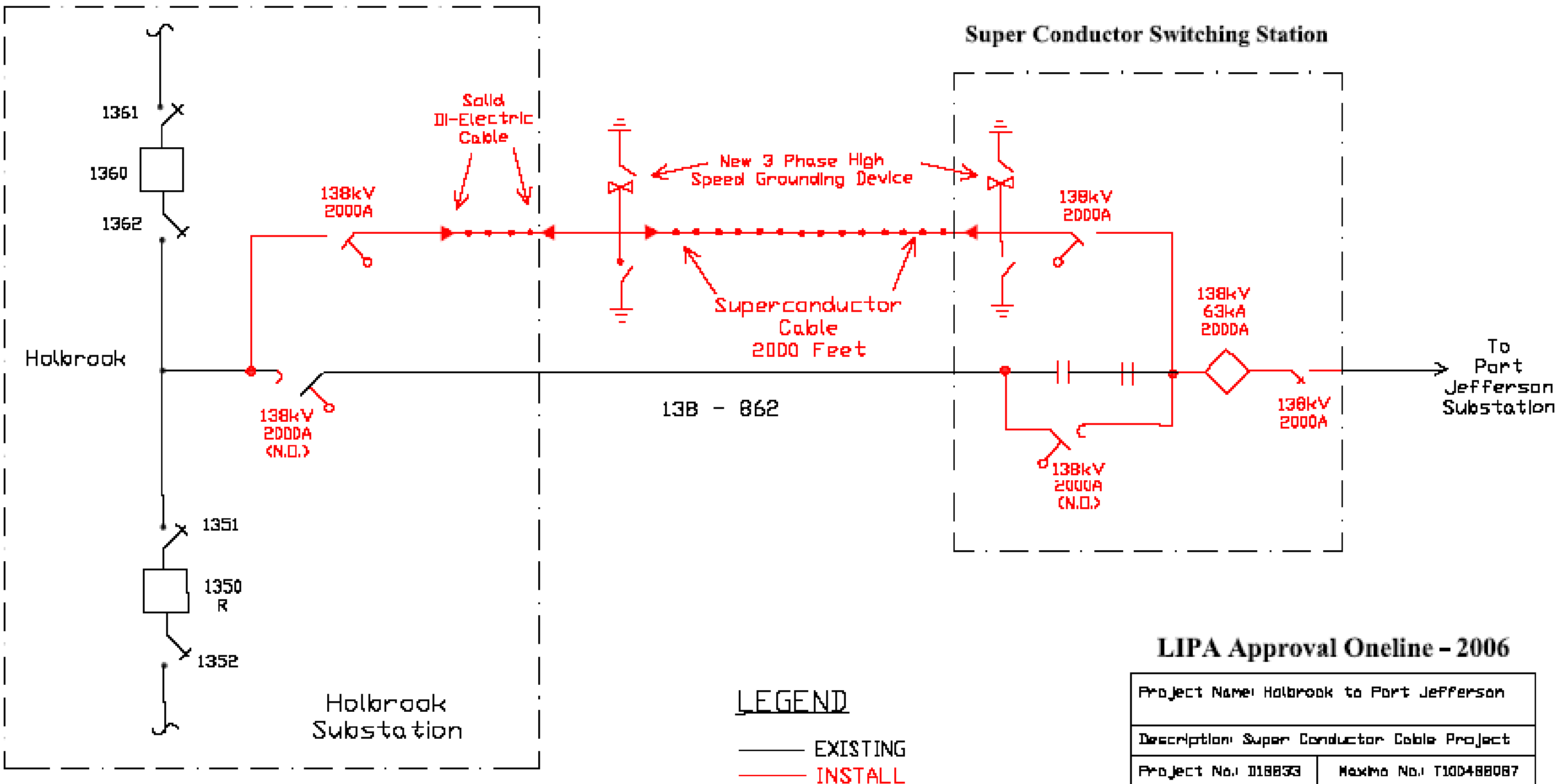
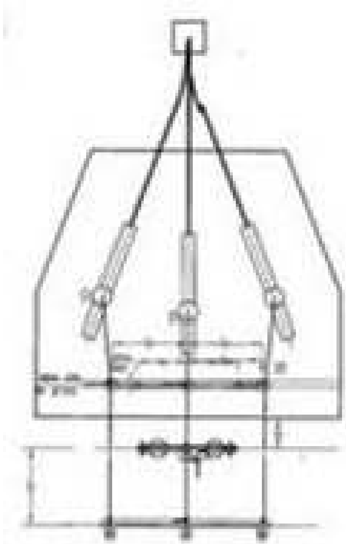
Superconductor System One-Line

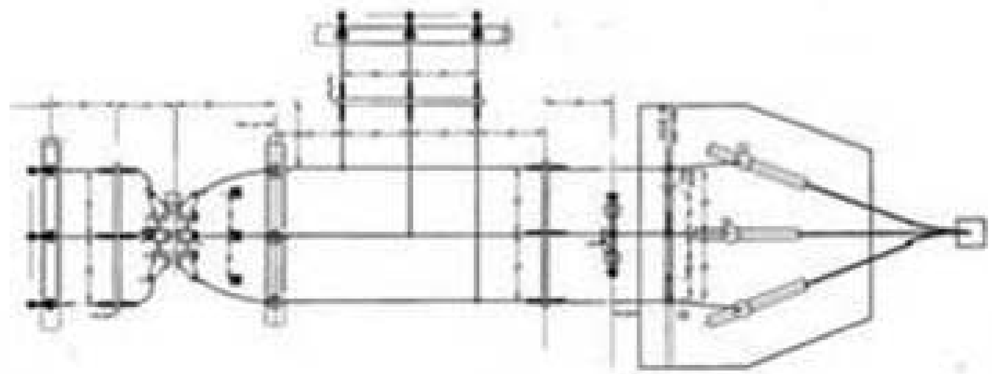


LIPA Approval Oneline – 2006

Project Name: Holbrook to Port Jefferson			
Description: Super Conductor Cable Project			
Project No.: 018833		Maximo No.: T100488087	
Rev.	Issued	Rev.	Issued
0	06-20-05		
1	07-07-05		

Switching Station & South Termination





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Refrigerator Status

Project Status-Refrigerator Subsystem, Air Liquide

- Refrigerator
  - Re-use of Detroit refrigerator from previous Pirelli SPI Cable Program
  - Upgrades to system are necessary to adapt it to LIPA project and will include:
    - Upgraded cooling capacity (+38%) for primary and back up systems
    - New system for the cable cool down
    - New buffer for fault reaction and recovery
    - Telemetry to allow remote monitoring and control
    - New 9 000 Gal tank for LN2 supply

  - Will be operated 6 months prior to cable commissioning

Refrigerator Upgrade

- Process study in order to minimize the modifications on the He cycle :
- Adjusting the HP, LP, flowrate has an impact on :
  - The modification of the turbines
  - The modification of the existing compressor
  - The new compressor

⇒ Optimized solution is : higher HP; higher flowrate; lower LP

⇒ Same power for existing compressor

⇒ increase the turbine speed of 2%

⇒Add a bigger new compressor (higher flowrate to compensate the lower LP)

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Refrigerator Upgrade

- He cycle
  - Turbines :no modifications
  - Primary compressor upgrade :
    - No change on existing compressor
    - addition of a bigger complementary helium compressor for capacity increase **New component**

  Back up cycle :
  - No modification, addition of a new module **New component**

- LN2 loop :
  - Buffer tanks : no modification, addition of a new buffer **New component**
  - BN pumps
    - no modifications if we stay in the range of 375g/s

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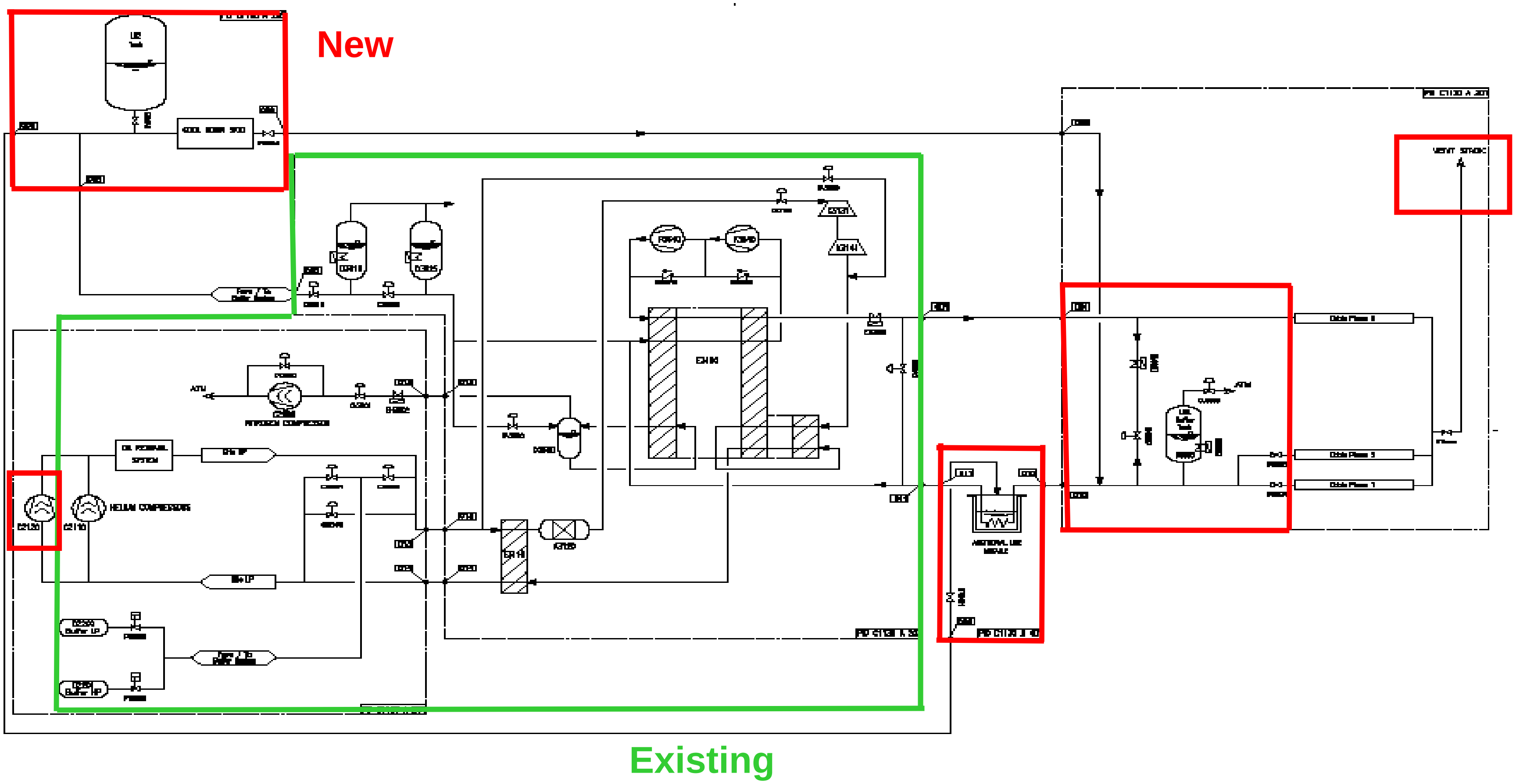
Upgrade and New Components



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Project Status-Refrigerator Subsystem, Air Liquide

- Refrigerator Status
  - Optimization of the new process (primary and back up) complete
  - Detailed definition of the new process lines complete
  - Preliminary lay out drawing complete
  - Definition of the new components in progress
  - Equipment specifications in progress
  - Final lay out in progress

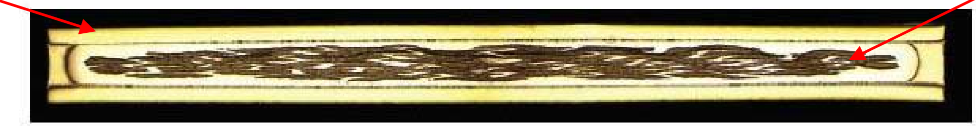
HTS Wire Status

AMSC HTS Hermetic Wire

Bismuth based, multi-filamentary high temperature superconductor wire encased in a silver matrix and laminated with brass to increase mechanical strength and provide a hermetic seal.

Brass Lamination

HTS Insert



Specifications:	
Average thickness:	0.36-0.44 mm
Minimum width:	4.0 mm
Maximum width:	4.45 mm
Min. double bend diameter (RT):	70 mm[i]
Max. Rated tensile stress (RT):	175 MPa[i]
Max. Rated wire tension (RT):	20 kg[i]
Max. Rated tensile stress (77K):	200 MPa[i, ii]
Max. Rated tensile strain (77K):	0.30%[i, ii]
Hermeticity	30 atm LN2 for 16 hours[iv]

Customer Options:	
Minimum amperage (Ic)	**Average engineering current density (Je)[iii]**
115 A[ii]	6,700 A/cm^2 [ii]
125 A[ii]	7,300 A/cm^2 [ii]
135 A[ii]	7,900 A/cm^2 [ii]
145 A[ii]	8,500 A/cm^2 [ii]
Continuous piece length	Up to 800 m
Insulation options	PTFE or Kapton wrap
Splice options	Spliced wire is available in longer lengths

[i] Greater than 95% Ic retention
[ii] 77K, self-field, 1μV/cm
[iii] Je is a calculated value based upon average thickness and width
[iv] Thickness inspection after pressurized LN2 test

Designed for use in applications where the wire is exposed to pressurized liquid cryogens

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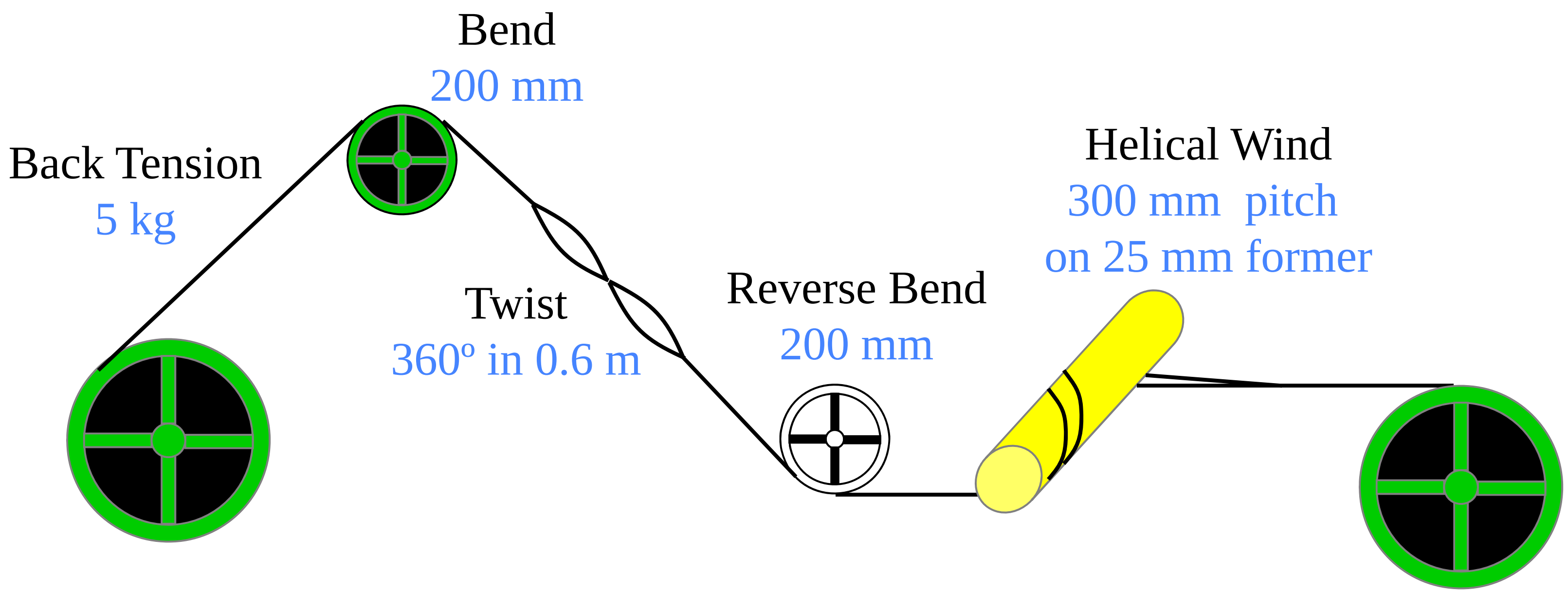
Reliability Testing: Mechanical Aging Test

Wire and splices designed to be hermetic and survive bending & twisting



Test parameters in blue

Tested to meet or exceed conditions of cable stranding processes

Wire Production Status

- Length Requirements:
  - 105 pieces x 680 meters each = 71,400 meters
  - 120 pieces x 700 meters each = 84,000 meters
  - Total production wire volume = 155,400 meters
- Status as of July 31, 2005
  - HTS *insert* wire manufacturing is 100% complete
  - Lamination and testing is in progress (~25% complete)
  - Finished wires will ship in September and October 2005

AMSC commercial HTS wire manufacturing meets large volume cable requirements

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Plans for GFY 06

Plans for GFY '06

- System Analysis
  - Complete fault and contingency studies
- Cable and Terminations
  - Complete qualification of termination for 161kV
  - Complete 30 meter cable system electrical qualification testing
  - Fabricate 610 meter cable
  - Fabricate 6 Terminations
- Refrigerator
  - Complete upgrade
  - Install at Holbrook site
  - Operate and qualify 3-6 months prior to cable install
- System
  - Install cable and terminations
  - Install data and control system and interconnects to SCADA
  - Prepare for energization

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Project Confidence Matrix

Parameter	Production Item				
	Factory/Site Tested	Sample Tested	Full Scale Type Test	Subscale Test	Analysis
Voltage Withstand					
Termination					
Operating					
Lightning Impulse					
Cable					
Operating					
Lightning Impulse					
Current Carrying Capacity					
Termination					
Cable					
Heat Loads					
Cable					
AC Losses					
Dielectric Losses					
Cryostat Losses					
Termination					
AC Losses					
Cryostat Losses					
Refrigerator					
Capacity					
Flow capacity/pressure					
Wire					
Critical Current					
Hermeticity					
splice resistance					
splice hermeticity					
splice integrity					
Pressure Drop					
Faults					
Major Fault response					
Thru-fault response					
Material Properties used in model					n/a
Installation Methods					
Cable					
Termination					

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Demonstration of a Pre-Commercial Long-Length HTS Cable System Operation in the Power Transmission Network

DOE Peer Review Update
July, 2006
Arlington, VA

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Agenda

• Introduction	Jim Maguire, AMSC
• Project Overview	Jim Maguire, AMSC
• FY 2006 Results and Performance	Jim Maguire, AMSC
- System Design for LIPA Utility Grid Operation	
- System Contingency Planning	
- Program Status	
• Wire	Jim Maguire, AMSC
• Cable and Terminations	Frank Schmidt, Nexans
• Refrigerator	Shawn Bratt, Air Liquide
• Site/Installation	Tom Welsh, LIPA
• FY 2007 Plans	Jim Maguire, AMSC

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Project Overview

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LIPA Project Overview

- Long Island Power Authority – Holbrook Substation
- Electrical Characteristics
  - Design Voltage/Current – 138kV/2400A ~ 574MVA
  - Design Fault Current – 51,000A @ 12 line cycles (200ms)
- Physical Characteristics
  - Length ~ 600m
  - HTS Conductor Length ~155km
  - Cold Dielectric Design
- Hardware Deliverables
  - Three ~600 m Long Phase Conductors
  - Six 138kV Outdoor Terminations
  - One 138kV Splice (Laboratory Test)
    - No splices for grid installation required
  - One Refrigeration System + Laboratory Pulse Tube System
- Installation/Commissioning – Spring 2007

World's First Installation of a Transmission Voltage HTS Cable

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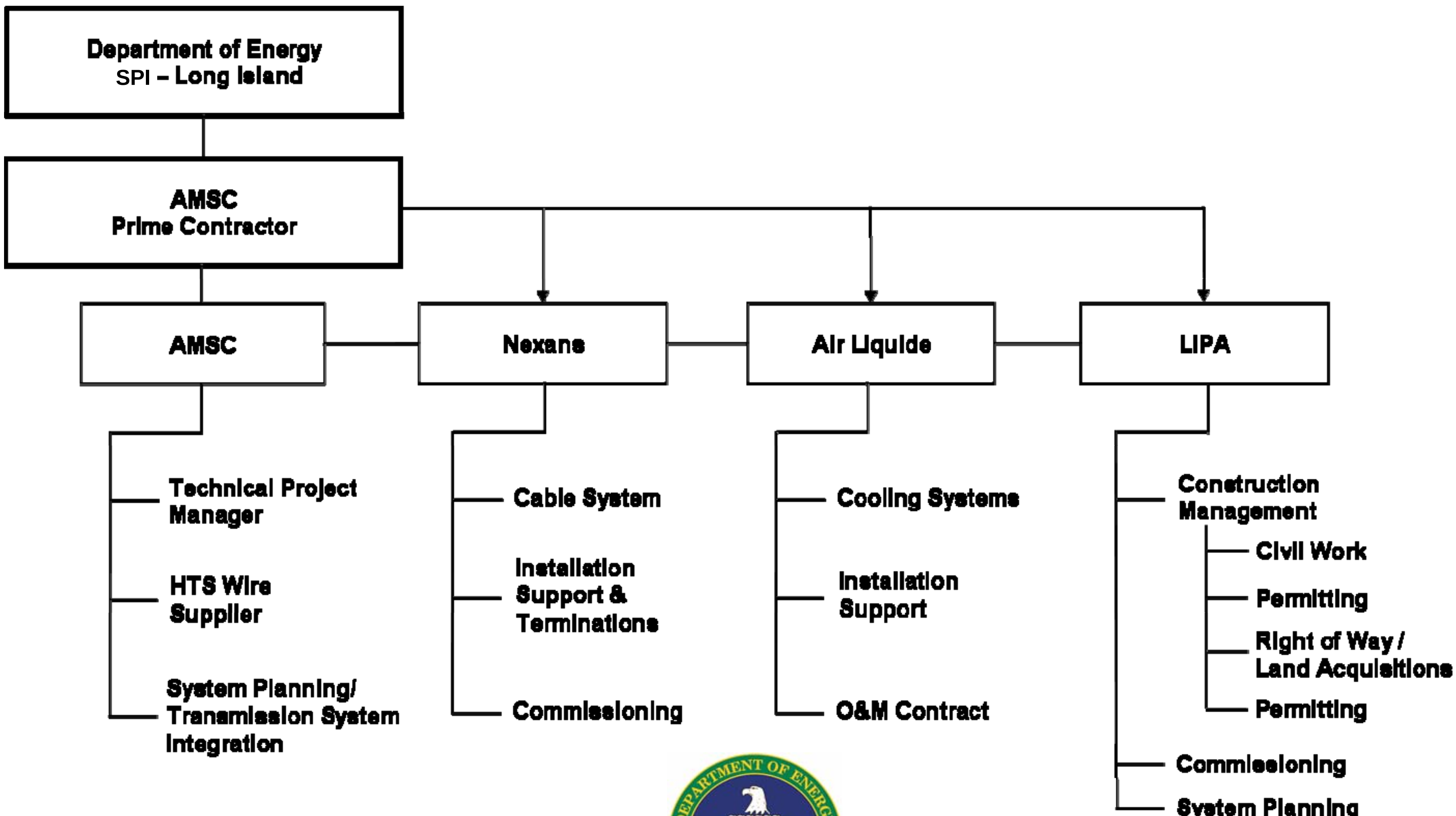
LIPA Cable Project and Project Team



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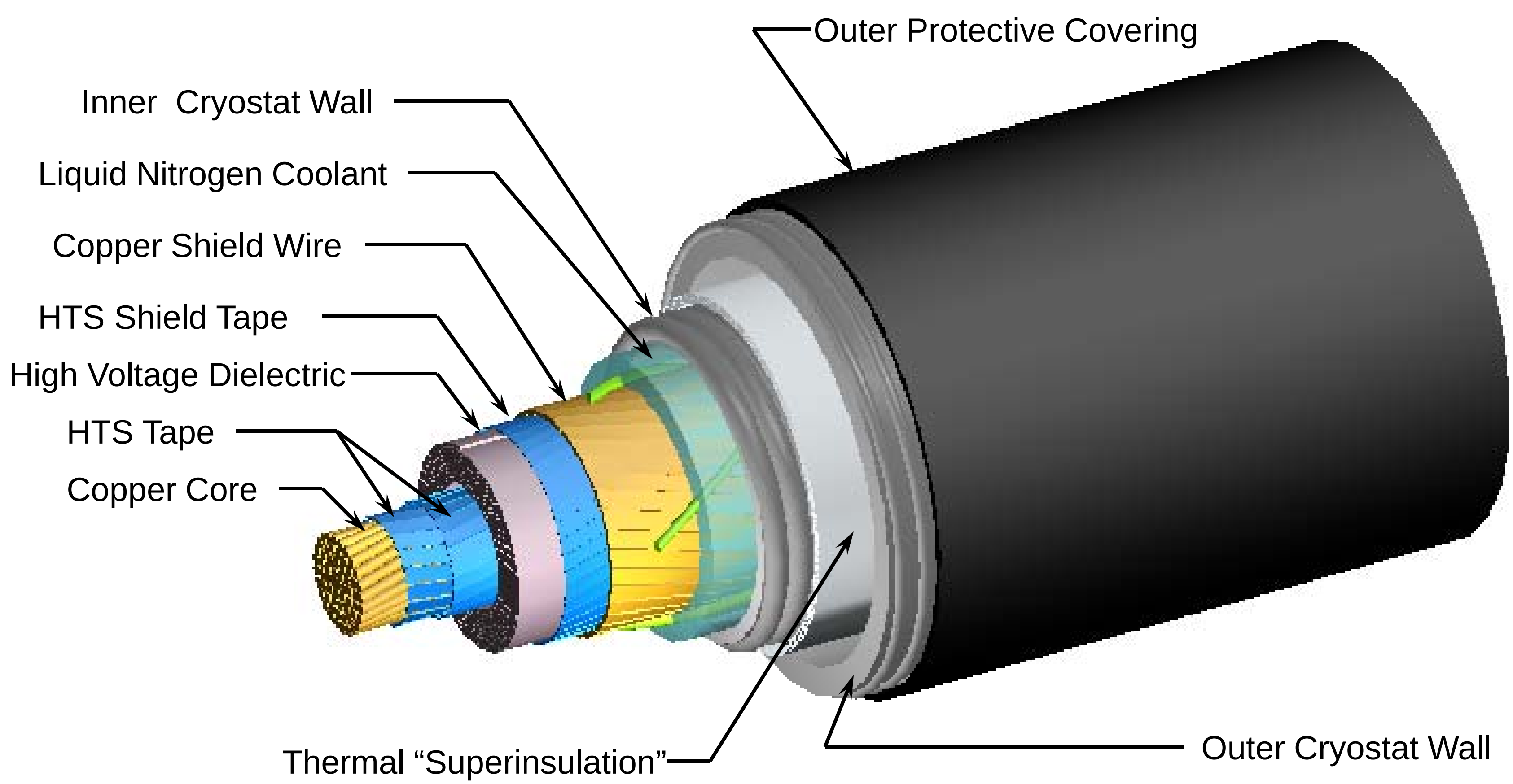
Typical Cable Cross Section



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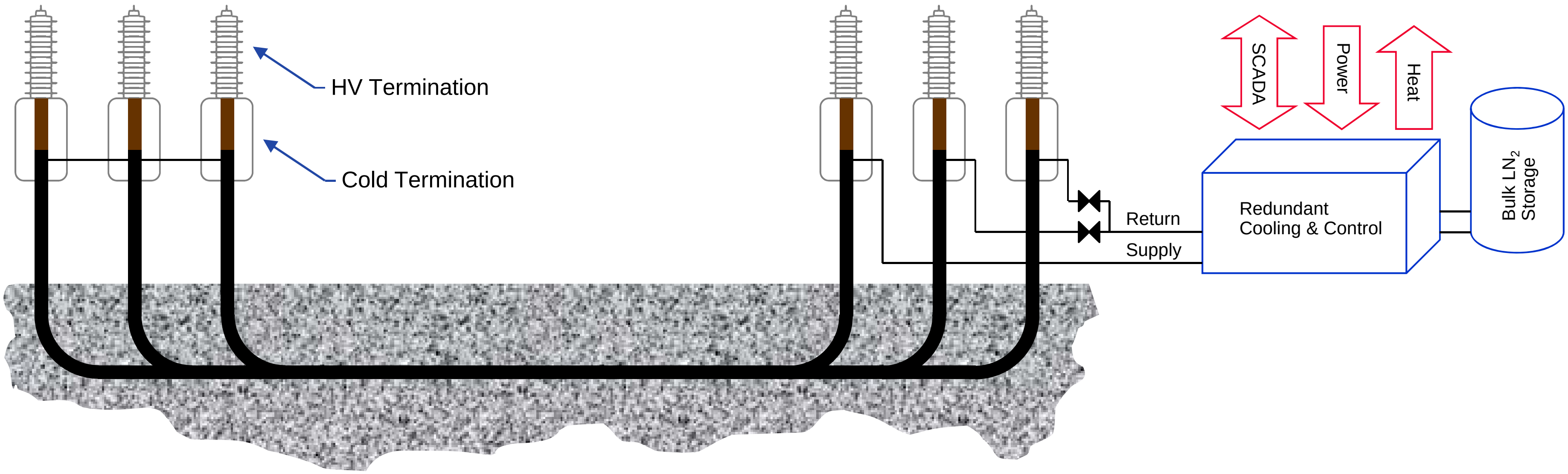
LIPA HTS Cable System



System Design for LIPA Utility Grid Operation

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System Design Philosophy

- The LIPA Cable Project Team Has Taken the View That the Cable System Design Must Be Driven by the Operational Requirements of the LIPA Transmission System.
- Operating Modes:
  - Pre-operation Cool Down (Not Included)
  - Normal Operation
    - Steady State Operation
    - System Fault Tolerance
    - Contingency Operation
  - Post-operation Warm-up (Not Included)

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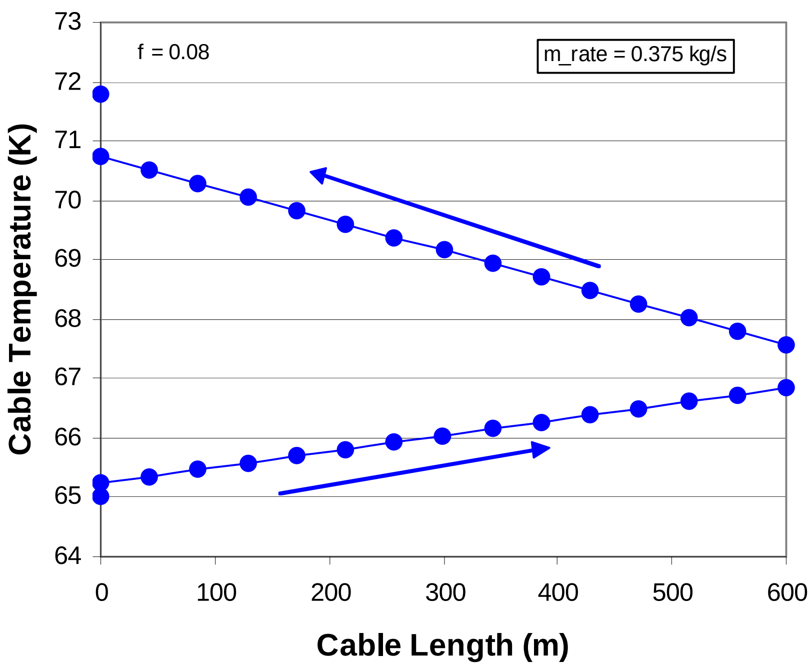
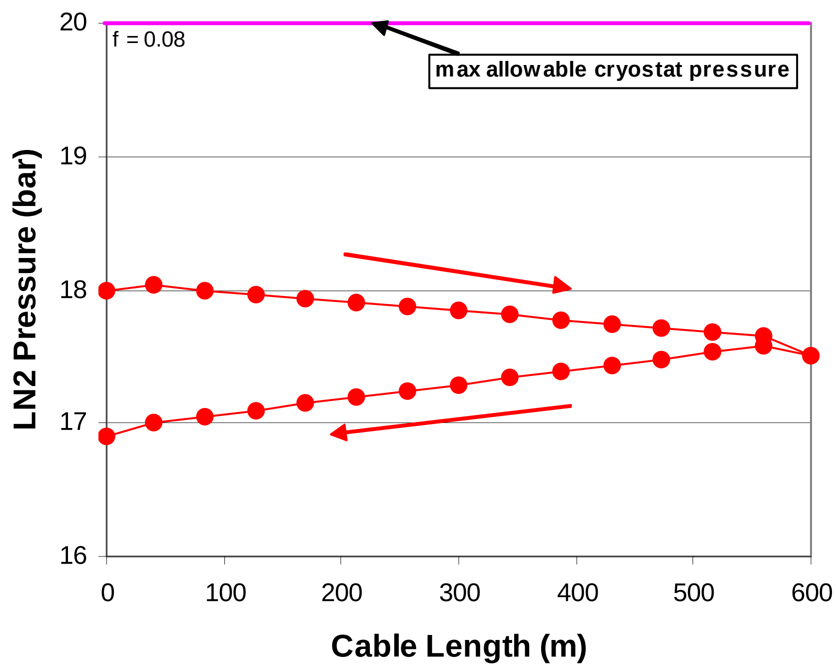
Steady State Operation





- Maximum Conductor Temperature < 72 K
- Total Pressure Drop < 1.5 bar
- Total Refrigeration Required: 5,600 Watts

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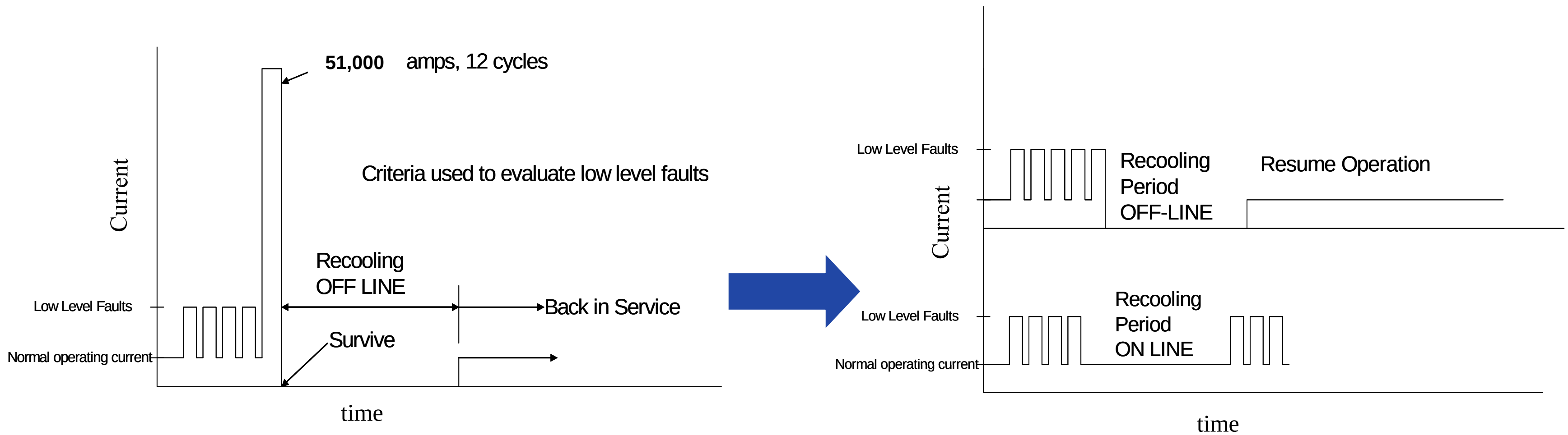
Fault Scenarios

- The Cable System Must Always Be Able to Withstand a Major Fault Without Damage, Even After Sustaining Multiple Through Fault Events Prior to the Major Fault Event
- In Cases Where Many Through Faults Occur Within a Short Time Period, the Protection System Needs to Remove the Cable From Service for a Brief Period to Maintain the Ability to Survive a Major Fault.



Impedance relay protection systems not adequate for HTS transmission cables

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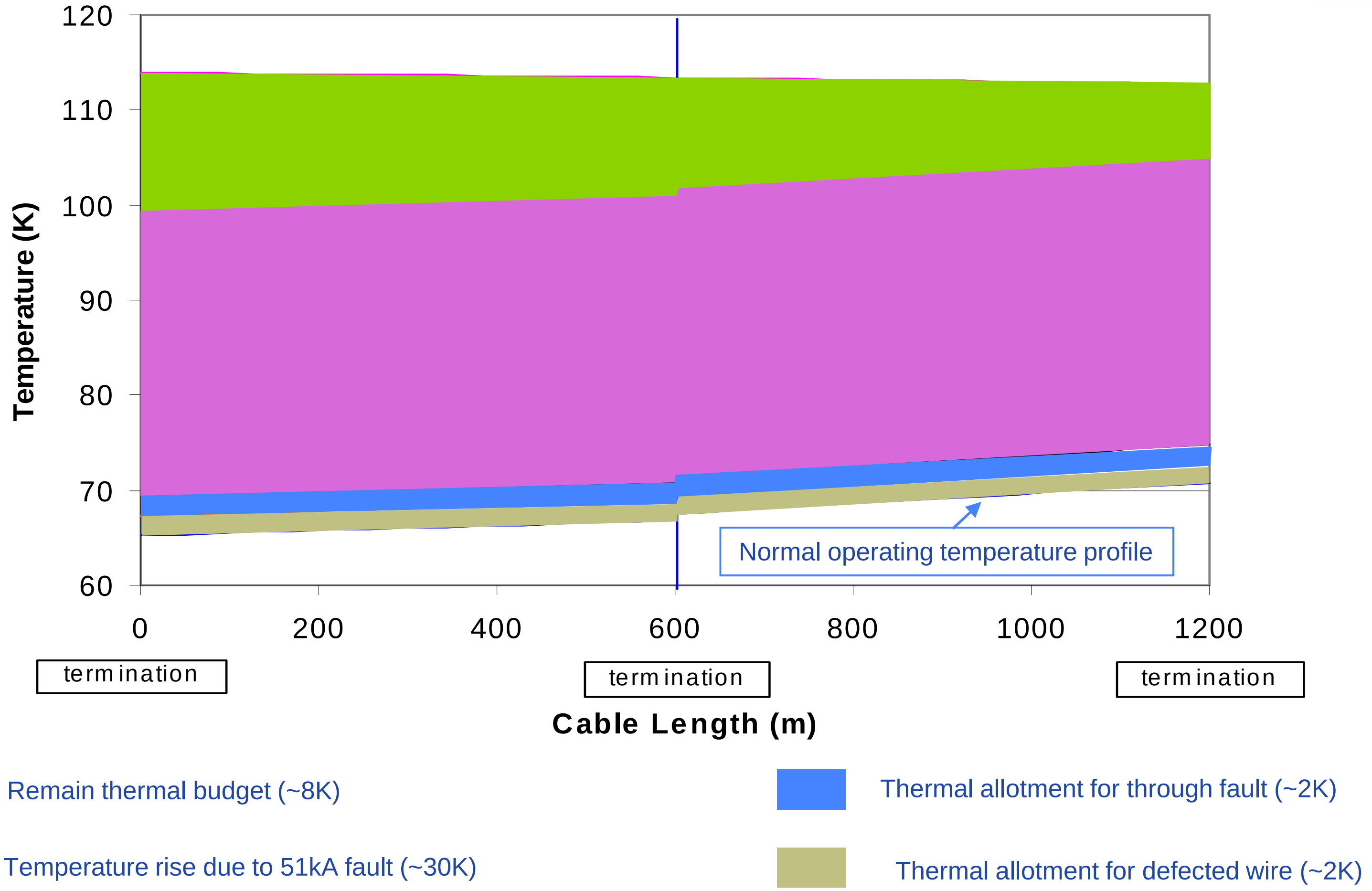
LIPA Cable Thermal Budget



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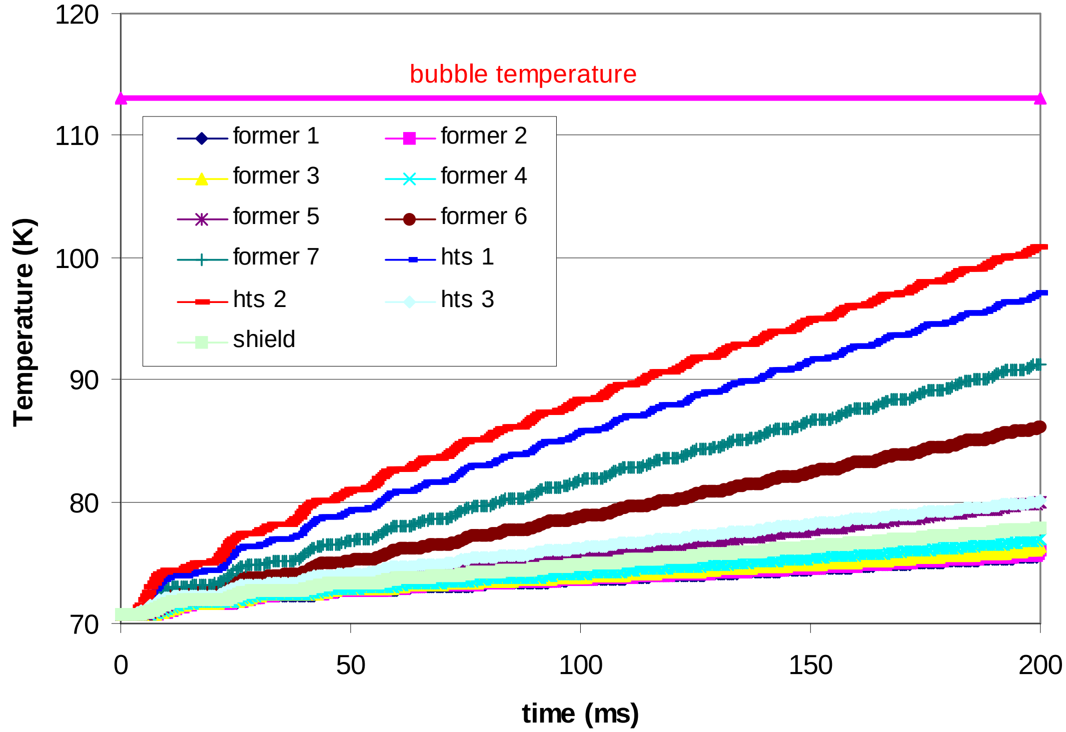
Thermal Behavior of Major Fault: 51kA



- Total Dissipated Energy (3 phase): 24MJ
- Temperature Rise Based On Adiabatic Model (Worst Scenario)
- Temperature Margin with Through Fault and Wire Defect: ~8K

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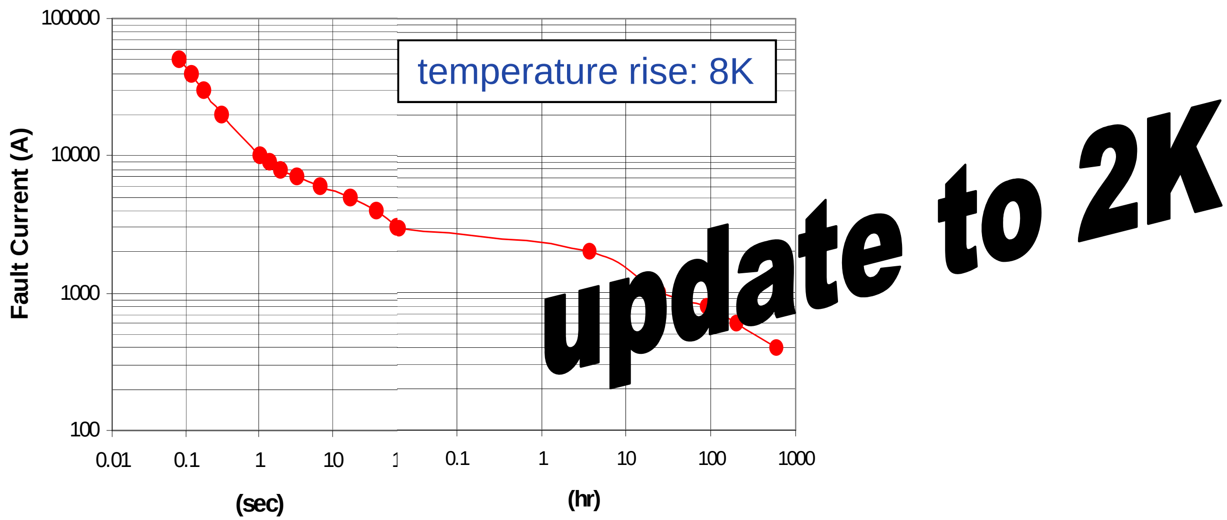
I-T Curve of Through Faults for 51kA



LIPA Holbrook Substation Fault Condition

138 kV Substation	Amps in Cable	Clearinging Time	Design	Remain on Line (Single Fault)
Holbrook	51000	12 cycles	√	Off Line
Port Jefferson	9500	12 cycles	√	On Line
Holtsville GT	3700	0.48 sec	√	On Line
Ronkonkoma	3100	12 cycles	√	On Line
Miller Place	1100	0.75 sec	√	On Line
Wading River	1200	0.75 sec	√	On Line
Caithness	2000	N/A	√	On Line
Brookhaven	1500	0.90 sec	√	On Line
Brentwood	1300	N/A	√	On Line
Ruland Road	1200	12 cycles	√	On Line

Thermal Hydraulic Issues in CD Cable

- Over Pressure Scenarios
  - Cryostat Vacuum Break-Down
    - 900 kg/phase LN2
    - Design Cryostat Pressure: 20 bara
    - Heat Load ~165 time Higher (Based on CGA- S-1.3-200)
  - Voltage Break-Down Inside Termination
    - 500 kg/termination LN2
    - Tremendous Energy Dumped Into LN2 in Very Short Time (200 ms)

System will react in a controlled manner in the event of all foreseen contingencies

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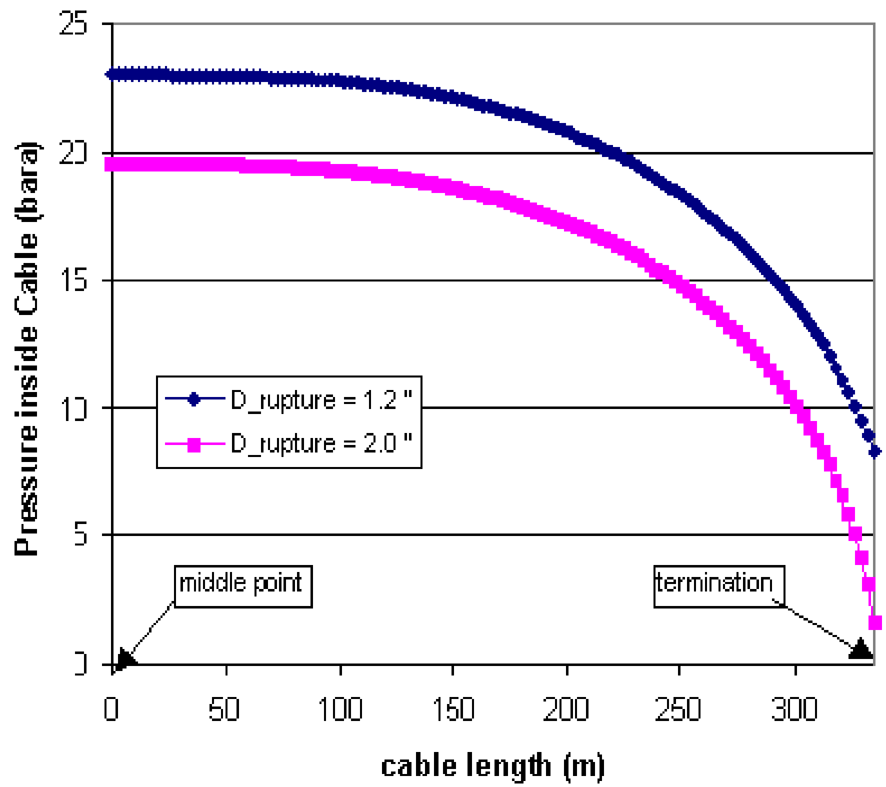
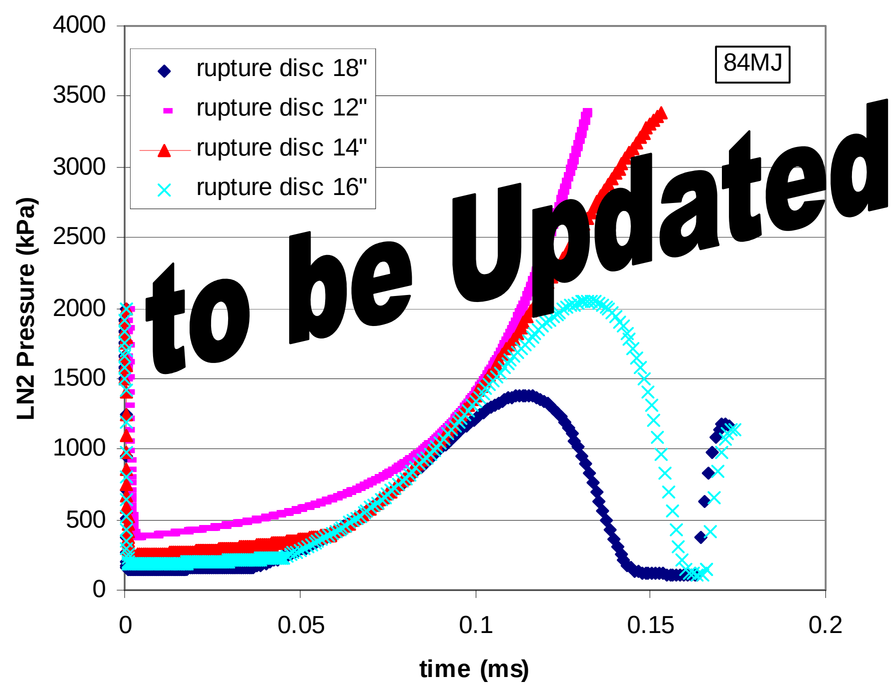
Loss of Cable Vacuum Insulation

- Maximum Pressure
  - Middle of Cable
- Flow Rate to Be Evacuated
  - 2681 kg/h
- Rupture Disk Size
  - 2”

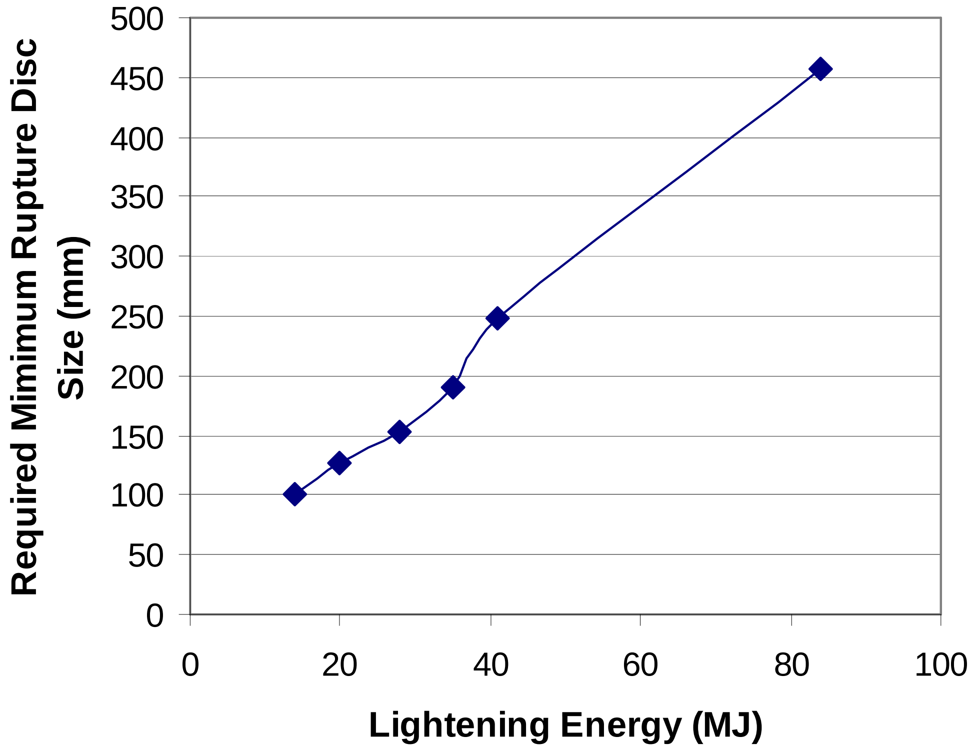


Thermal Hydraulic Model of Termination

- Voltage Break Down Inside Termination
- Assumption
  - Energy Absorbed Only by N2
  - Uniform Pressure Inside Termination
  - Termination Envelope Is Rigid
  - Initial State: 15 bara 67K
- Relieving Process of Different Rupture Disc Size involves Different Nitrogen States



Burst Disc Size vs. Break Down Energy

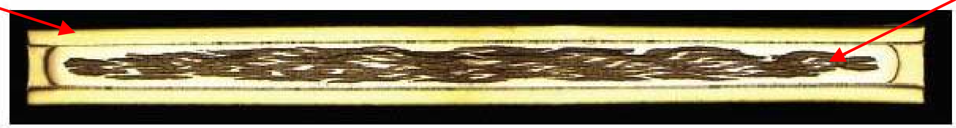


Burst Disc Design for Termination Can Withstand Breakdown Energy of 40 MJ

HTS Wire Status

AMSC HTS Hermetic Wire

Bismuth based, multi-filamentary high temperature superconductor wire encased in a silver matrix and laminated with brass to increase mechanical strength and provide a hermetic seal.



Specifications:

Average thickness:	0.36-0.44 mm
Minimum width:	4.0 mm
Maximum width:	4.45 mm
Min. double bend diameter (RT):	70 mm[i]
Max. Rated tensile stress (RT):	175 MPa[i]
Max. Rated wire tension (RT):	20 kg[i]
Max. Rated tensile stress (77K):	200 MPa[i, ii]
Max. Rated tensile strain (77K):	0.30%[i, ii]
Hermeticity	30 atm LN2 for 16 hours[iv]

Customer Options:

Minimum amperage (Ic)	Average engineering current density (Je)[iii]
115 A[ii]	6,700 A/cm^2 [ii]
125 A[ii]	7,300 A/cm^2 [ii]
135 A[ii]	7,900 A/cm^2 [ii]
145 A[ii]	8,500 A/cm^2 [ii]
Continuous piece length	Up to 800 m
Insulation options	PTFE or Kapton wrap
Splice options	Spliced wire is available in longer lengths

[i] Greater than 95% Ic retention
[ii] 77K, self-field, 1μV/cm
[iii] Je is a calculated value based upon average thickness and width
[iv] Thickness inspection after pressurized LN2 test

Designed for use in applications where the wire is exposed to pressurized liquid cryogens

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Wire Production Status

- Length Requirements:
  - 105 pieces x 680 meters each = 71,400 meters
  - 120 pieces x 700 meters each = 84,000 meters
  - Total production wire volume = 155,400 meters
- Status as of Today
  - All wires delivered to factory

AMSC commercial HTS wire manufacturing meets large volume cable requirements

Cable and Termination Status

Components of an HTS Cable System

- Superconducting Cable System
  - Cable Core
    - Cable Conductor
    - Dielectric
    - Shield
  - Cryostat
  - Termination

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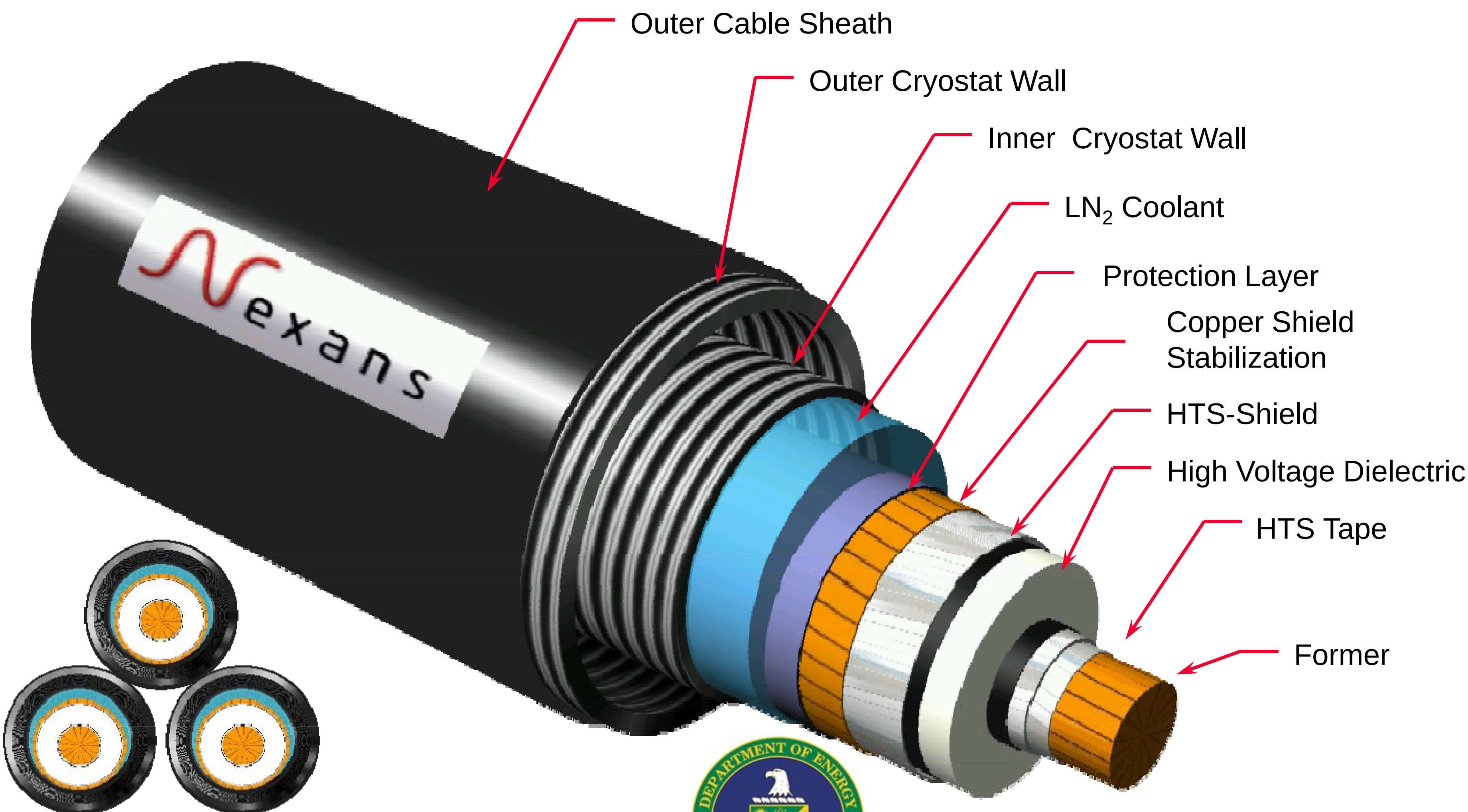
LIPA HTS Cable Concept



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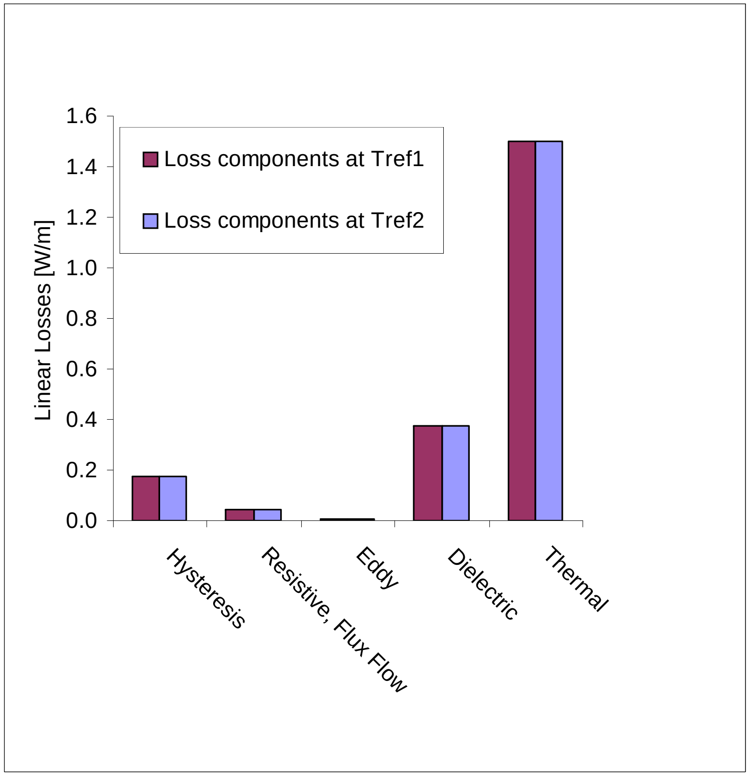
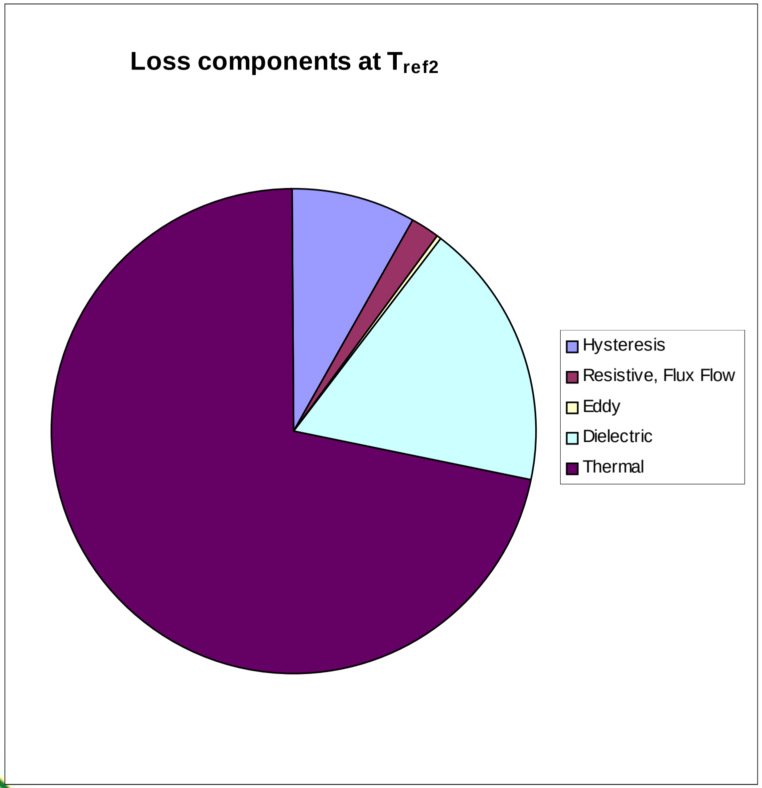
Cable – Calculated losses

Cable Power	MVA	220
Cable Current	Arms	920
Cable Temperatures Tref1	K	65
Cable Temperatures Tref2	K	72





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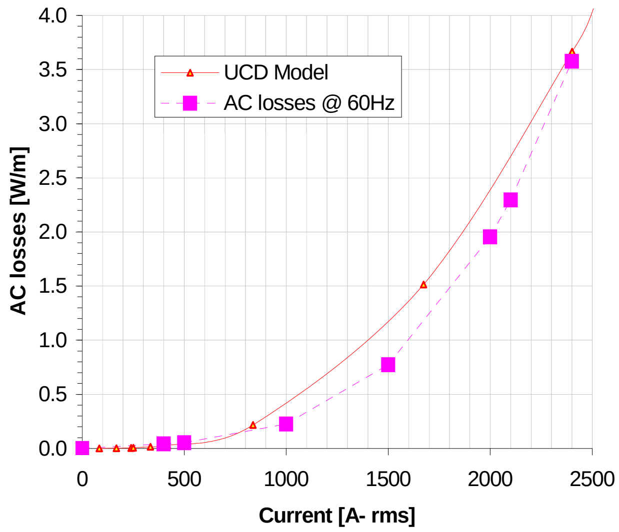
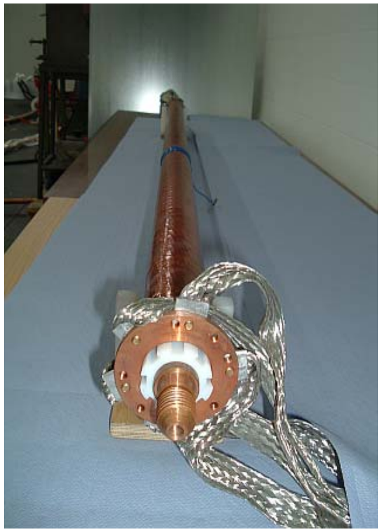
Cable – AC losses measurement / short samples





- Measurement of AC-losses to confirm the cable design was done on 2 meter samples by means of electrical measurement

- The AC losses are confirmed:
- 0.04 W/m (400 A @60Hz)
- 0.25 W/m (1000 A @60Hz)
- 3.6 W/m (2400 A @60Hz)

Measurements done validate the calculation and cable design

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Cable – Thermal Contraction Solution

- Cable thermal shrinkage of app. 0.3% is expected
  - The contraction is managed in the termination by a compensation element (1.2 m at each end) requiring motion of the cable core inside the cryostat

    → Termination is adapted to manage the contraction taking into account forces and displacement
  - The equal distribution of the motion between the two ends is achieved by a friction point in the middle of the cable

    → Implemented in the cable route on site
  - The friction forces between the cable core and cryostat need to be taken into account in the design

    → Forces were measured on a 40 meter sample and the outermost core layer was adapted to ensure the correct friction and prevent cable damage

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Cable: Manufacturing Process

- Cable manufacturing on existing machines
  - Adaptation of machine parts to address specific needs of HTS wire material
  - Qualification of manufacturing process under industrial conditions for long length HTS cables
    - Manufacturing of Dummy cables using Copper wire as HTS replacement
- Process verification done through
  - Superconducting tape stranding
    - Measurement of Ic and n-value to validate process
  - High voltage dielectric
    - Dry bending tests on lapped dielectric to ensure mechanical integrity of the high voltage insulation
    - Dielectric testing on cable samples
  - Cryostat manufacturing
    - Manufacturing trial using dummy cable

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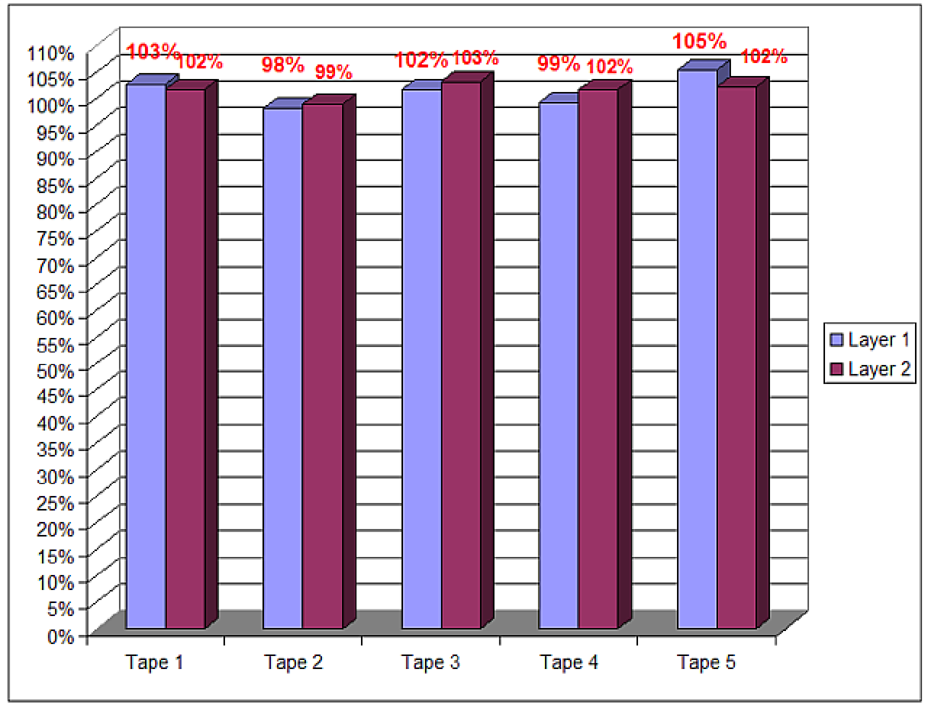
Cable Manufacturing Process - Results

- Superconductor Tape Stranding
  - Requirement: 95 % of original Ic
  - Result: no degradation in any tape after manufacturing and additional bending (>98 %)
  - Validated on three different cables
- High Voltage Dielectric
  - Requirement: no degradation of insulating paper after large number of dry bends
  - Result: Dielectric layers in very good shape after excessive bending test
- Cryostat Manufacturing
  - Requirement: no damage of cable due to welding of stainless steel tube
  - Result: cable didn´t show any damage on sensitive outer layer



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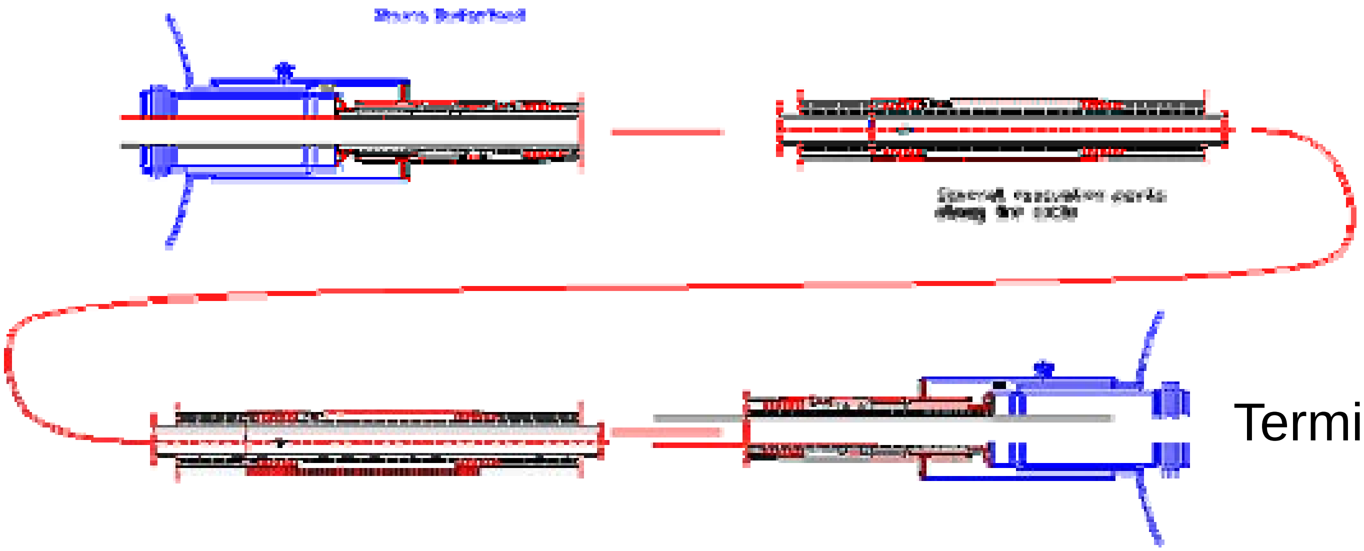
Cable Cryostat: Description

1. Corrugated Inner Pipe
2. Spacer
3. Vacuum Space
4. Multi Layer Super Insulation
5. Corrugated outer pipe
6. PE jacketing

Cable Cryostat: Design

Termination

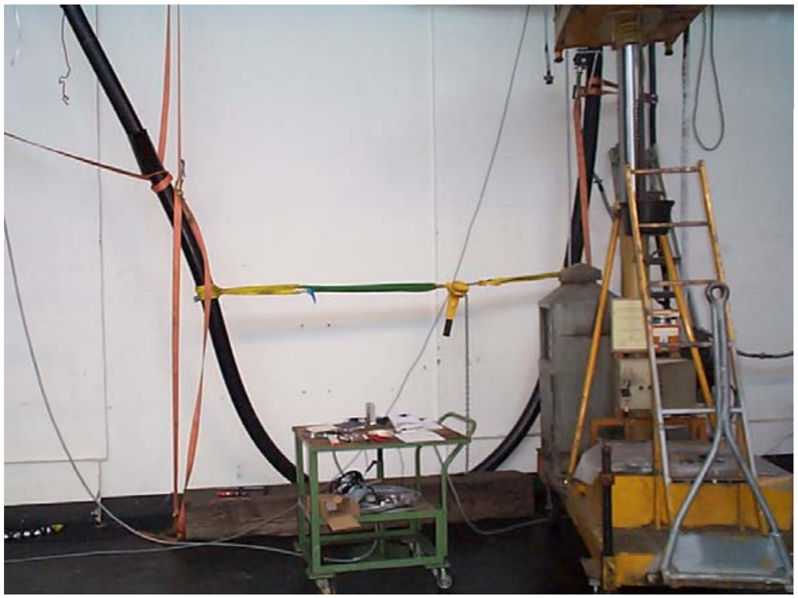
Additional evacuation ports along the cable



Termination

- For long term vacuum insulation several evacuation ports along the cable are required.
- Cable cryostat is equipped with pressure relief devices and vacuum monitoring ports

Cable Cryostat: Heat loss measurement with evaporating LN2



- 10 meter long cryostat heat loss measurement
- Measurement of LN2 evaporating rate
- Measurement various radial load conditions
- Measurement under various vacuum conditions
- Further reduction of the heat load for the final cryostat design was achieved

Confirmed heat load for the Lipa cable cryostat : 1,5 W/m

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ASME Code applied on superconducting cable

- ASME B31.5 Refrigeration Piping and Heat Transfer Components applicable to SC-cables
- Longitudinal welding tested at tube and cable
- 5% of circumferential welds tested
- Cable installation tested with 110% design pressure (pneumatic test)
- Proof test according to Section VIII-Division1, UG101

Review or Modification Needed

The superconducting cable meets the ASME code requirements

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Termination overview
Main characteristics of the terminations (1)

Physical description

- Length: 6.7 m
- Height: 4.2 m
- Weight: ≈ 4 tons
- Net capacity: ≈ 600 liters of LN_2

- Operating voltage: 161 kV AC
- Operating current: 2400A

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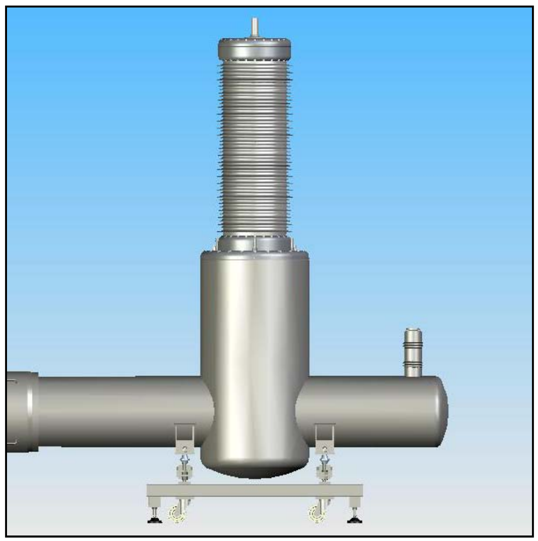
Termination overview

Main characteristics of the terminations (2)

- Horizontal part:
  - Connection of the HTS cable
  - Management of cable thermal shrinkage (> 1m)



- Vertical part:
  - Thermal gradient 300 K-77K management with a specific bushing
  - High voltage management for network connection

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Termination: Development method

- **<u>Test & measurements of components material properties:</u>**
  - Especially for the 300K- 77K transition ⇨ Bushing
  - Thermal properties and evolution with cryogenic temperature were studied
  - Influence of cryogenic temperature on material Electrical properties (dielectric strength…)
  - Compatibility between two materials interface (differential shrinkage)
- **<u>Test of components prototypes</u>**
  - AC resistance measurements on resistive parts at cryogenic conditions
  - Thermo-mechanical tests of single components
  - High Voltage tests (AC-withstand & lightning impulse) on partial assembling of the termination
- **<u>Validation of fully assembled components:</u>**
  - Complete assembling tests of the termination with cable connection
  - Thermo-mechanical tests on assembled components
  - High voltage tests on the complete loop (termination + HTS cable)

To be Updated less words

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Termination: Material Selection

- Shrinkage measurements of bushing materials properties from 300 to 77 K was done confirming design value
- Dielectric strength measurement of bushing insulating material sample at 300 & 77 K
  - In accordance with Electrostatic calculation requirements with good margin
- Mechanical measurements (tensile test) of bushing materials properties at 300 & 77K (samples)
  - Break elongation and ultimate tensile stress measurements
  - Results at cryogenic conditions combined with shrinkage measurements confirms the bushing material compatibility
    - No mechanical overload (stresses or elongation) in cold conditions
  - Compatibility valid considering static mode (cooling down achieved)
    - Conductive & insulating material have far different thermal conductivities which can have a strong influence in transient mode (during cooling down)

To be Updated less words

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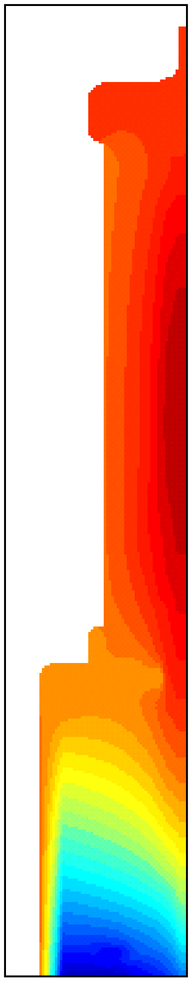
Termination: Thermal Design

Design optimization with thermal calculations



- In different working conditions:
  - No current / rated current phase 1 / full current (2400 A)
  - Extreme ambient temperature (standard, summer & winter conditions)
  - Total heat flux in LN2 < 300 W @ Tamb = 313 K ; I =2400 A
- Study of materials with different thermal behavior
- Study of termination dimensions & components shapes

Optimal thermal distribution = Best compromise between:

✓ Temperature compatible with HV components in outdoor sealing end
✓ Minimum heat flux in liquid nitrogen
✓ No hot spot in bushing with full current load
✓ Minimum vertical part height
✓ Material compatible with cryogenic temperature at the cold end (contact with LN2)

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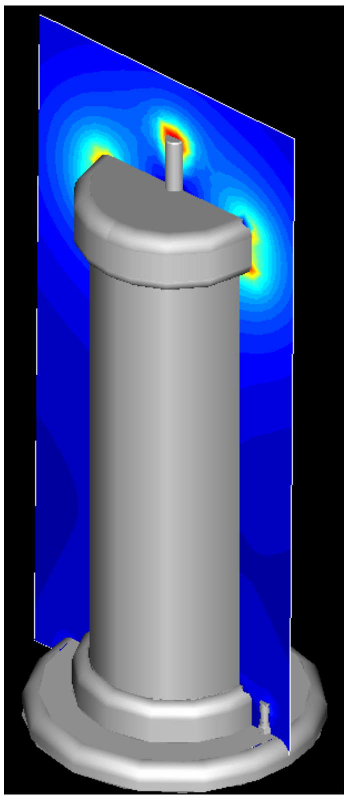
Termination: High Voltage Design

Design optimization with electrostatic calculations



- **For the vertical part:**
  - Optimization of the E field deflection before the HTS cable / bushing connection (bottom of the bushing)
  - Optimization of the E field deflection before the connection to HV network (top of the bushing)
  - Check of the E field for different possible bushing designs
- **For the horizontal part**
  - Optimization of the E field deflection on the connection area between HTS cable and bushing

Best compromise between:

✓ Material electrical properties (no risk of breakdown)

✓ Compatibility of the HV components materials with temperature distribution

✓ High Voltage accessories position and geometry

✓ Termination dimensions for High Voltage considerations in accordance with thermal design optimization (creepage path…)

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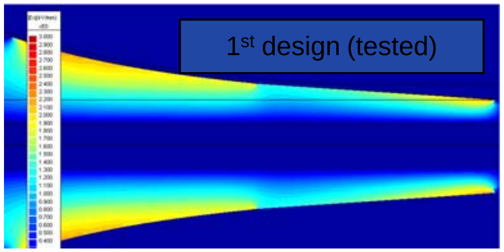
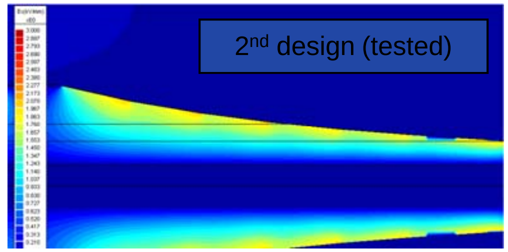
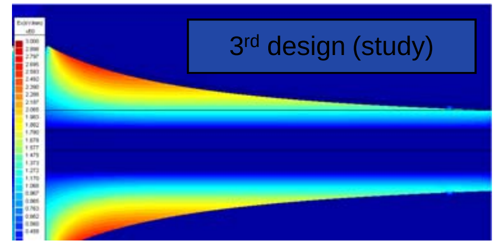
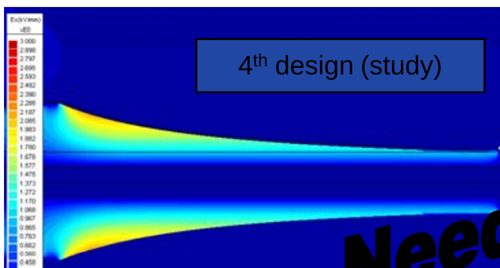
Termination: E field distribution – Condensor cone



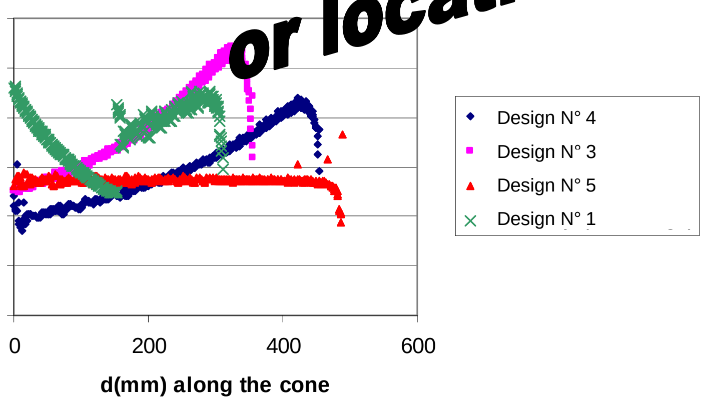






Needs an introduction or location on drawing

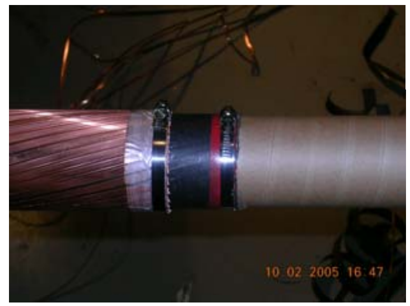
Comparison of E field along the cone



Constant low value of E-field along the cone for the final design

Cable System Complete Assembly

- *Different complete assemblies have been achieved with different cable prototypes*
- *Cable and Termination full scale testing was achieved*
- *Optimization in different areas was done*



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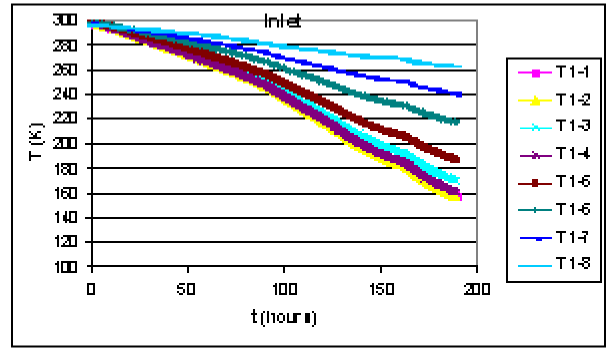
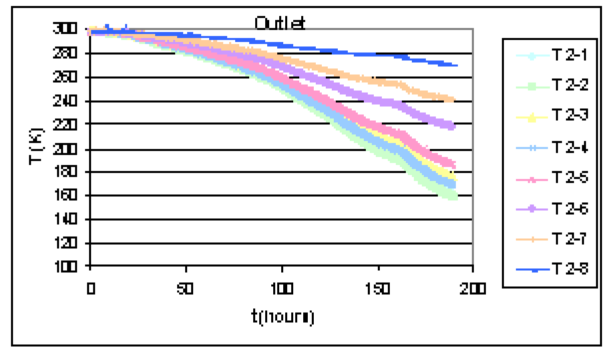
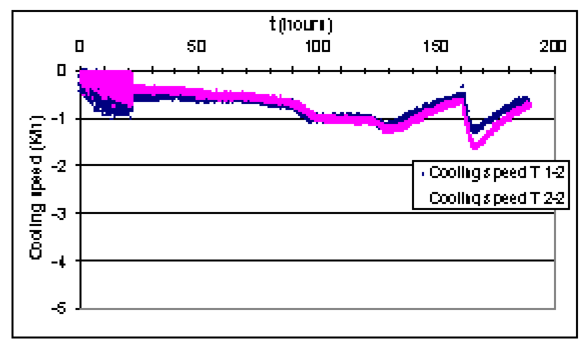
Cable System Cool Down Method

- As the cable system cool down has been proved to be important a process was established based on temperature measurements in specific areas of the cable system during cool down phase
- Limitation of cooling speed has been achieved
- Fully automated cool down was achieved and good results obtained







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Cable and Termination Electrical Testing

- Cable and Termination was type tested to a test requirement that was discussed and agreed to by the Team and the DOE Review Panel
- Cable type tests – completed prior to cable manufacturing
  - Ic- and n-value measurement
  - Power frequency voltage test – 190 kV 30 min
  - Partial discharge measurement in acc. To IEC 60840
  - Measurement of tan d and capacitance
  - Lightning impulse voltage test – 650 kV ±10 shots
  - Power frequency voltage test after lightning impulse voltage – 190 kV 15 min

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Cable and Termination Electrical Testing

- Termination type tests in addition to cable type tests
- Load cycle test
  - Cycles of 8 hours 100% rated current followed by 16 h of n… current, contin… voltage of 2* U0
  - Minimum of 10 complete cycles required prior to release of termination manufacturing

Check completeness of load cycles - show data

Cable and Termination fully qualified regarding the electrical testing

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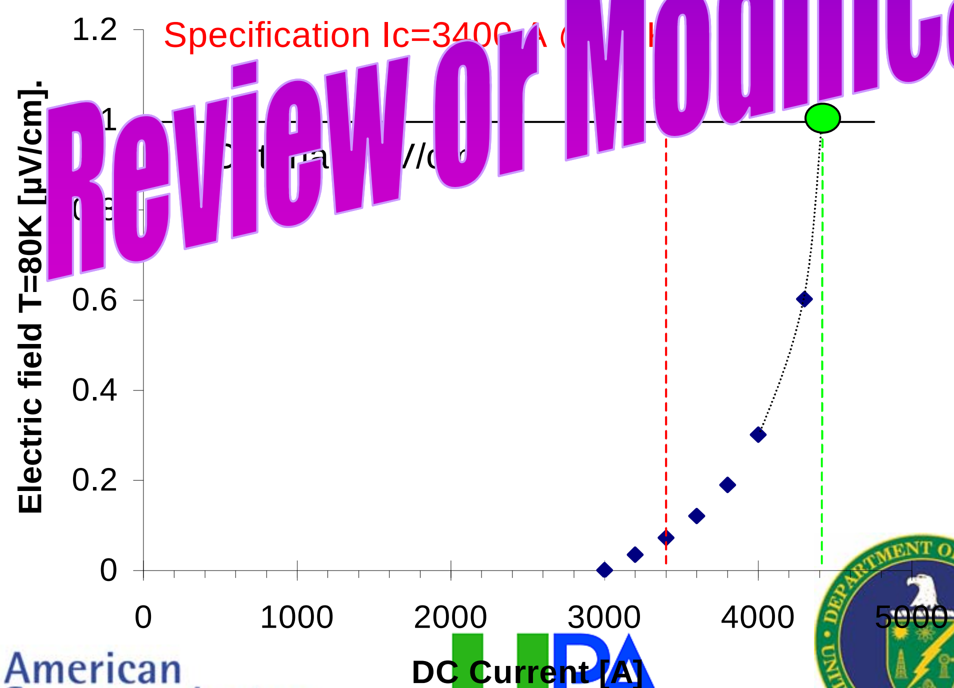
Prototype 1 (30m) – Critical Current Measurement

- The critical current measurement shows that
  - Sufficient margin regarding the designed Ic for the cable is obtained
  - No degradation is visible after manufacturing, assembly and cooling of the prototype



30 % of security margin on the critical current of the core

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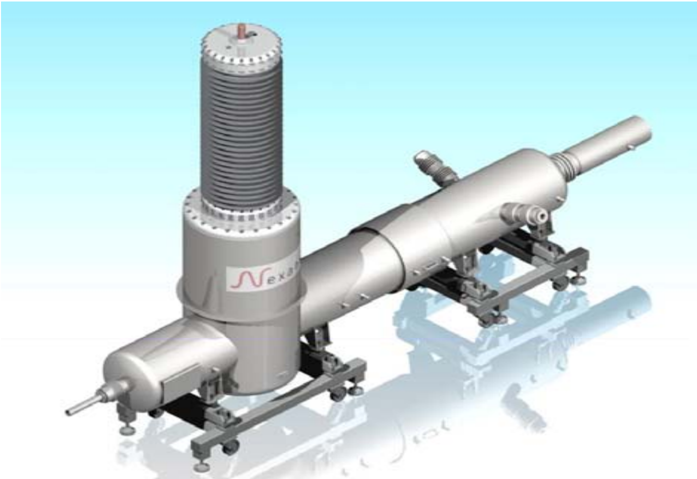
Project Status: Cable Components, Nexans

- **Termination Components**
  - ☑ Design: Complete
  - ☑ Prototype (s): Fabricated
  - ☑ Material Being Ordered
  - ☑ Routine Tests Underway



- **Final Cable**
  - ☑ Type Testing Complete
  - ☑ Former Manufacturing Complete
  - ☑ Phase Layers Being Stranded

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Project Status: Cable Subsystem, Nexans

- **30m System Test**
  - ☑ Test Facility: Complete
  - ☑ Prototype: Installed
  - ☑ Ic Retention (HTS wire performance): Verified
  - ☑ Hydraulic Parameter: Verified
  - ☑ Cryostat Performance: Verified
  - Voltage Level:
    - ☑ AC Withstand (190 kV) Verified
    - ☑ PD (<5 pc): Verified
    - ☑ **BIL (650 kV Min): Cable test complete**
    - ☑ **Load Cycles**

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Project Status-Refrigerator Subsystem, Air Liquide

- Refrigerator Status
  - Refrigerator Design Review completed Oct 2005
  - Mechanical and Electrical Design completed March 2006
- Installation Status - Equipment
  - Delivery of all new components completed June 2006
- Installation Status – Site
  - Bidding and Selection of subcontractors completed June 2006
  - Construction managers on site
- O&M Plan
  - Startup Plan
  - Ongoing O&M
- Update – Pulse Tube

Refrigerator Status – Final Design

Final Design-Refrigerator Subsystem

- Refrigerator
  - Re-use of Detroit refrigerator from previous Pirelli SPI Cable Program
  - Upgrades to system were necessary to adapt it to LIPA project and include:
    - Upgraded cooling capacity (+38%) for primary and back up systems
    - New system for the cable cool down "Cool Down Skid"
    - New buffer for fault reaction and recovery "Distribution Box"
    - Telemetry to allow remote monitoring and control "Control/Command Cabinet"
    - New 13,000 Gal tank for LN2 supply

  - Will be operated 4-5 months prior to cable commissioning

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Final Design Performance Summary

- Primary System Refrigeration: 5.65 kW @ 65K (5% Margin)
  - 33% Increase with Flow & Turbine Speed Enhancements
- Backup System Refrigeration: 6.77 kW (20% Margin)
  - Existing Backup System: 4.27 kW
  - New Added LN2 Module: 2.5 kW
- LN2 Consumption
  - Existing Backup System: 30 g/s (135 L/hr)
  - New LN2 Module: 13.4 g/s (60 L/hr)
  - A 13,000 gal Tank Will be Able to Provide at minimum 3 Day Supply (4000 gal heel)

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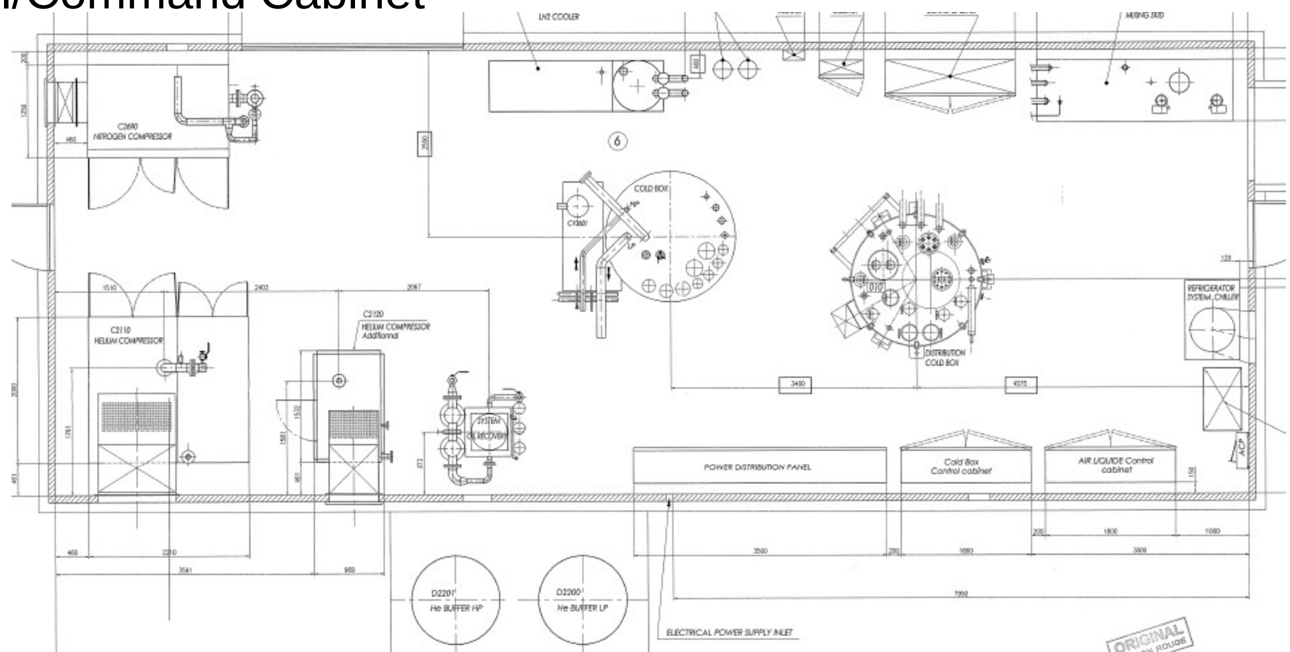
Installation Status - Equipment

New components

- Additional He Compressor
- LN2 Subcooler Cryotherm module
- LN2 Tank
- Control/Command Cabinet
- Distribution box : cryo valves, instrum., buffer
- Cool down skid
- Warm and cold transfer lines
- Vent stack at the end of the cable



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Helium Compressor

- **Delivered May 11**

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LN2 Subcooler

- **Delivered July 14**

Control Command Cabinet

- **Delivered June 16**

Distribution Box

- **Delivered**

  May 11

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Cool Down Skid

- **Delivered May 11**

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Installation Status - Site

Milestones & Status

Task	Status	Completion Date
Equipment Set	Completed	July 21
Piping Survey	Underway	July 28
Piping Prefab	Planned July 31	Sept 9
Piping Installation	Planned Aug 14	Oct 10
Electrical Installation	Planned Sept 15	Oct 12
System Checkout	Planned Oct 6	Oct 24
Startup	Planned Oct 25	Dec 5

O&M Plan

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Startup Objectives

Test Plan Key Points

- Full System Inspection and Checkout (P&ID conformity, safety valves)
- Full Electrical tests / Automation synchronization
- Pressure test / Leak test
- Pre-commissioning / System Conditioning
  - Charcoal filter regeneration and drying
  - He Loop purge and fill (Buffers, Compressors station, Oil Removal System, **Cold-Box**) with H_2O&O_2 measurement
  - LN2 Loop purge and fill with H_2O&O_2 measurement
- Startup and test Primary and Back-up refrigerator:
  - Performance tests (Cold Power, Flow rate, Pressure Drop)
  - Function test (Switch over Backup system, parallel operation Primary + Backup)
  - Cool down validation without cable

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O&M Plan

Short Term O&M (1st 20 months)

- Managed by Air Liquide DTA with remote and local technicians
- System Monitored by AMSC & DTA

O&M Plan

Long Term O&M (After 1st 20 Months)

- Integration into Air Liquide Operations Control Center (OCC)
  - Refrigeration Equipment O&M by Air Liquide Field Service Techs
  - Gas (LN2 & He) Supply Management by the National Scheduling Center (NSC)

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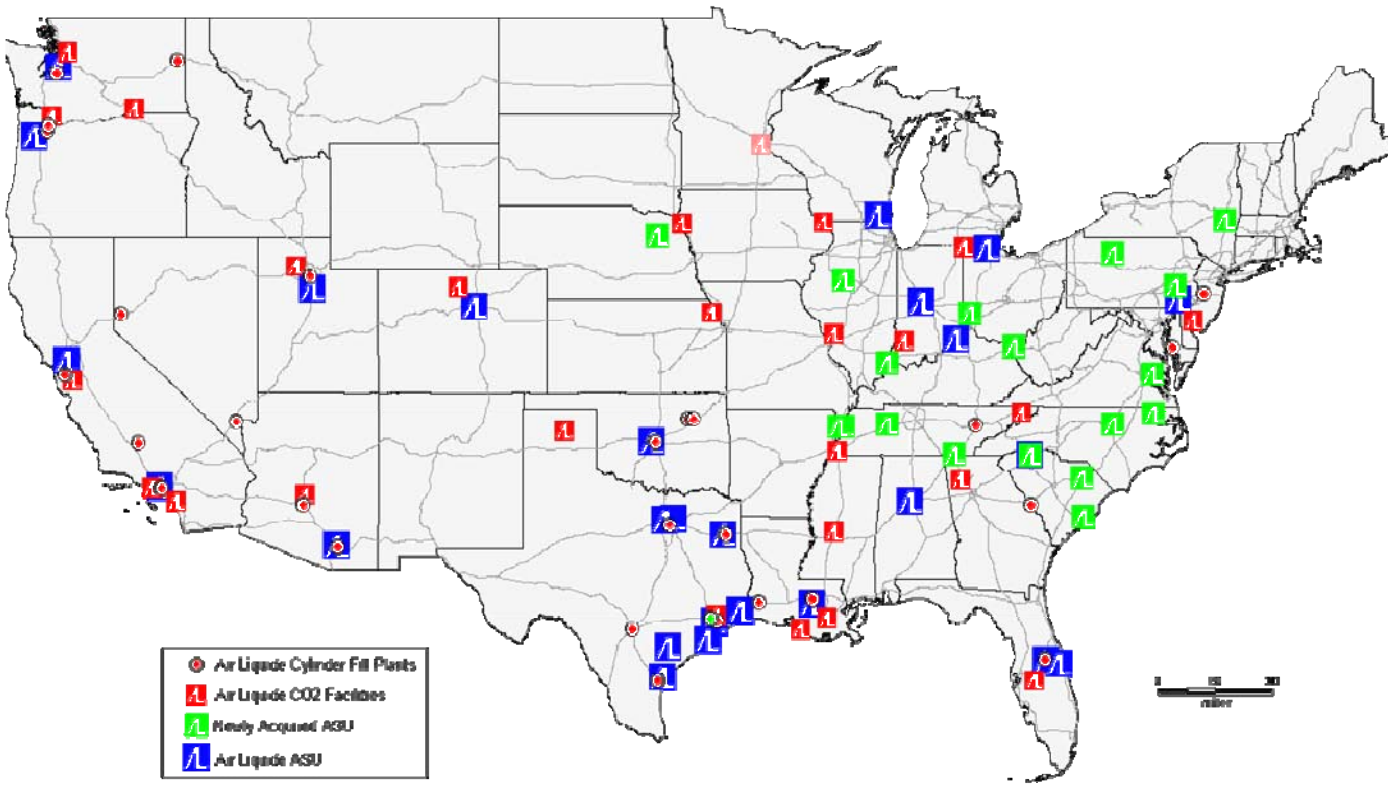
Air Liquide OCC

Managed Assets:

135	ASU's at 110 Locations
26	CO2 Plants
10	Cogen Units
1	Industrial Water Facility
11	Hydrogen/Syngas Units
6,800	Liquid Vessels
650	HP Gas Storage
700	Trucks (820 Drivers)
860	Liquid Bulk Trailers
430	Gas Tube Trailers
300	Railcars



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OCC On-line Capabilities

- Real-time customer data
  - Customer volumes
  - Customer pressures
- Real-time plant data
  - Equipment status
  - Power consumption
  - Production volumes
  - Product purity

- Real-time utility company data
- Historical operations data
- Customer profiles

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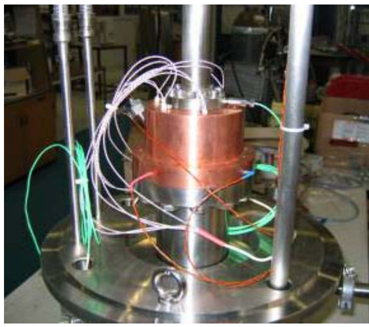
Update on Pulse Tube Development

DESIGN AND MANUFACTURE

GENERAL VIEWS OF THE PULSE TUBE COMPONENTS

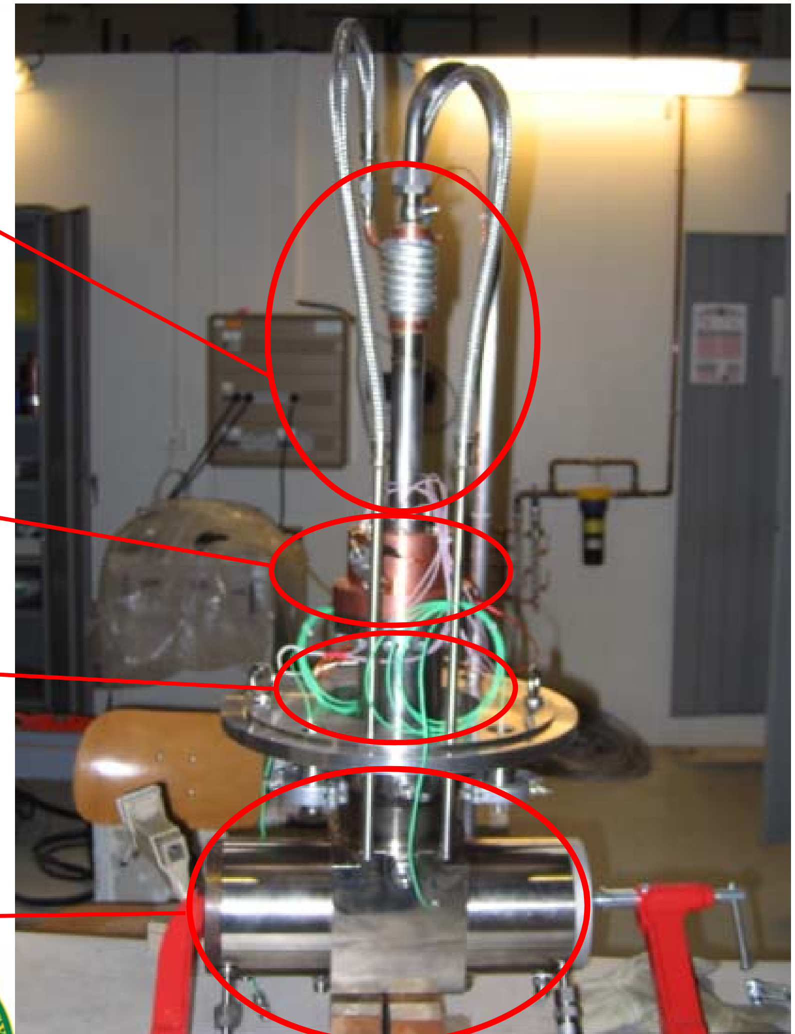
Pulsation Tube and warm end HX



Cold HX

Aftercooler

Regenerators



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TESTS AND OPTIMIZATION

Conclusion

- **Objective:** **280W@65K**
- **Results with 7.5 kW (6kW PV) and 5.5 kW (4.4kW PV) elect input power**

-- 7.5 kW --

⇨ **39 K no-load temperature**

⇨ **210 W @ 65K (10% Carnot)**

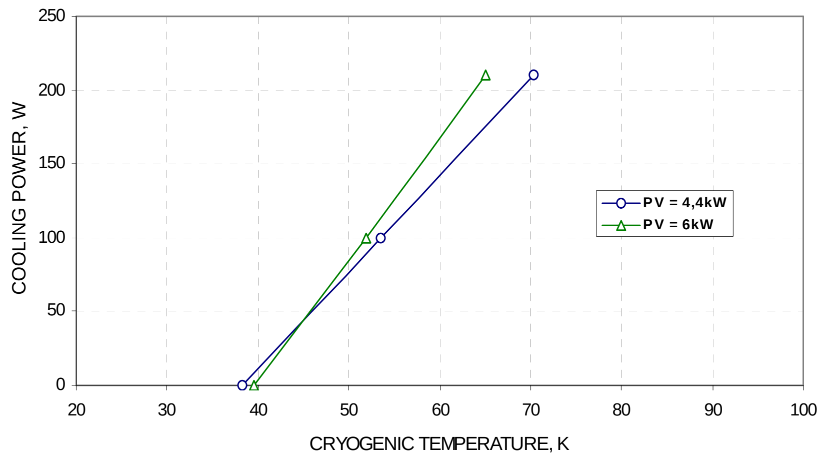
⇨ **305 W @ 77K (11.8% Carnot)**

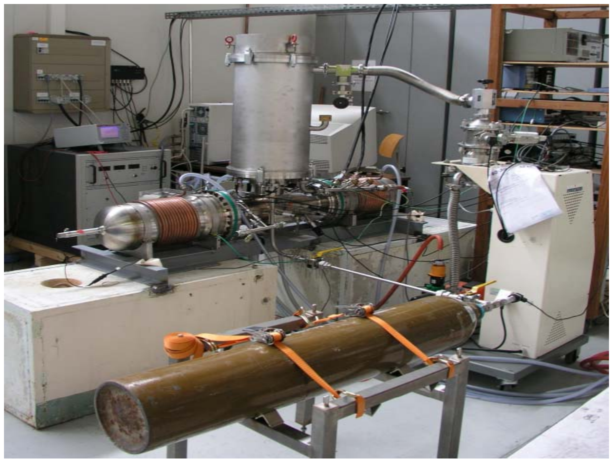
-- 5.5 kW --

⇨ **38 K no-load temperature**

⇨ **175 W @ 65K (11.6% Carnot)**

⇨ **255 W @ 77K (13.3% Carnot)**





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Project Status: Refrigerator Subsystem, Air Liquide

- Refrigerator
  - ☑ Optimization of the new process (primary and back up): Complete
  - ☑ Detailed definition of the new process lines: Complete
  - ☑ Preliminary lay out drawing: Complete
  - ☑ Definition of the new components: Complete
  - ☑ Equipment specifications : Complete
  - ☑ Final subsystem lay out: Complete
  - ☑ Building: shipping
  - ☑ Additional Component Fab. On site
  - ☑ Pulse Tube Prototype Developed

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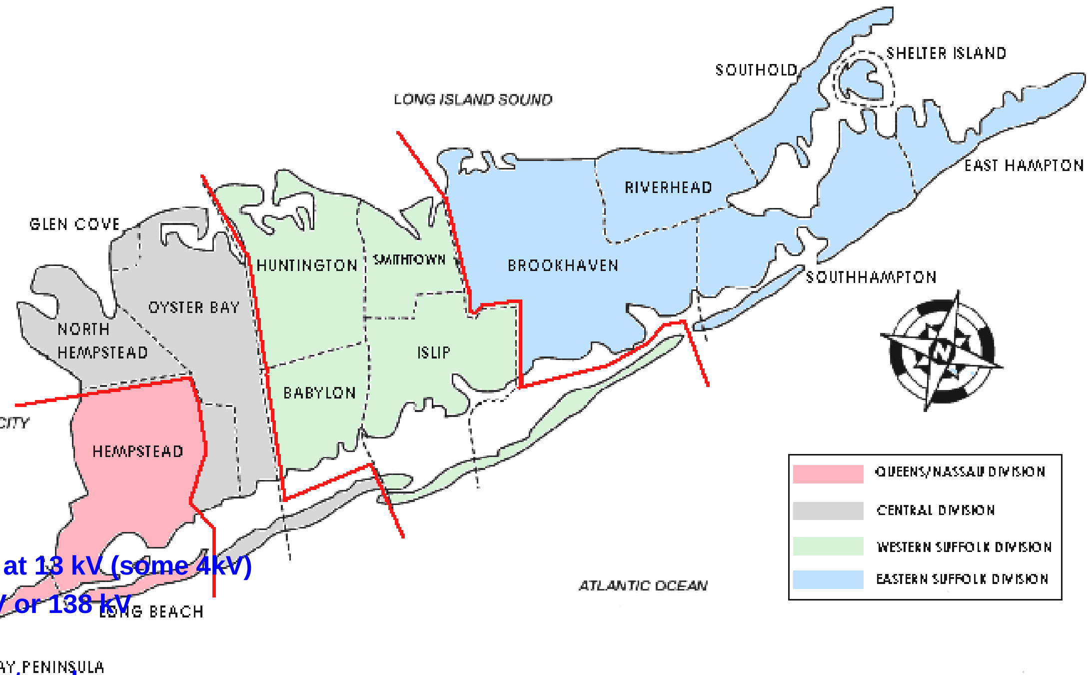
Site Status and Update

LIPA's Electric System

- **Service Territory ~ 1207 mi²**
  - **Nassau and Suffolk Counties**
  - **Rockaway Peninsula**
- **Population ~ 3 million**
  - **1,086,000 residential customers**
  - **100,000 commercial customers**
- **Peak Loads**
  - **normal ~ 3,500 MW**
  - **peak ~ 5,267 MW** *(August 5, 2005)*
- **Supply**
  - **On-Island Generation ~ 4,934 MW**
  - **Tie Lines ~ 1,462 MW capacity** *(if available)*
- **The System**
  - **Distribution system operates primarily at 13 kV (some 4kV)**
  - **Transmission system operates at 69 kV or 138 kV**
  - **About 95% of the system is overhead**
  - **Primarily a radial system with limited networks**



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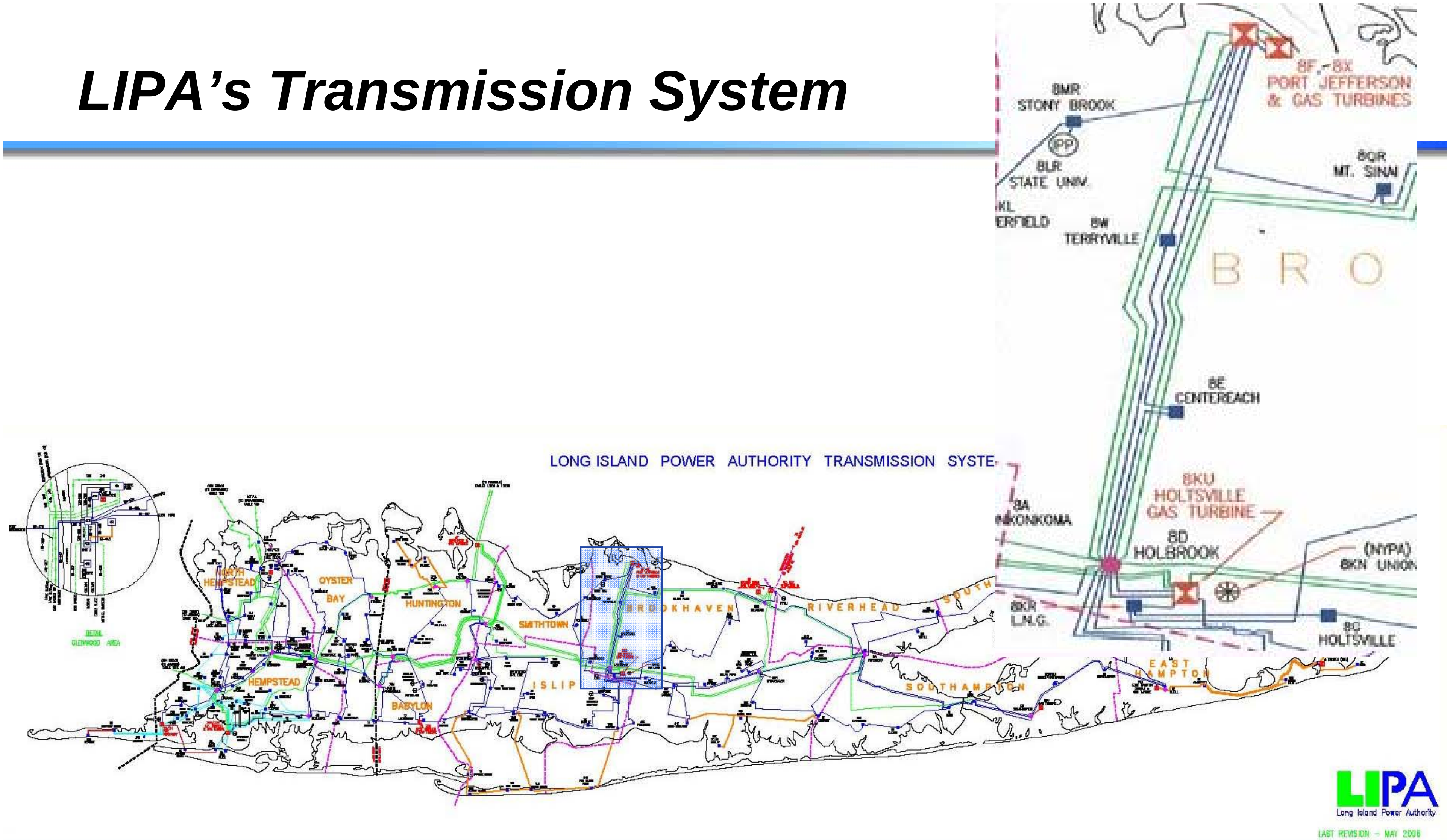
LIPA's Transmission System



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LIPA Project Overview

- Long Island Power Authority – Holbrook Substation
- Electrical Characteristics
  - Design Voltage/Current – 138kV/2400A ~ 574MVA
  - Design Fault Current – 51,000A @ 12 line cycles (200ms)
- Physical Characteristics
  - Cable Length ~ 600m
  - Cold Dielectric Design
- Hardware Deliverables
  - Three ~600 m Long Phase Conductors
  - Six 138kV Outdoor Terminations
  - Refrigeration System
- Installation/Commissioning – Spring 2007

Original Site

The Site Today

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Completed Site *(photo simulation)*

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Plans for GFY 07

Plans for GFY '07

- System Analysis
  - Review as installation progresses
- Cable and Terminations
  - Fabricate 600 meter cable
  - Fabricate 6 Terminations
- Refrigerator
  - Complete upgrade
  - Install at Holbrook site
  - Operate and qualify prior to cable install
  - Operate PT refrigerator
- System
  - Install cable and terminations
  - Install data and control system and interconnects
  - Energize

Project Confidence Matrix

Parameter	Production Item				
	Factory/Site Tested	Sample Tested	Full Scale Type Test	Subscale Test	Analysis
Voltage Withstand					
Termination					
Operating					
Lightning Impulse					
Cable					
Operating					
Lightning Impulse					
Current Carrying Capacity					
Termination					
Cable					
Heat Loads					
Cable					
AC Losses					
Dielectric Losses					
Cryostat Losses					
Termination					
AC Losses					
Cryostat Losses					
Refrigerator					
Capacity					
Flow capacity/pressure					
Wire					
Critical Current					
Hermeticity					
splice resistance					
splice hermeticity					
splice integrity					
Pressure Drop					
Faults					
Major Fault response					
Thru-fault response					
Material Properties used in model					n/a
Installation Methods					
Cable					
Termination					

Demonstration of a Pre-Commercial Long-Length HTS Cable System Operation in the Power Transmission Network

DOE Peer Review Update
August, 2007
Arlington, VA

Agenda

- **Introduction** — **Jim Maguire, AMSC**
- **Project Overview** — **Jim Maguire, AMSC**
- **FY 2007 Results and Performance**
  - **Cable and Terminations** — **Frank Schmidt, Nexans**
  - **Refrigerator** — **Shawn Bratt, Air Liquide**
  - **Site/Installation** — **Tom Welsh, LIPA**
- **FY 2008 Plans** — **Jim Maguire, AMSC**

Project Overview

LIPA Project Overview

- Long Island Power Authority – Holbrook Substation
- Electrical Characteristics
  - Design Voltage/Current – 138kV/2400A ~ 574MVA
  - Design Fault Current – 51,000A @ 12 line cycles (200ms)
- Physical Characteristics
  - Length ~ 600m
  - HTS Conductor Length ~155km
  - Cold Dielectric Design
- Hardware Deliverables
  - Three ~600 m Long Phase Conductors
  - Six 138kV Outdoor Terminations
  - One Refrigeration System + Laboratory Pulse Tube System
- Installation/Commissioning – Fall 2007

World's First Installation of a Transmission Voltage HTS Cable

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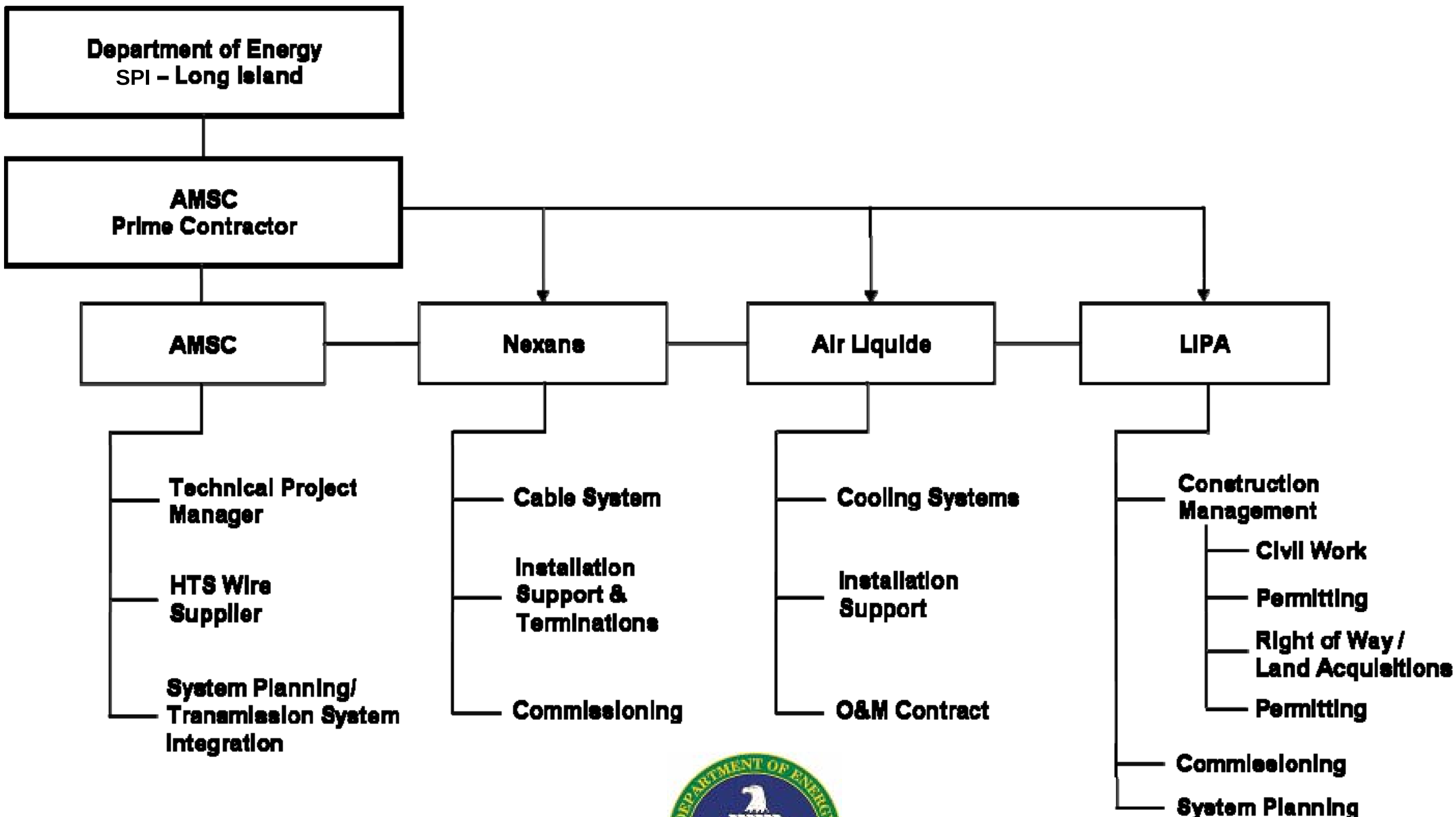
LIPA Cable Project and Project Team



Major Challenges of LIPA Project

- System Design
  - 138 kV, 2,400 amp Operation
  - Survive 51kA@200ms Fault
  - Manage Through-Faults
- HTS Conductor Design
  - Handle Real-world Cabling Stress Using Standard Manufacturing Equipment
- Termination Design
  - Qualify to 138 kV operation, 650kV BIL
  - Safely Manage Voltage Breakdown
  - Manage results from Loss of Cryostat Vacuum

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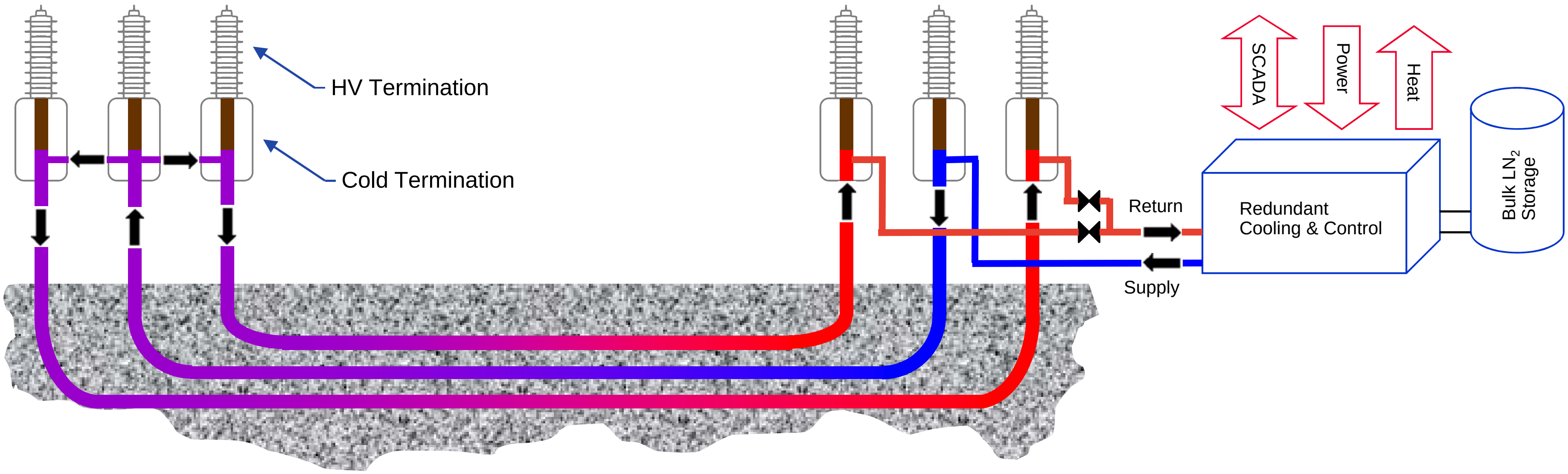
LIPA HTS Cable System



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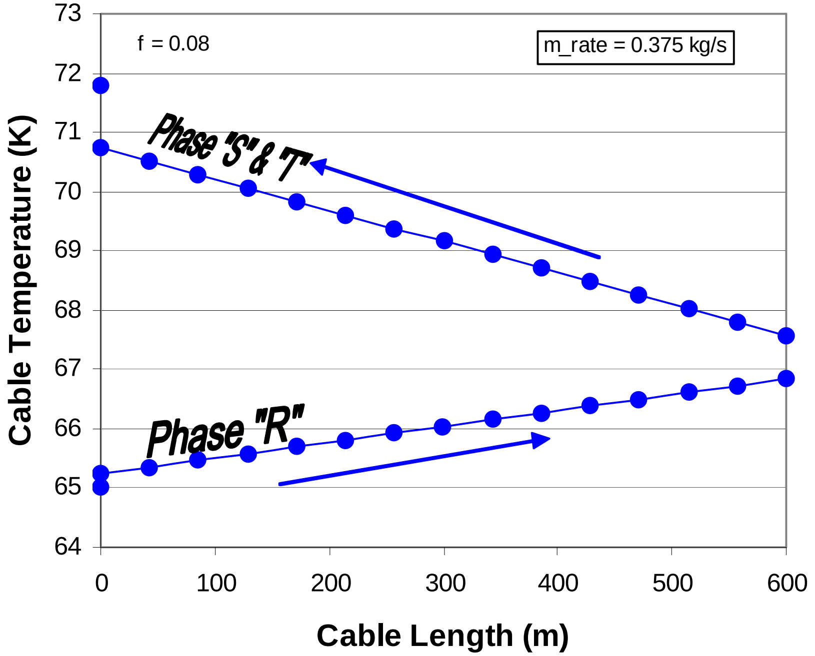
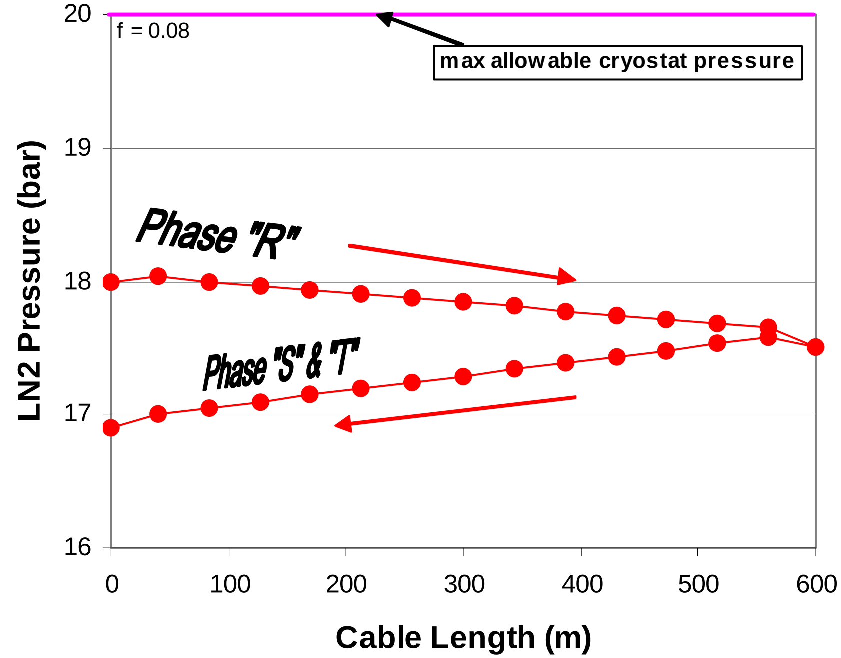
Steady State Operation





- Maximum Conductor Temperature Expected to be < 72 K
- Maximum Conductor Temperature Required to be < 77 K
- Total Pressure Drop < 1.5 bar
- Total Refrigeration Required: 5,600 Watts

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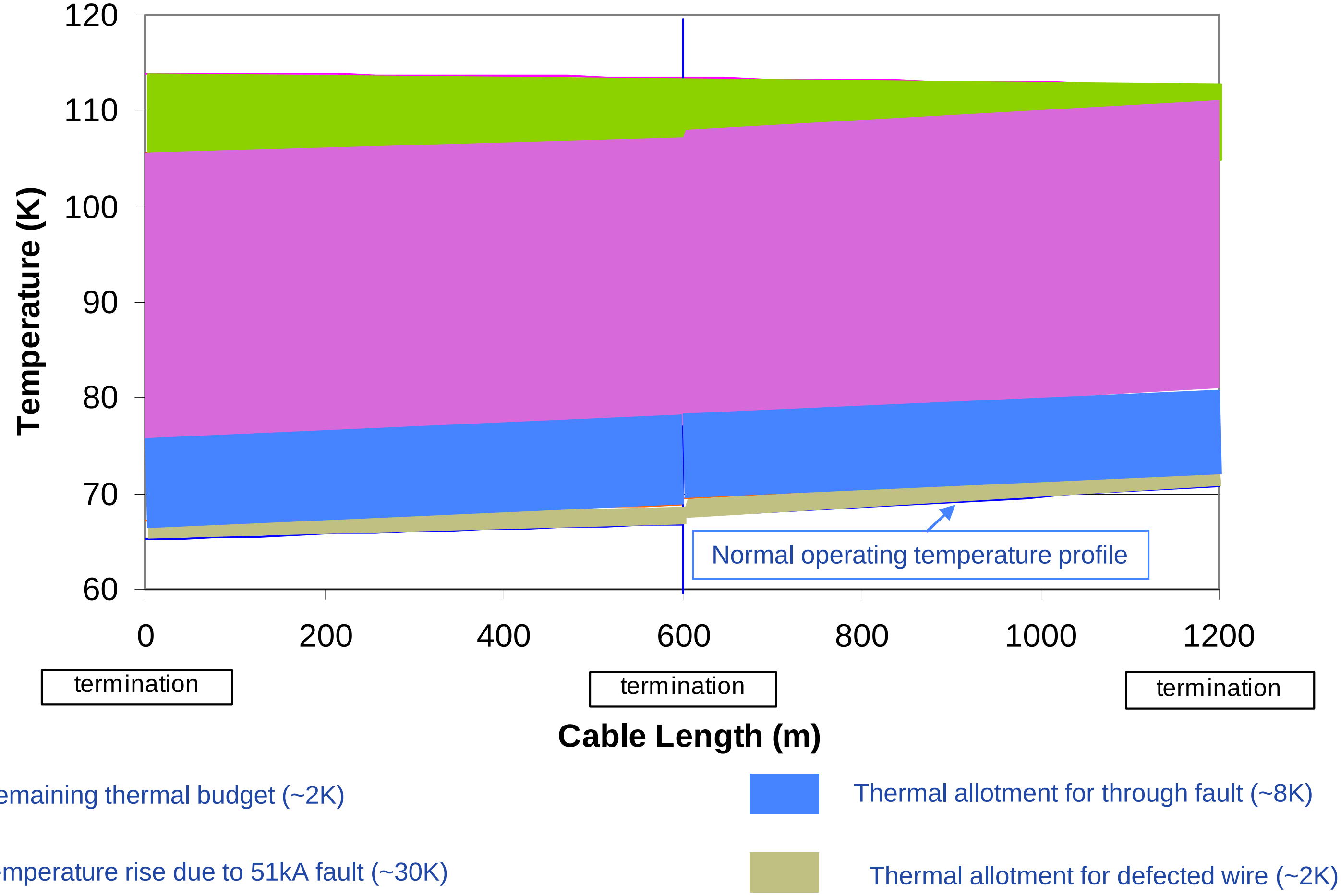
LIPA Holbrook Substation Fault Requirements

138 kV Substation	Amps in Cable	Clearinging Time	Design	Remain on Line (Single Fault)
Holbrook	51000	12 cycles	√	Off Line
Port Jefferson	9500	12 cycles	√	On Line
Holtsville GT	3700	0.48 sec	√	On Line
Ronkonkoma	3100	12 cycles	√	On Line
Miller Place	1100	0.75 sec	√	On Line
Wading River	1200	0.75 sec	√	On Line
Caithness	2000	N/A	√	On Line
Brookhaven	1500	0.90 sec	√	On Line
Brentwood	1300	N/A	√	On Line
Ruland Road	1200	12 cycles	√	On Line

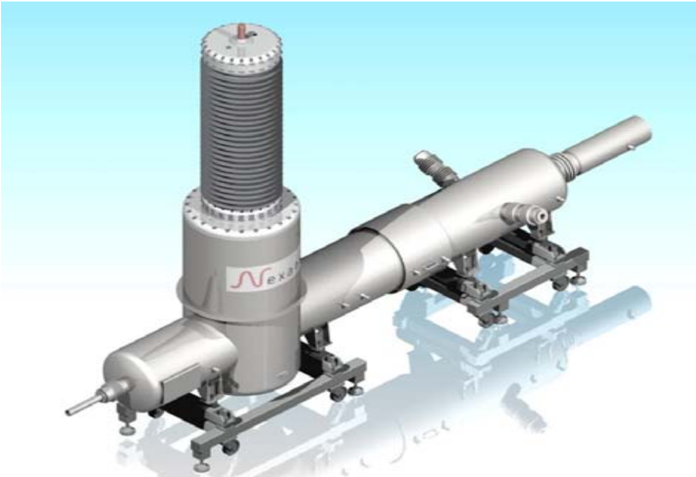
LIPA Cable Thermal Budget



Project status as of last peer review: Cable & Terminations

Termination Components

- ☑ Design: Complete
- ☑ Prototype (s): Fabricated
- ☑ Type Tests Completed
- ☑ Material Being Ordered
- ☑ Routine Tests Underway



- **Final Cable**
  - ☑ Type Testing Complete
  - ☑ Former Manufacturing Complete
  - ☑ Phase Layers Being Stranded

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Project status as of last peer review: Cable & Terminations

- **<u>30m Cable System Test</u>**
  - ☑ Test Facility: Complete
  - ☑ Prototype: Installed
  - ☑ Ic Retention (HTS wire performance): Verified
  - ☑ Hydraulic Parameter: Verified
  - ☑ Cryostat Performance: Verified
  - Dielectric Testing:
    - ☑ AC Withstand (190 kV) Verified
    - ☑ PD (<5 pc): Verified
    - ☑ **BIL (650 kV Min): Cable test complete**
    - ☑ **Load Cycle Testing complete**

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Project status as of last peer review:

- Refrigerator Subsystem, Air Liquide
  - ☑ Optimization of the new process (primary and back up): Complete
  - ☑ Detailed definition of the new process lines: Complete
  - ☑ Preliminary lay out drawing: Complete
  - ☑ Definition of the new components: Complete
  - ☑ Equipment specifications : Complete
  - ☑ Final subsystem lay out: Complete
  - ☑ Building: Installed
  - ☑ Additional component fabrication on site
  - ☑ Pulse tube prototype developed

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LIPA Project Status Update

- Cable and Termination
  - Two phases in ground
  - Two terminations installed on first phase
  - Two terminations installed on second phase

- Refrigeration System
  - Installation completed
  - Testing on going
- Site Preparation
  - On Schedule

World's First Transmission Voltage HTS Cable Will Be Operating in 2007

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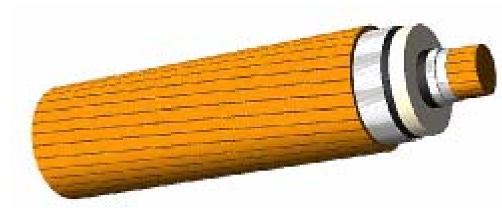
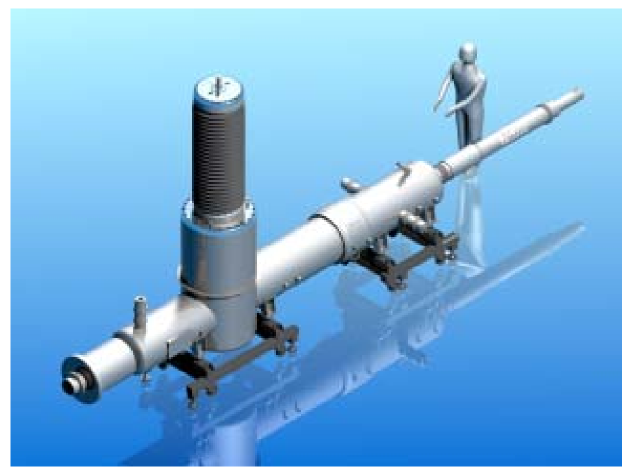
Cable and Termination Status

Components of the HTS Cable System

- Superconducting Cable System
  - Cable Core
    - Transport the current
    - Withstand the voltage
  - Cryostat
    - Insulate thermally – keep the cable cold
    - Transport the liquid nitrogen
  - Termination
    - Connect the system to the grid
    - Manage the transition between cold temperature and room temperature
    - Provide connection to the cooling system





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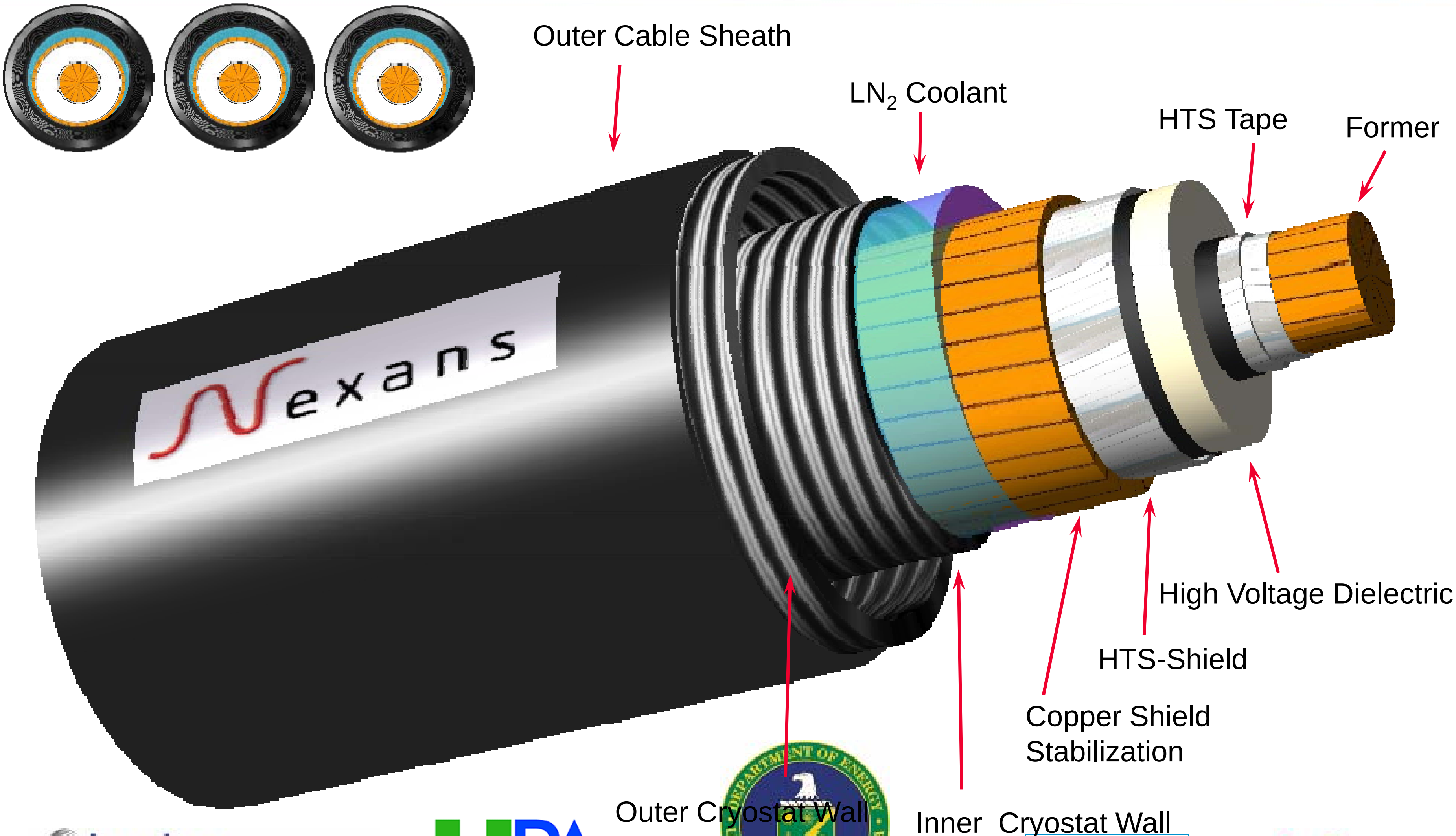
LIPA HTS Cable Design



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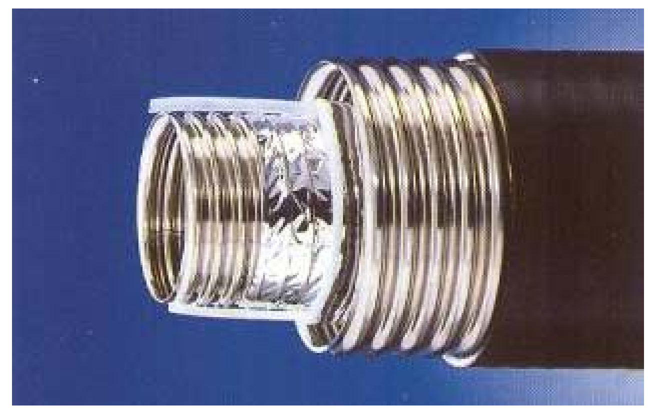
Cryogenic Envelope

- Design
  - Two concentric longitudinal welded corrugated stainless steel tubes
  - Superinsulation (Al coated foil with spacer fleece) in between the tubes
  - Low loss spacer
  - Vacuum space
  - Pumping ports every 100 meter
- Manufacturing using longitudinal welding and corrugation process
- Quality assurance
  - High sensitivity helium leak testing to ensure long term vacuum quality



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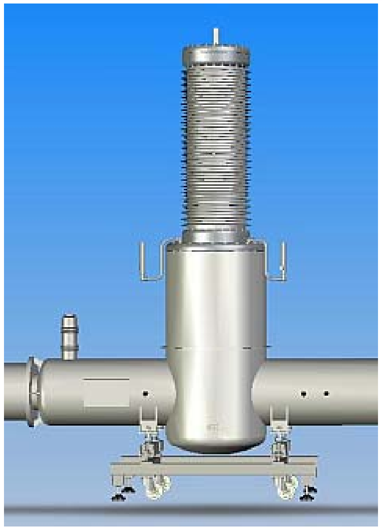
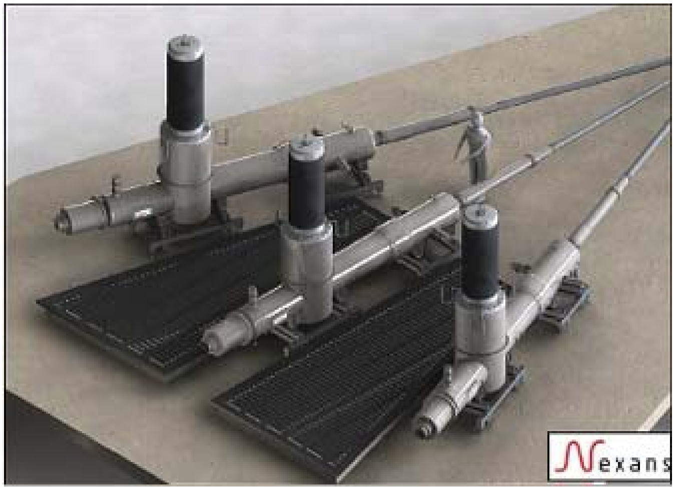
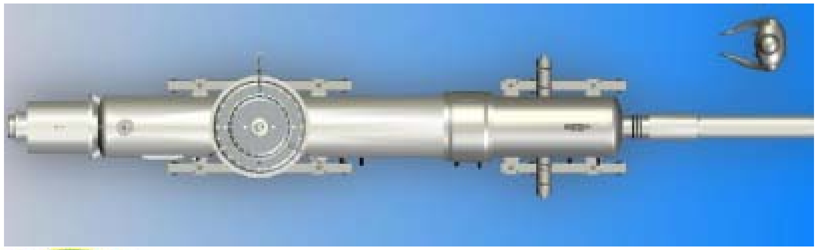
LIPA Project - Termination Concept



- Vertical part:
  - Thermal gradient management (from 65 to 300 K)
  - Connection to grid



- Horizontal part:
  - Connection to HTS cable
  - Management of cable thermal shrinkage



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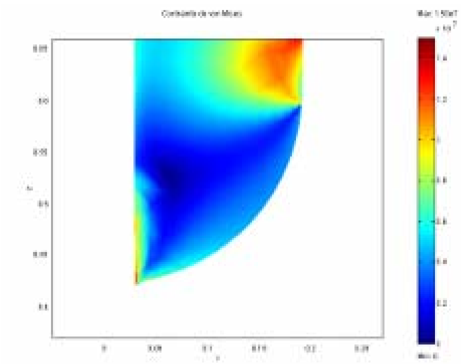
Termination - Pressure Test of the Bushing

Last technical point of termination closed

- The bushing bottom is submitted to 20 bars of pressure
- IEC 60137 standard was applied for this test as a guiding standard
- Thermo-mechanical calculations done – proving system safety
- A pressure type test of a bushing was achieved by TUV (Hanover) in cold condition
- No failure or leakage at P= 60 bars for one hour tested with helium



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Cable Core Manufacturing

- Cable core manufacturing done at Nexans facility in Norway
- Manufacturing process done on machines qualified prior to final core manufacturing
- Manufacturing process established using quality control sections to verify machine setup
  - Samples of QCA and QCB were taken and HTS wire Ic measurement performed
  - no degradation observed

QCA Phase R Phase S Phase T QCB

No damage experienced during cable core manufacturing

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Cable Core Manufacturing Steps

- Conductor stranding
- Dielectric lapping
- HTS screen stranding
- Copper screen stranding
- Protection layer

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Cryostat - Tube Manufacturing

- Cryostat tube manufacturing

- Cable drum arrival in Germany for cryostat tube manufacturing

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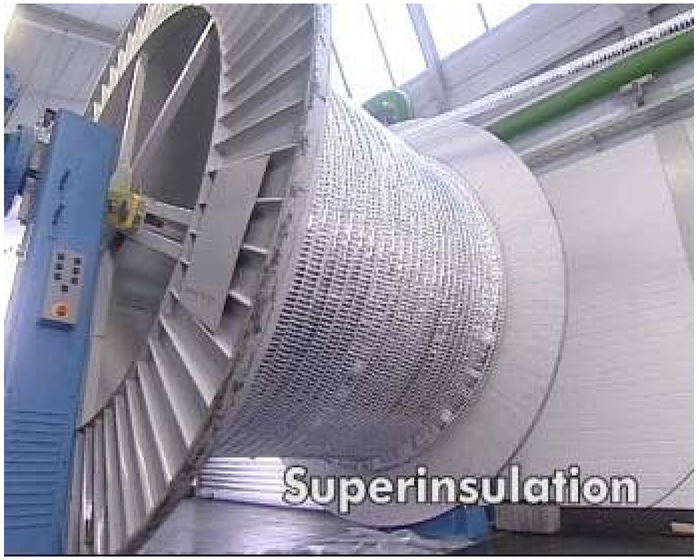
Cryostat - Lapping of Superinsulation



- After inner tube leak testing the superinsulation wrapping was done with several runs through the lapping machine due to the number of spacer and MLI layers

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Cryostat - Pump out Port Welding

- Pump out ports were welded every 100 meters of cryostat
- Continuous vacuum space
- Burst disc and vacuum sensor on one end
- Each welding He-leak tested

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Cryostat – Final Vacuuming Process and Shipping

- Final vacuum was done with parallel pumping on each pumping port
- Additional heating was applied to improve vacuum level
- Cable reels were shipped to the site on special transport frame

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Termination – Bushing Routine Test

- According to the critical aspect of this component for the termination, each bushing unit are routine tested in Calais according IEC 60840:
  - Cryogenic conditions (liquid nitrogen, atm. Pressure)
  - AC withstand test 190 kV / 30 minutes
  - Partial discharge measurement (no PD at 114kV)
- Status:
  - 9 bushings routine tested and shipped to the site (6 plus spares)

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Termination Cryostat Manufacturing

- Six termination cryostats manufactured and He-leak tested
- Initial vacuum done in factory for most areas
- Connection areas to be vacuumed after installation on site

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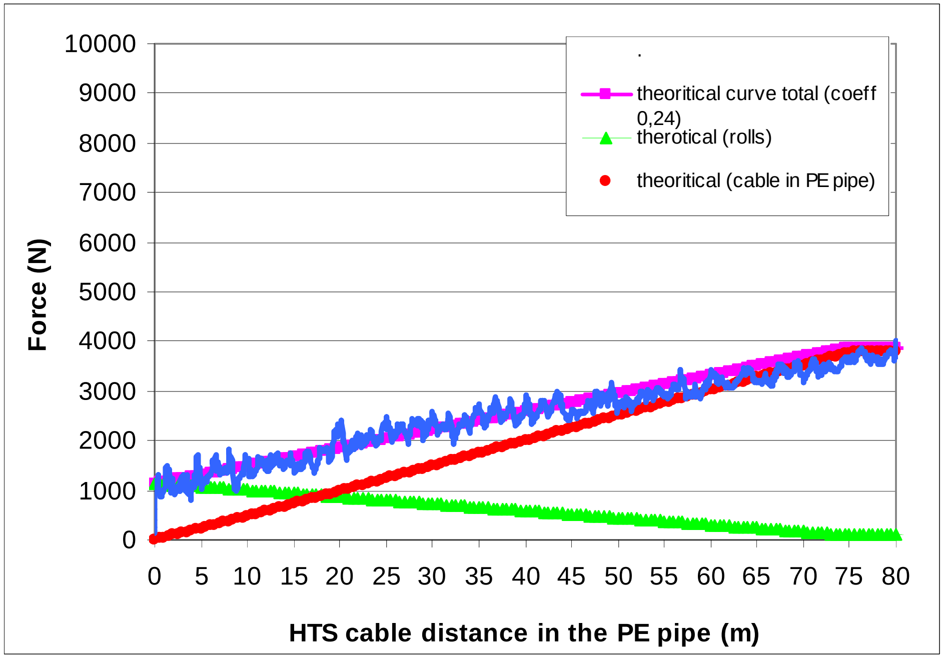
Installation - Cable Pulling Test

- In order to prepare cable pulling a test was done to get expected pulling force and test different lubricants
- 70 meter of the original conduit has been installed for this test
- Result showed that pulling forces for the 600 meter cable are expected to be about 2.5-3.0 tons



Installation - Cable Pulling

- Cable phases have been pulled as they arrive on site
- Pulling was achieved for two phases without any issues
- Third cable phase pulling this week
- No issues occurred during cable pulling
- Vacuum integrity verified

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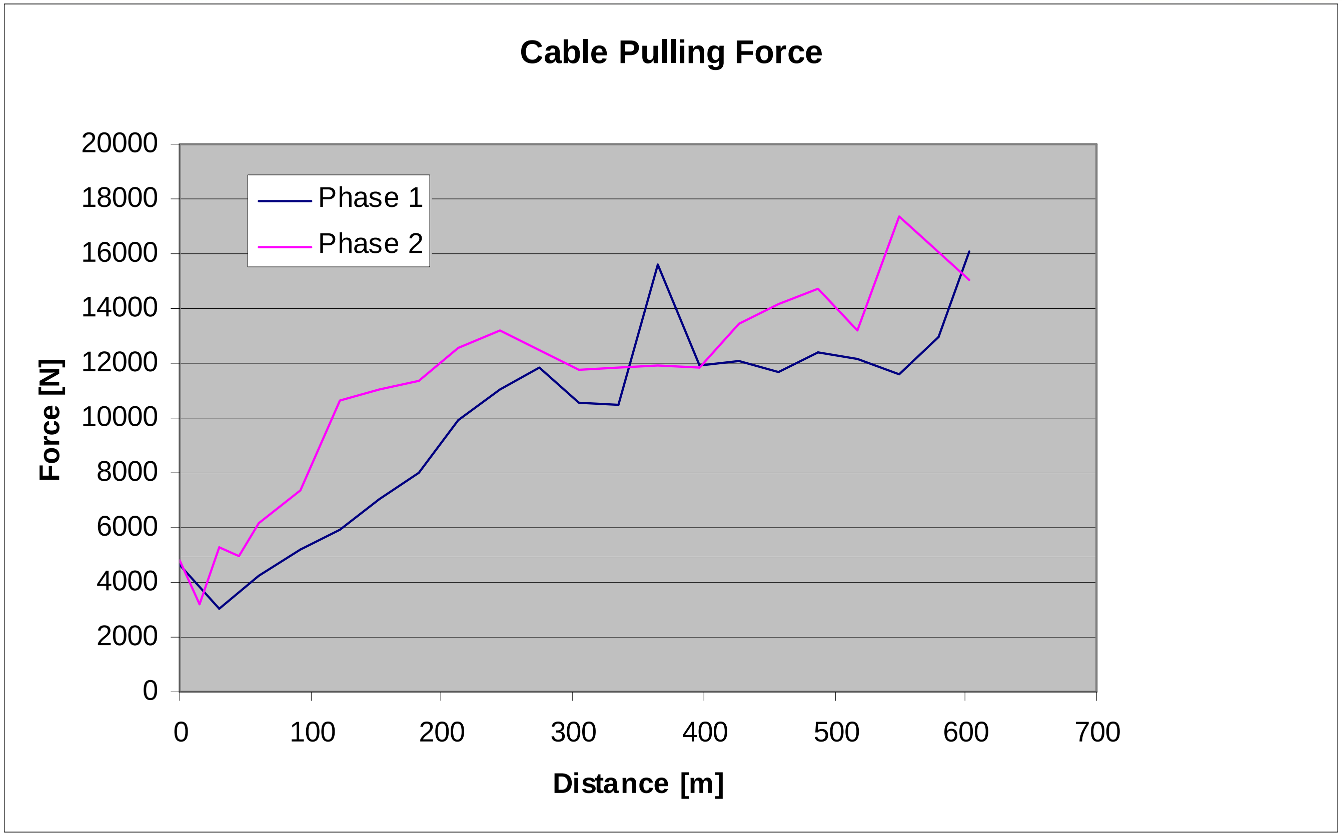
Installation - Cable Pulling Forces

- Pulling force less than 20 kN
- Lubricant used on site seems even better than the lubricant tested



Installation - Status

- Two cable phases pulled
- Due to custom issues with one container 2 weeks of delay occurred
- 4 Terminations installed (main parts) earlier than expected
- Third phase and remaining terminations starting during the week of August 6, 2007

Installation on track despite custom delay

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Refrigerator Status – Performance

Progress Update

- Installation completed Jan. 19th
- Pre-Commissioning completed Feb. 16th
- Startup completed March 14th
- Performance Testing ongoing

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REVIEW- Final Design-Refrigerator Subsystem

- Refrigerator Design Summary
  - Re-use of Detroit refrigerator from previous Pirelli SPI Cable Program
  - Upgrades to system were necessary to adapt it to LIPA project and include:
    - Upgraded cooling capacity (+38%) for primary and back up systems
    - New system for the cable cool down “Cool Down Skid”
    - New buffer for fault reaction and recovery “Distribution Box”
    - Telemetry to allow remote monitoring and control “Control/Command Cabinet”
    - New 13,000 Gal tank for LN2 supply
  - Operated 6 months prior to cable commissioning

Final Design Performance Criteria

- Primary System Refrigeration: 5.65 kW @ 65K – 72K, 375 g/s LN2, 78 g/s GHe
  - 5.066 kW cable cryostat/termination loss
  - 333 W refrigeration system loss
  - 251 W extra capacity (5% Margin)
- Backup System Refrigeration: 6.77 kW (20% Margin)
  - Existing Backup System: 4.27 kW
  - New Added LN2 Module: 2.5 kW
- LN2 Consumption
  - Existing Backup System: 30 g/s (135 L/hr)
  - New LN2 Module: 13.4 g/s (60 L/hr)
  - A 13,000 gal Tank to Provide at minimum 3 Day Supply (4000 gal heel)

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Performance Testing

First Testing Period – Feb 21st to March 14th

- Performed Primary Refrigerator functional and limited performance testing
- Performed Backup functional testing

Results

- LN2 pressure instability limited functionality
- Shutdown March 14 to April 30
  - **Modifications performed:**
    - Buffer level control algorithms modified to suit performance testing.
    - Re-evaluated turbine HP/LP ratio for optimal performance – increased from 5.75 to 6.03 for a He temp. drop of 3K (implemented May 15).

Performance Testing

Second Testing Period – April 30th to June 26th

- Performed Primary Refrigerator performance testing
- Performed Backup performance testing
- Performed Primary + backup parallel operation
- Performed Primary to Backup to Primary switchovers
- Performed system fault scenarios

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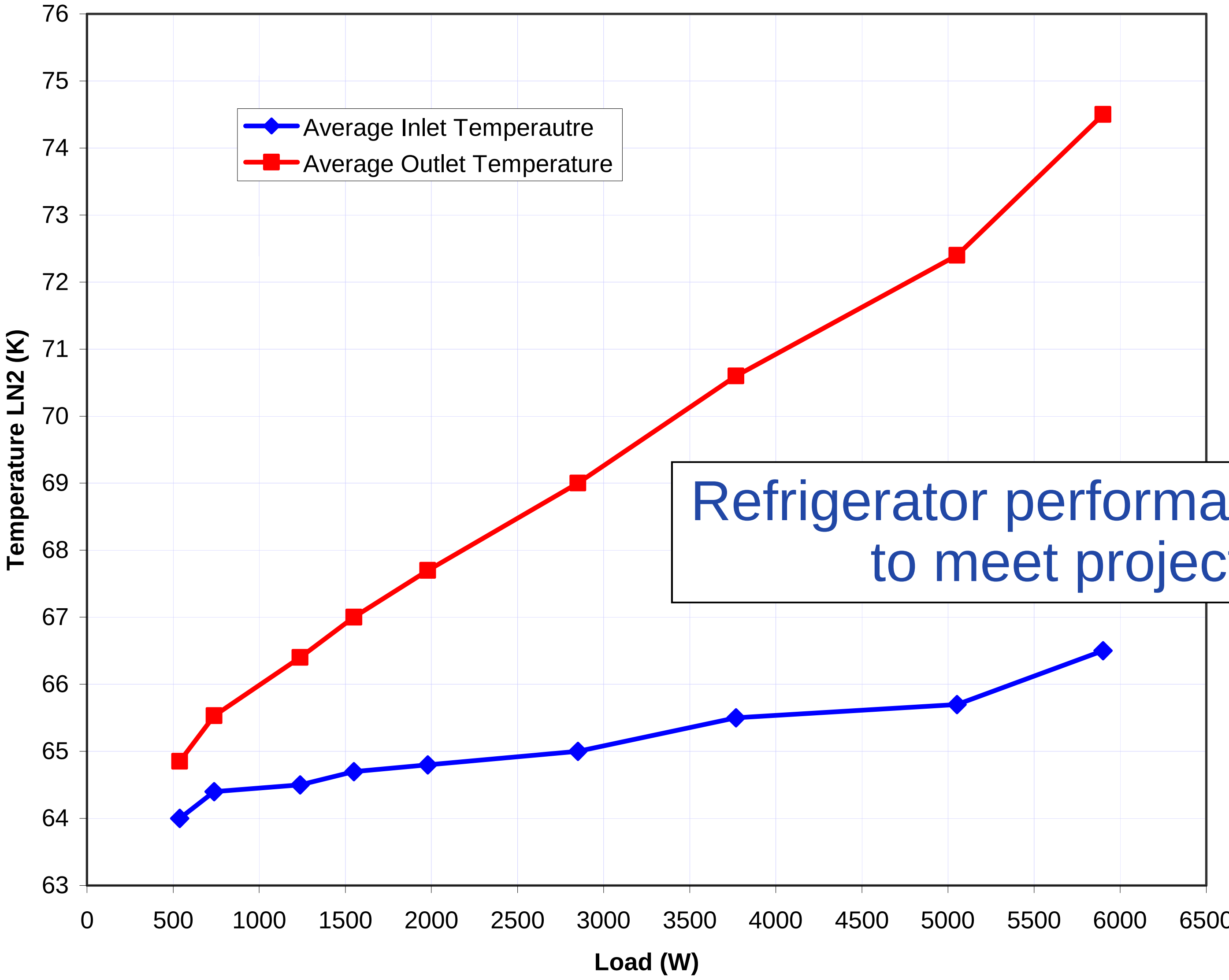
Performance Testing

Primary Performance Load Curve @ 375 g/s LN2, 18 bara – 14.8 bara*



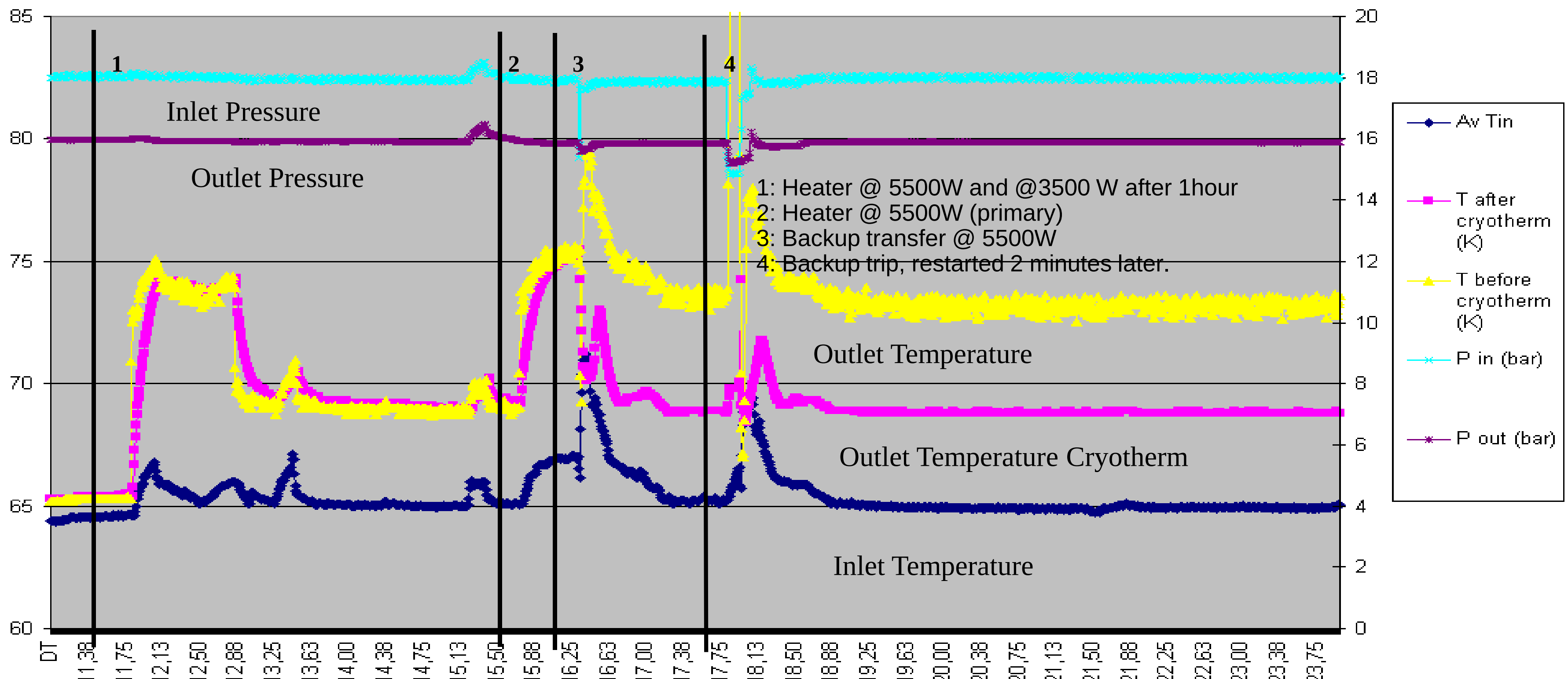
Refrigerator performance sufficient to meet project goals

* Results after turbine parameter adjustment

Performance Testing

- **Results Primary to Backup Switchover Operation**

System Heat Load	Calculated	**6715 W**
Liquid Nitrogen Loop		
Cable Inlet Temperature (K)	Average	**64.9**
Cable Outlet Temperature (K)	Average	**73.1**
Cable Inlet Pressure (bar abs)	PT6611	**18**
Cable Outlet Pressure (bar abs)	PT3631	**16**
Nitrogen Mass flow (g/s)	FT6610	**375**



Performance Testing

Third Testing Period – July 13th to July 17th

- Performed Primary Refrigerator performance testing
- Performed Backup performance testing
- Performed Primary + backup parallel operation
- Performed Primary to Backup to Primary switchovers

Results Primary Operation

- Data being analyzed.
- Primary still limited by break water temperature issue.
- Valve CV3618 still leaking a little.

Current Performance Summary

Parameter	Design	Required	Measured**
Primary Capacity	5650 W @ 65K, dT 7K, 375 g/s LN2, 78 g/s He	5400 W @ 77K Max. return 375 g/s LN2	5025 W @ 65.7K, dT 6.8K, 375 g/s LN2, 85.5 g/s He 5900 W @ 65.9K, dT 8.3K,
Backup Refrigerator	6770 W @ 65K, dt 7K, 375 g/s LN2		5900 W @ 64.9K, dT 8.2K, 375 g/s LN2
Primary mode LN2 Consumption	< 1 g/s		~0.8 g/s (1" per day)
Linde Backup LN2 Consumptuion	30 g/s		to be confirmed
Cryotherm Module LN2 consumption	13.4 g/s		~5 g/s (6" per day)
Refrigeration System No-Load Loss	333 W		~ 700-800 W estimated (being addressed)

** Primary Capacity Results limited due to turbine break water over temperature issue, refrigerator has not been run to full capacity.

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Plan Forward

Task	Completion Date
Add additional chilled water capacity	Aug 17
Repair valve CV3618	Aug 17
Restart Refrigerator	Aug 20
Retest Operating Modes/Performances	Aug24
Simulate Cable Cooldown Operation	Aug 29
Perform 8000 Hr Maintenance	Sept 14
Connect to Termination Cryostat	Sept 24
Restart Refrigerator	Sept 26

Holbrook Superconductor Site Status

Tom Welsh
R&D Program Manager – T&D
Long Island Power Authority

LIPA Service Territory – New York State

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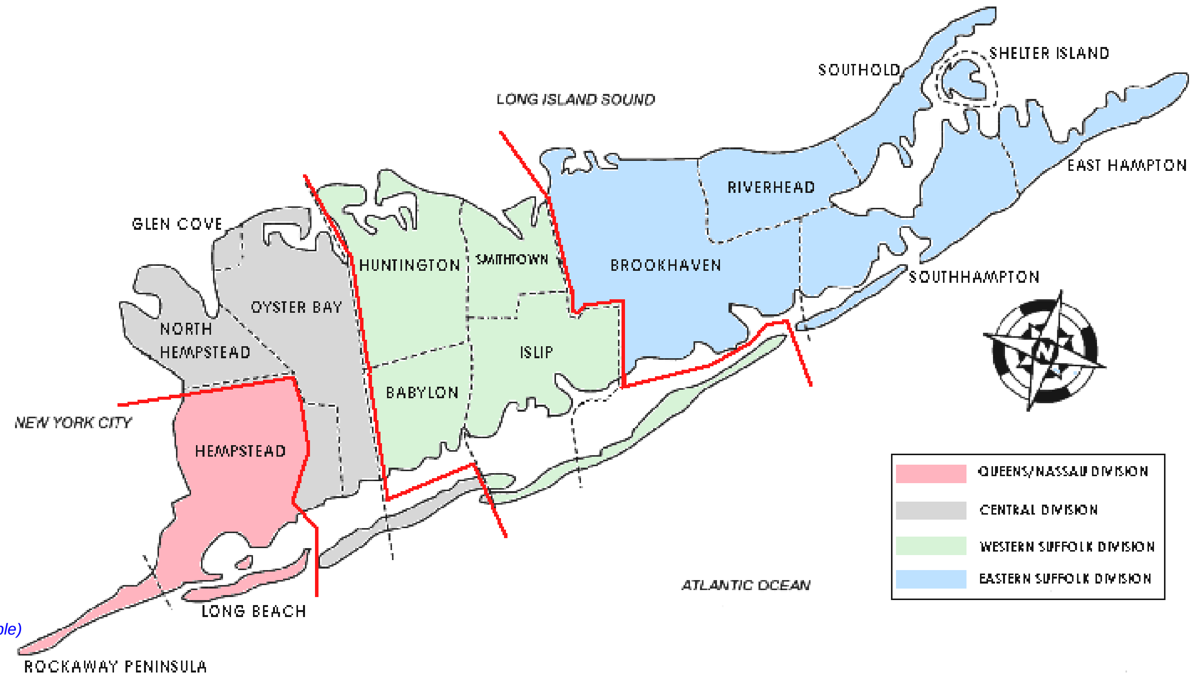
LIPA's Electric System

- **Service Territory ~ 1207 mi^2**
  - **Nassau and Suffolk Counties**
  - **Rockaway Peninsula**
- **Population ~ 3 million**
  - **1,086,000 residential customers**
  - **100,000 commercial customers**
- **Peak Loads**
  - **normal ~ 3,500 MW**
  - **peak ~ 5,792 MW** *(August 3, 2006)*
    - *10% increase over previous year, 2004 less than 5,000 MW*
  - **Demand ~ 113,951 MW** *(August 3, 2006)*
    - *15% increase over previous year*
- **Supply**
  - **On-Island Generation ~ 4,934 MW**
  - **Tie Lines ~ 1,462 MW capacity** *(if available)*
- **The System**
  - **Distribution system operates primarily at 13 kV (some 4kV)**
  - **Transmission system operates at 69 kV or 138 kV**
  - **About 95% of the system is overhead**
  - **Primarily a radial system with limited networks**



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LIPA Service Territory – Long Island

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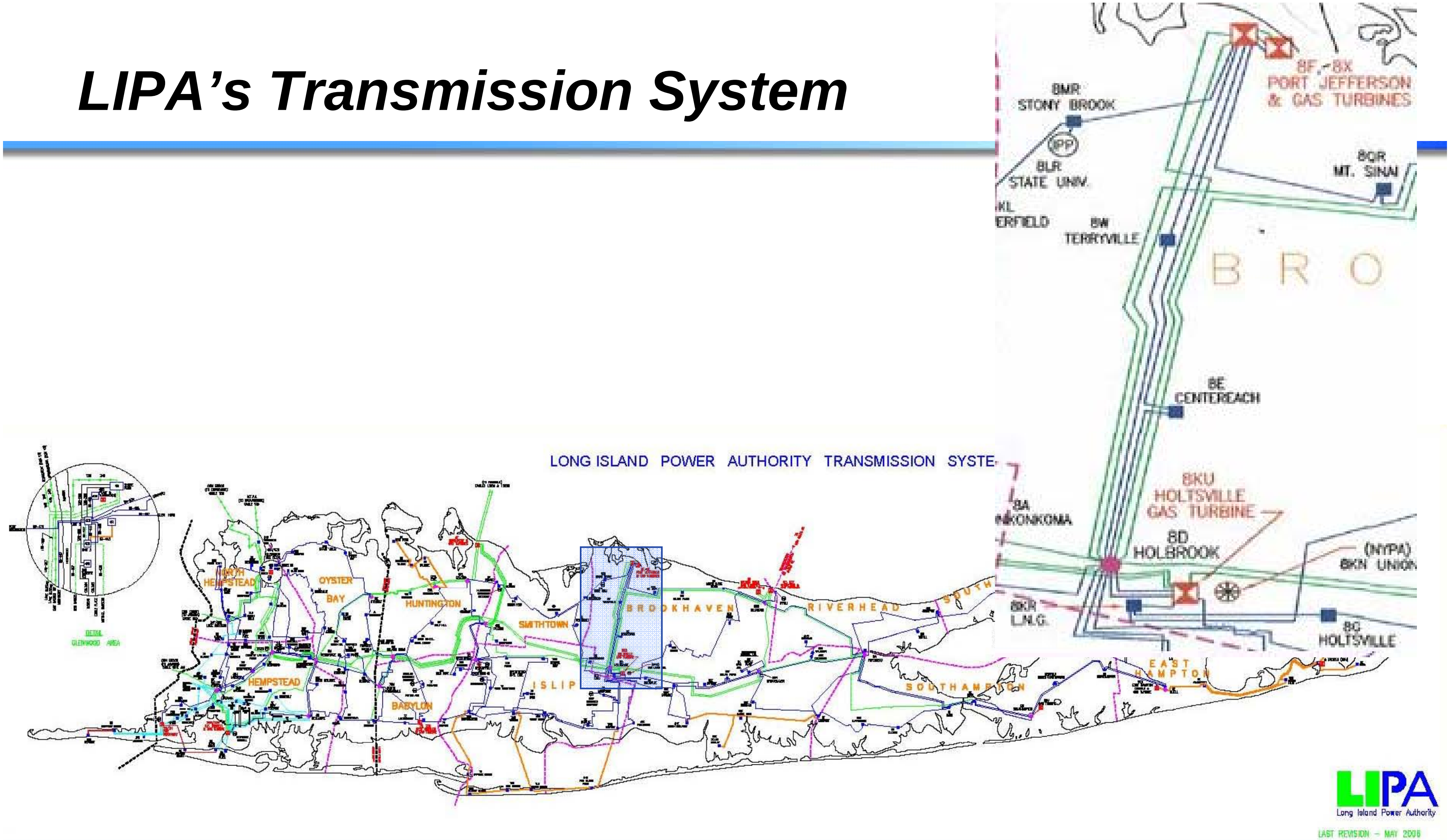
LIPA's Transmission System



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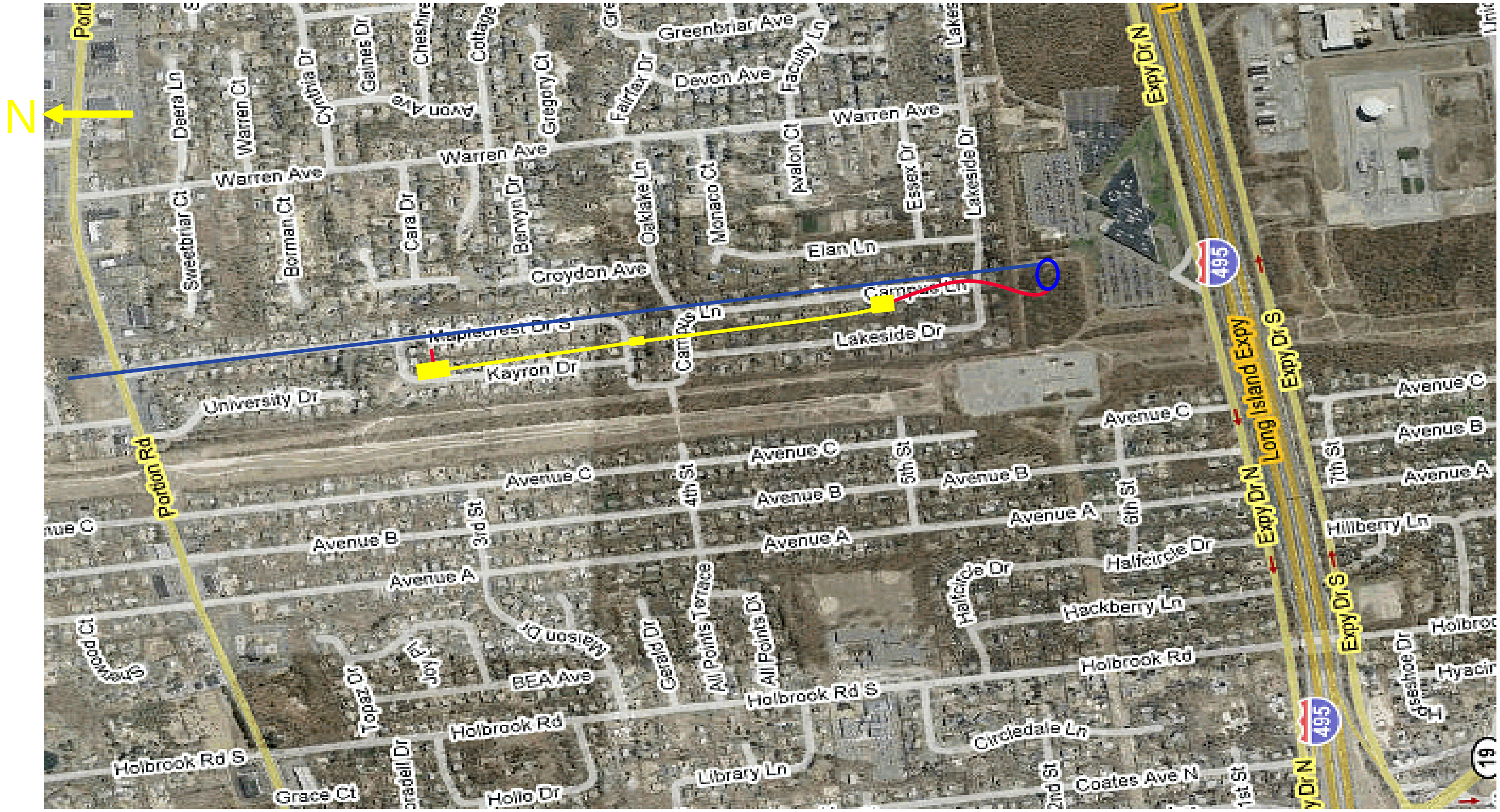

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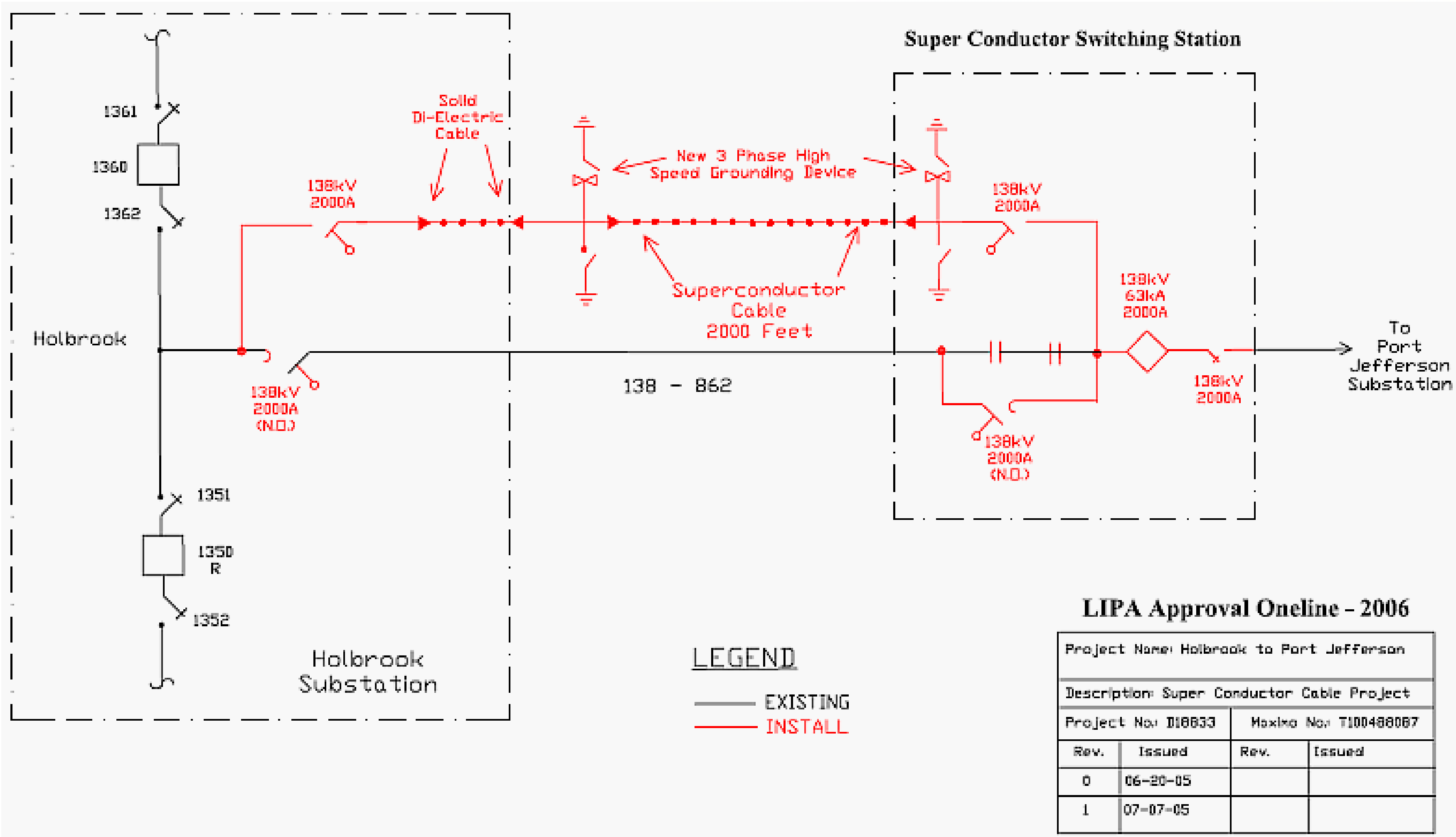
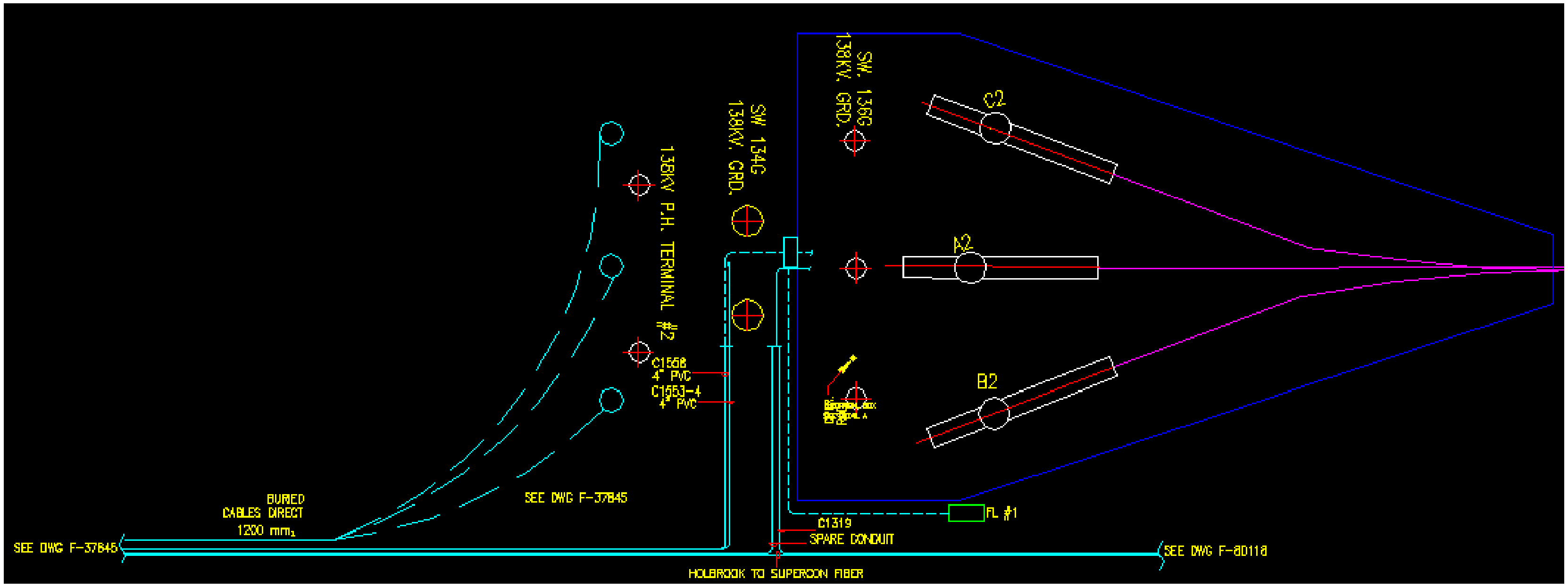
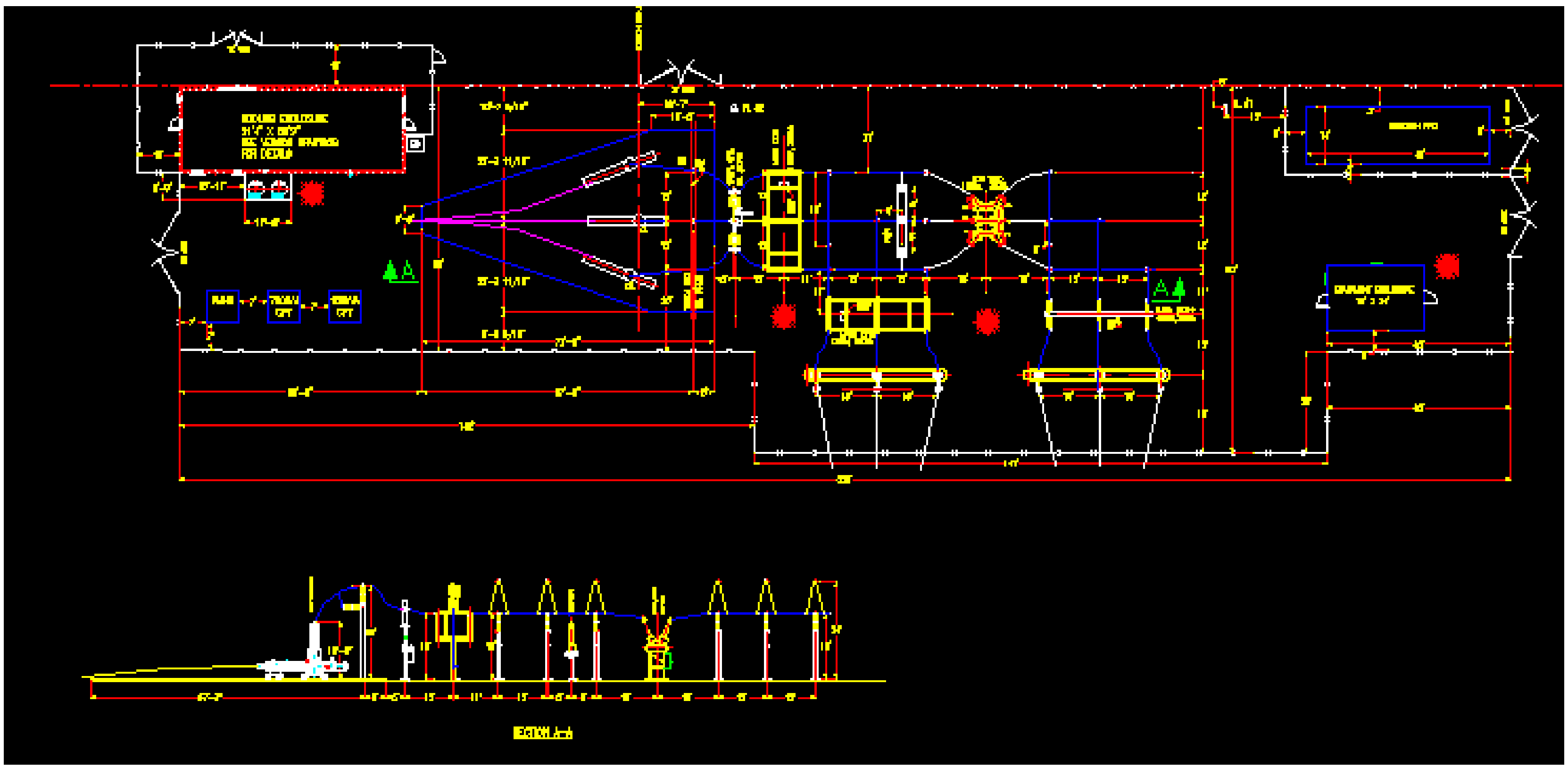
Holbrook Supercon One-Line



HOLBROOK SUPERCON





Original Site

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The Site Today

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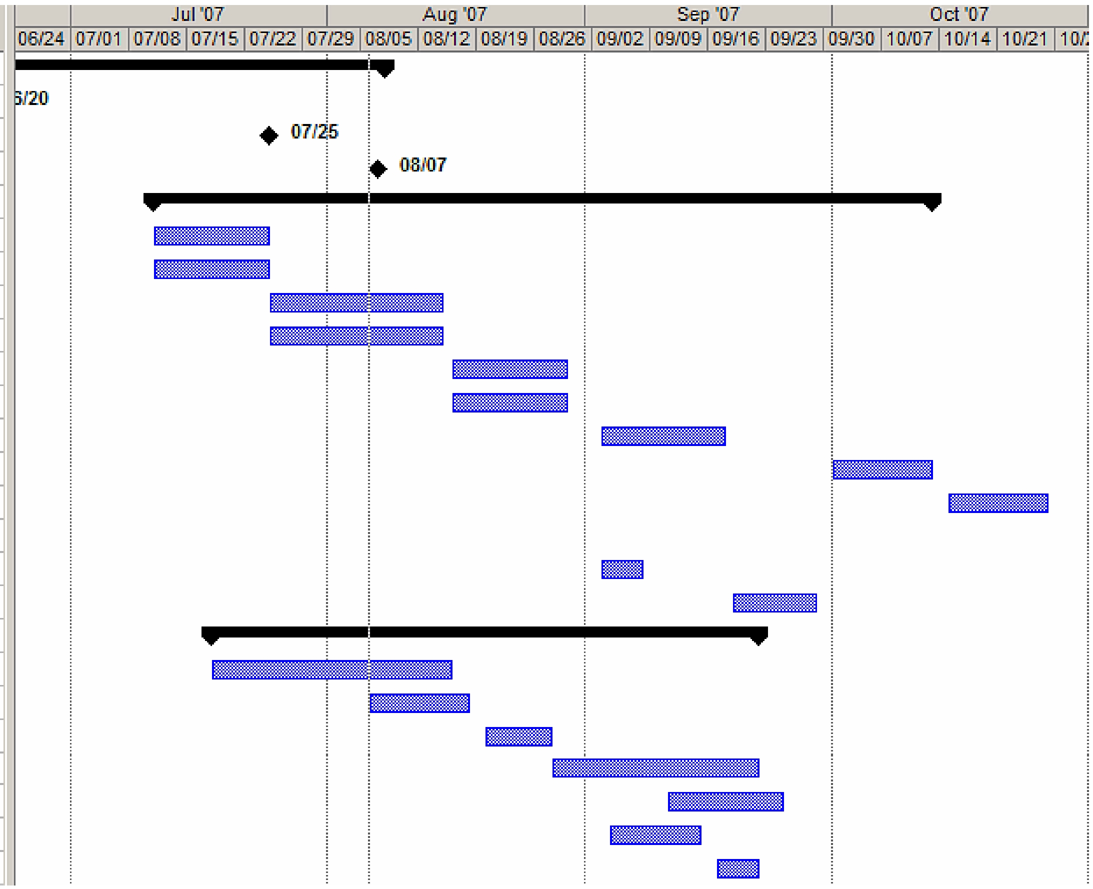
Remaining Construction

ID	Task Name	Start	Finish
1	**Cable Installation**	**06/20/07**	**08/07/07**
2	Pull Phase 1	06/20/07	06/20/07
3	Pull Phase 2	07/25/07	07/25/07
4	Pull Phase 3	08/07/07	08/07/07
5	**Terminal Installation**	**07/11/07**	**10/12/07**
6	Install Termination 1	07/11/07	07/24/07
7	Install Termination 4	07/11/07	07/24/07
8	Install Termination 2	07/25/07	08/14/07
9	Install Termination 5	07/25/07	08/14/07
10	Install Termination 3	08/16/07	08/29/07
11	Install Termination 6	08/16/07	08/29/07
12	Install Jumper Cables	09/03/07	09/17/07
13	Cable Cool Down	10/01/07	10/12/07
14	Commissioning	10/15/07	10/26/07
15			
16	Reinstall Fence at Grounding sub	09/03/07	09/07/07
17	Overhead Terminations	09/19/07	09/28/07
18	**138 kV Cable Dip**	**07/18/07**	**09/21/07**
19	Conduit	07/18/07	08/15/07
20	Steel work for 138 kV Dip	08/06/07	08/17/07
21	Pull Cable	08/20/07	08/27/07
22	138 kV Terminations	08/28/07	09/21/07
23	Tie in 138 kV Switches	09/11/07	09/24/07
24	Final Control Connections	09/04/07	09/14/07
25	Test Relaying	09/17/07	09/21/07



Summary

- ☑Cables Manufactured
- ☑Cryostats Manufactured
- ☑Terminations Manufactured
- ☑Refrigeration System Operational
- ☑Cables Installed
- ☑Terminations Installed (4/6)
- System Commissioned
- System Operational

World's First Installation of a Transmission Voltage HTS Cable is Imminent

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Project Confidence Matrix

Parameter	Production Item				
	Factory/Site Tested	Sample Tested	Full Scale Type Test	Subscale Test	Analysis
Voltage Withstand					
Termination					
Operating					
Lightning Impulse					
Cable					
Operating					
Lightning Impulse					
Current Carrying Capacity					
Termination					
Cable					
Heat Loads					
Cable					
AC Losses					
Dielectric Losses					
Cryostat Losses					
Termination					
AC Losses					
Cryostat Losses					
Refrigerator					
Capacity					
Flow capacity/pressure					
Wire					
Critical Current					
Hermeticity					
splice resistance					
splice hermeticity					
splice integrity					
Pressure Drop					
Faults					
Major Fault response					
Thru-fault response					
Material Properties used in model					n/a
Installation Methods					
Cable					
Termination					

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Plans for GFY-08

- Complete installation
- Energize Fall 2007
- Operate for 1 year
- Monitor fault current waveforms

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Demonstration of a Pre-Commercial Long-Length HTS Cable System Operation in the Power Transmission Network

DOE Peer Review Update
July 29-31, 2008
Arlington, VA

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Agenda

Introduction	**Jim Maguire, AMSC**
Project Overview	**Jim Maguire, AMSC**
FY 2008 Results and Performance	
Cable and Termination Installation	**Frank Schmidt, Nexans**
Refrigerator	**Shawn Bratt, Air Liquide**
Site	**Tom Welsh, LIPA**
Operating Experience	**Jim Maguire. AMSC**
FY 2009 Plans	**Jim Maguire, AMSC**

Project Overview

Jim Maguire, AMSC

LIPA Project Overview

- Long Island Power Authority – Holbrook Substation
- Electrical Characteristics
  - Design Voltage/Current – 138 kV/2400 A ~ 574 MVA
  - Design Fault Current – 51,000 A @ 12 line cycles (200ms)
- Physical Characteristics
  - Length ~ 600 m
  - HTS Conductor Length ~155 km
  - Cold Dielectric Design
- Hardware Deliverables
  - Three ~600 m Long Phase Conductors
  - Six 138 kV Outdoor Terminations
  - One Refrigeration System + Laboratory Pulse Tube System
- Commissioning – Spring 2008

World's First Transmission Voltage HTS Cable is Operational!

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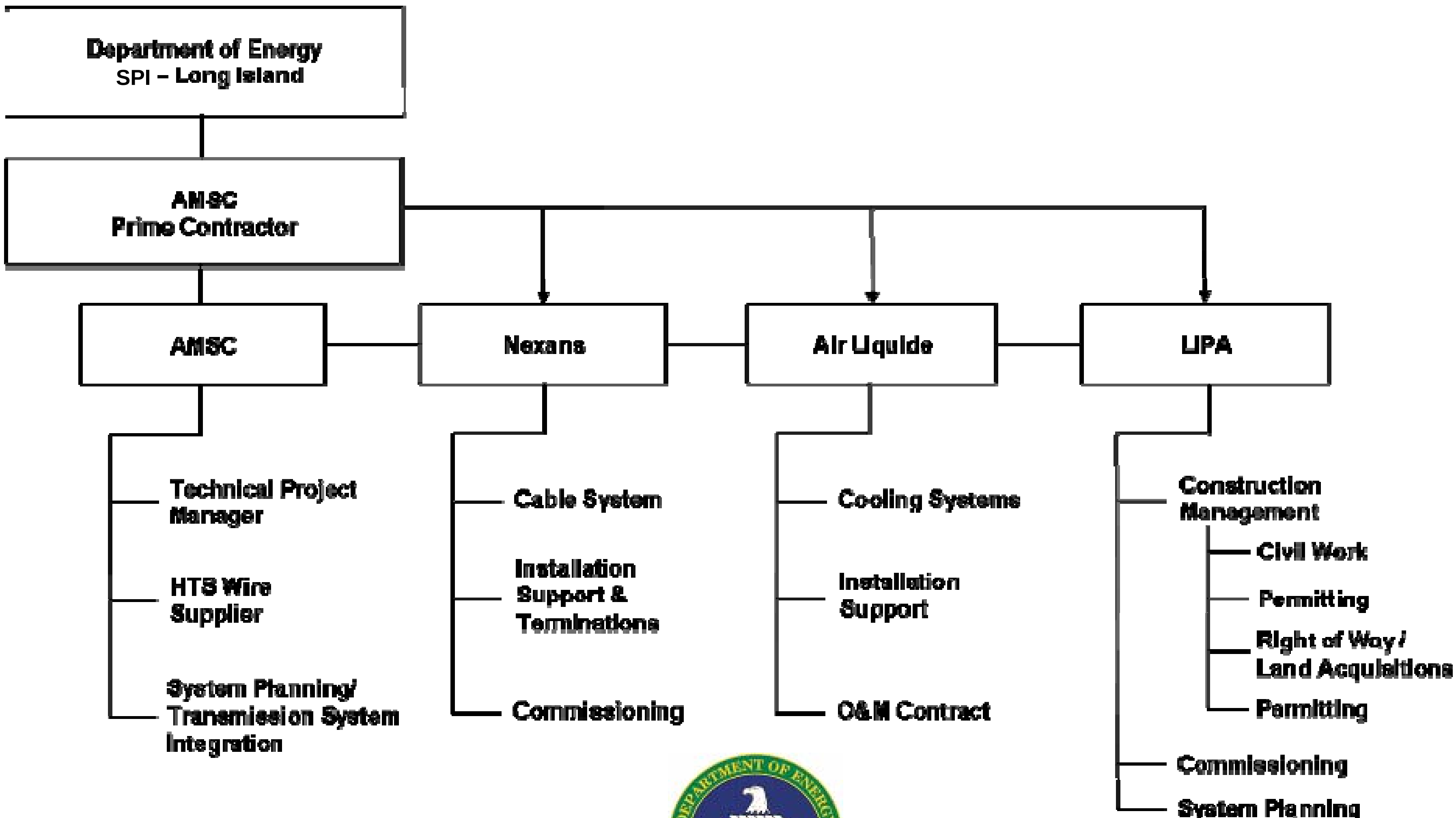
LIPA Cable Project and Project Team



LIPA Project Goals and Objectives

- Demonstrate a Transmission Voltage Level HTS cable in an operational Power Transmission Grid
- Demonstrate 138 kV Outdoor Termination for Superconducting Cable

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Major Challenges of LIPA Project

- System Design
  - 138 kV, 2,400 amp operation
  - Survive 51 kA @ 200 ms fault
  - Manage Through-Faults
- HTS Conductor Design
  - Handle real-world cabling stress using standard manufacturing equipment
- Termination Design
  - Qualify to 138 kV operation, 650 kV BIL
  - Safely manage voltage breakdown
  - Manage results from loss of cryostat vacuum

World's First Installation of a Transmission Voltage HTS Cable

Major Milestones in FY2008

- Complete Cable and Termination Manufacture – July 2007
- Complete Cable and Termination Shipping – August 2007
- Complete Cable and Termination Installation – October 2007
- Commission Refrigeration System – October 2007
- First Cool Down – November 2008
- Complete Cable Pre-energization tests – March 2008
- Cable Energization – April 2008

World's First Installation of a Transmission Voltage HTS Cable

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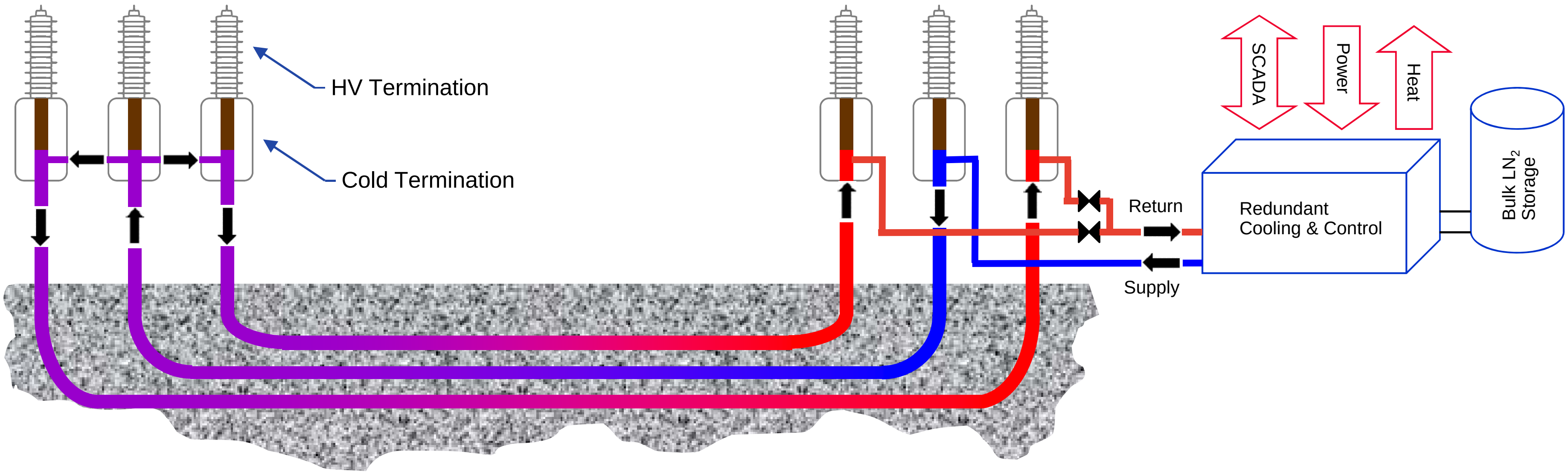
LIPA HTS Cable System



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LIPA Holbrook Substation Fault Requirements

138 kV Substation	Amps in Cable	Clearinging Time	Design	Remain on Line (Single Fault)
Holbrook	51000	12 cycles	√	Off Line
Port Jefferson	9500	12 cycles	√	On Line
Holtsville GT	3700	0.48 sec	√	On Line
Ronkonkoma	3100	12 cycles	√	On Line
Miller Place	1100	0.75 sec	√	On Line
Wading River	1200	0.75 sec	√	On Line
Caithness	2000	N/A	√	On Line
Brookhaven	1500	0.90 sec	√	On Line
Brentwood	1300	N/A	√	On Line
Ruland Road	1200	12 cycles	√	On Line

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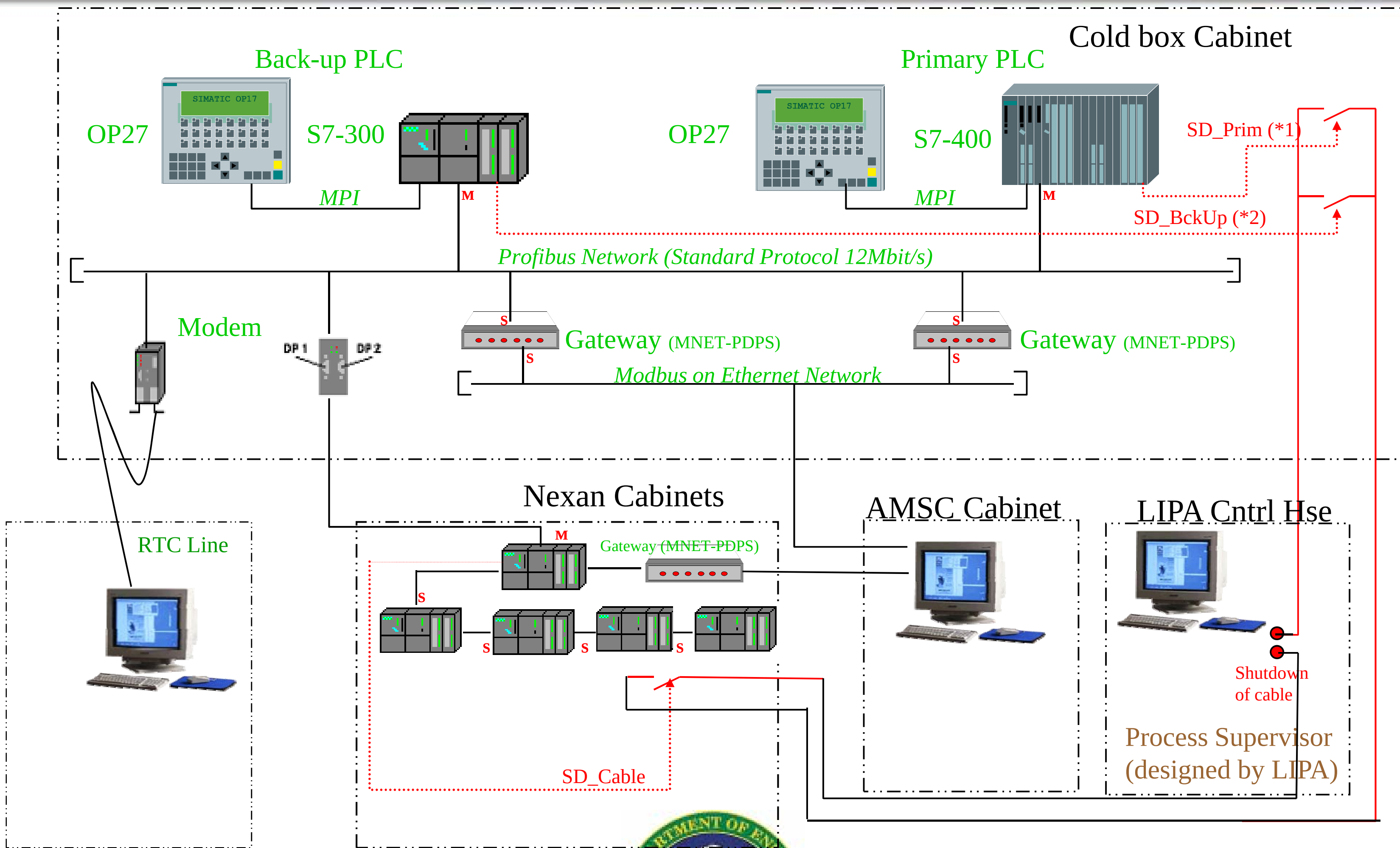
Cable System Monitoring and Controls



LIPA Project Status Update

- North End View
  - 3 terminations
  - Breakers
  - Grounding switches
  - 3 phase conductors

- South End View
  - 3 terminations
  - Grounding switches
  - 3 phase conductors

World's First Transmission Voltage HTS Cable Became Operational in 2008

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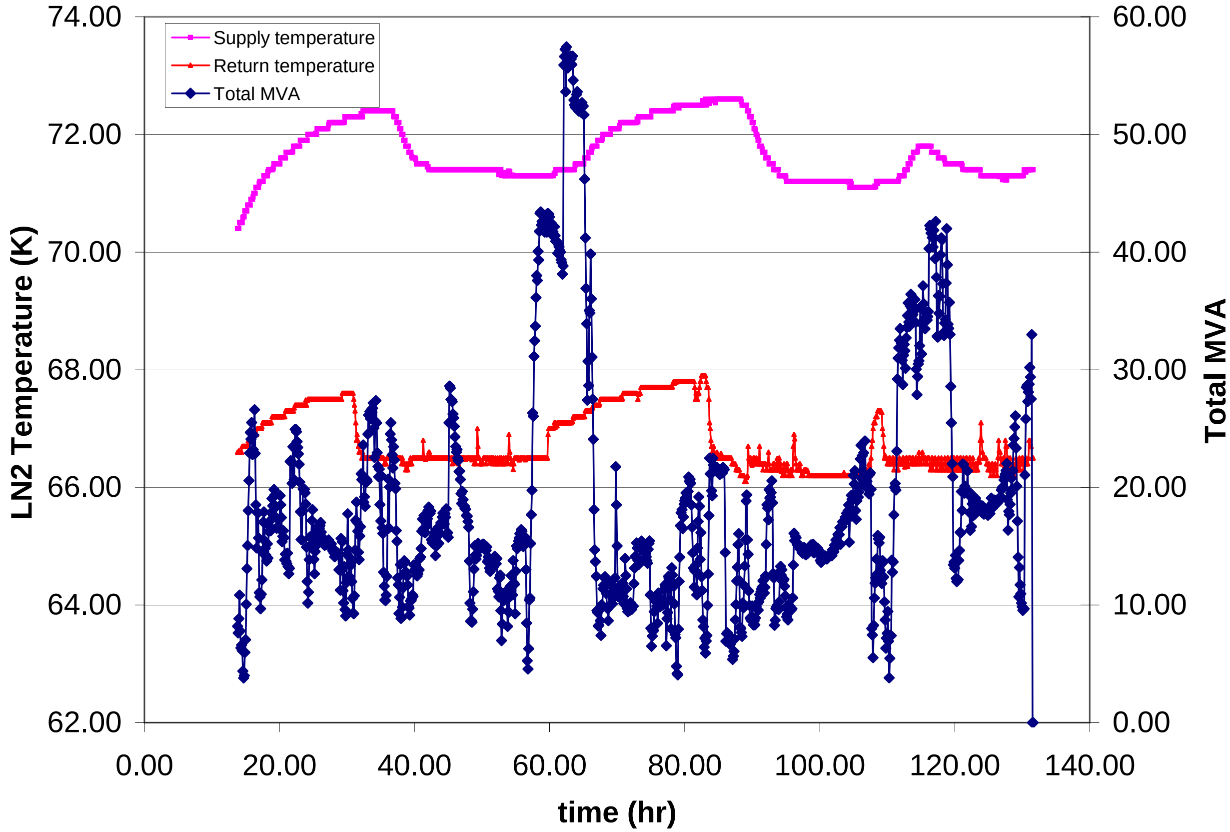
Steady State Operation

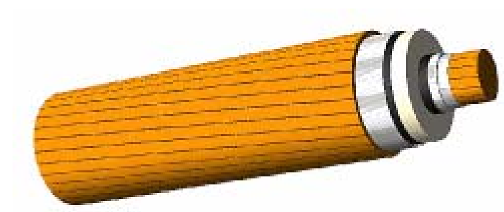


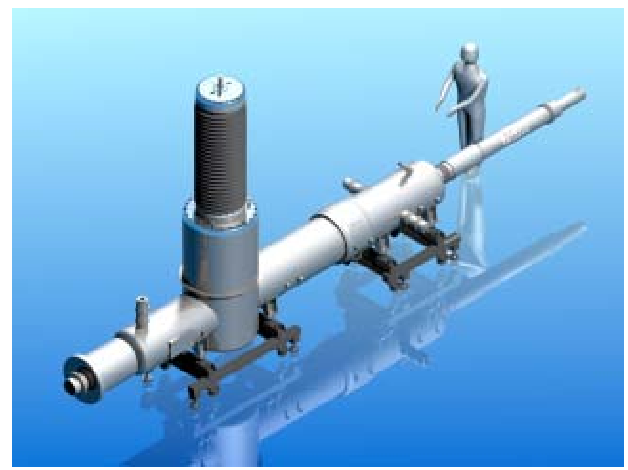
Cable and Termination Installation

Frank Schmidt, Nexans

Components of the HTS Cable System

- Superconducting Cable System
  - Cable Core
    - Transport the current
    - Withstand the voltage
  - Cryostat
    - Insulate thermally – keep the cable cold
    - Transport the liquid nitrogen
  - Termination
    - Connect the system to the grid
    - Manage the transition between cold temperature and room temperature
    - Provide connection to the cooling system





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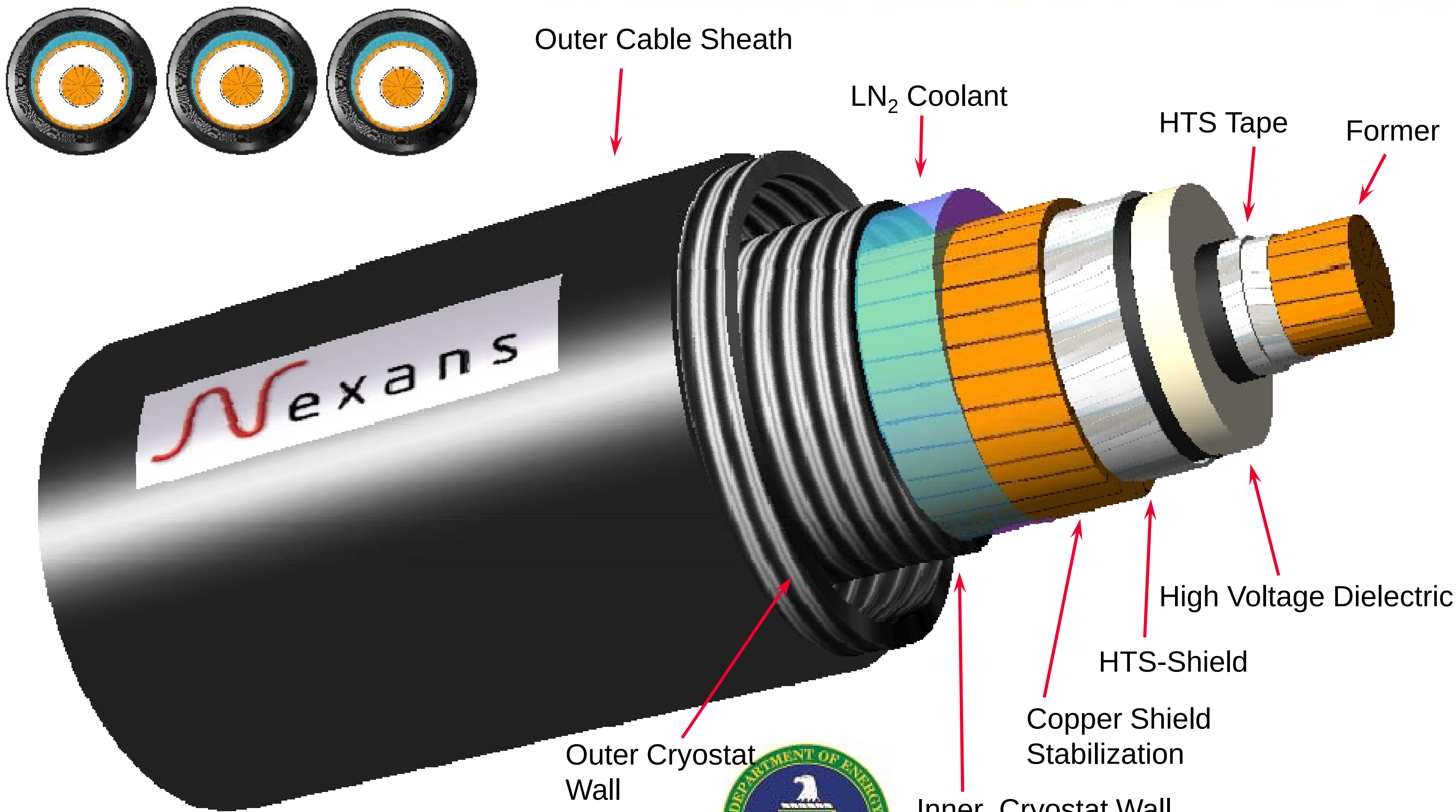
LIPA HTS Cable Design



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Cryogenic Envelope

- Design
  - Two concentric longitudinal welded corrugated stainless steel tubes
  - Superinsulation (Al coated foil with spacer fleece) in between the tubes
  - Low loss spacer
  - Vacuum space
  - Pumping ports every 100 meter
- Manufactured using longitudinal welding and corrugation process
- Quality assurance
  - High sensitivity helium leak testing to ensure long-term vacuum quality

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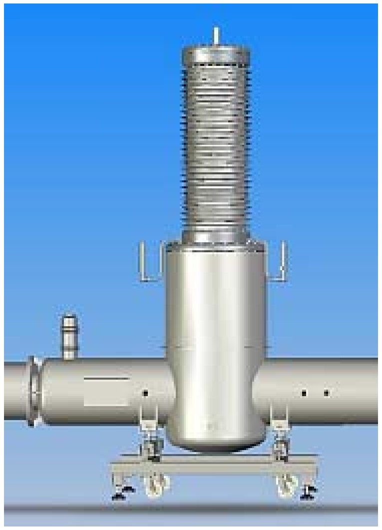
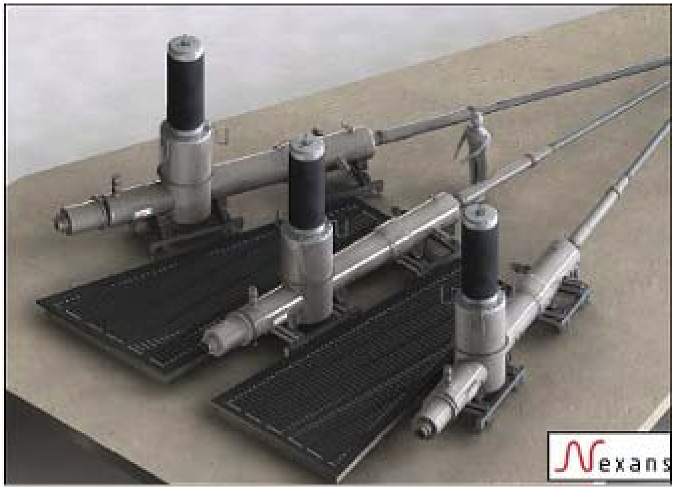
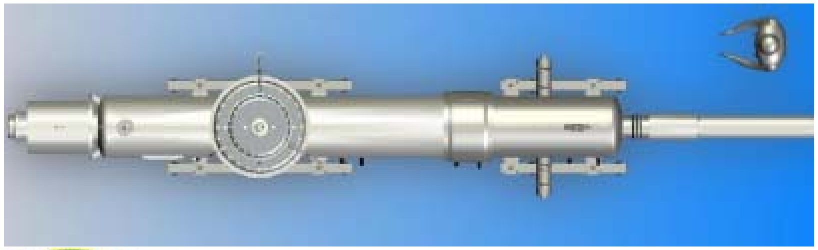
LIPA Project - Termination Concept



- Vertical part:
  - Thermal gradient management (from 65 to 300 K)
  - Connection to the grid



- Horizontal part:
  - Connection to HTS cable
  - Management of cable thermal shrinkage



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Prototype Testing

- A test program has been defined together with the DOE review team based on existing standards
- Tests included
  - High voltage dielectric tests
  - High current tests
  - Hydraulic tests
  - Load cycles
  - Loss measurements

Type test performed prior starting manufacturing

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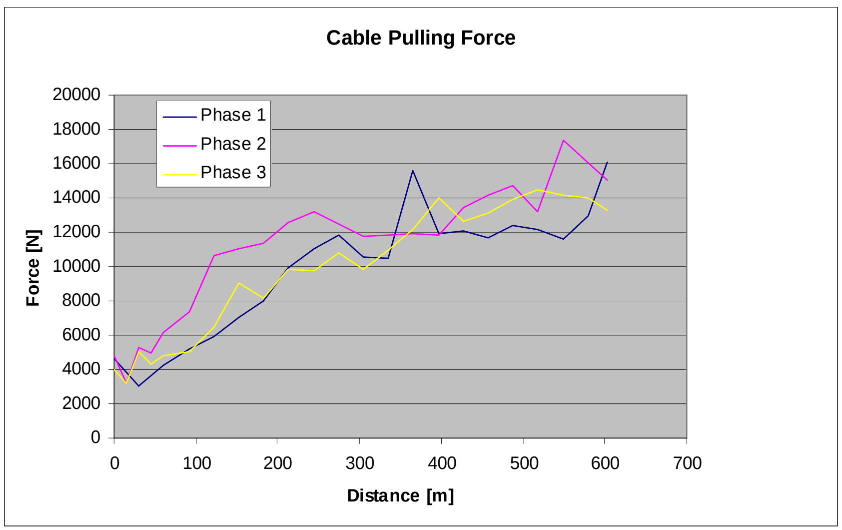
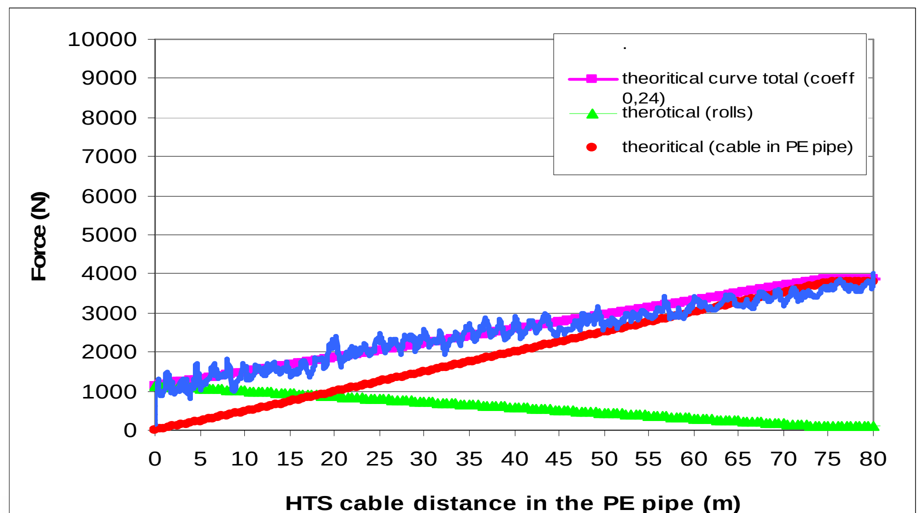
Installation - Cable Pulling

- Cable pulling operation was tested using a 70 meter long test setup to verify method and estimate force
- Cable puling on site was achieved without issues
- Vacuum level of cryostat was checked before and after pull
- Pulling force was recorded and compared to estimated values





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Installation - Terminations

- Terminations were installed with the cable phase in place
- No issues identified during termination work

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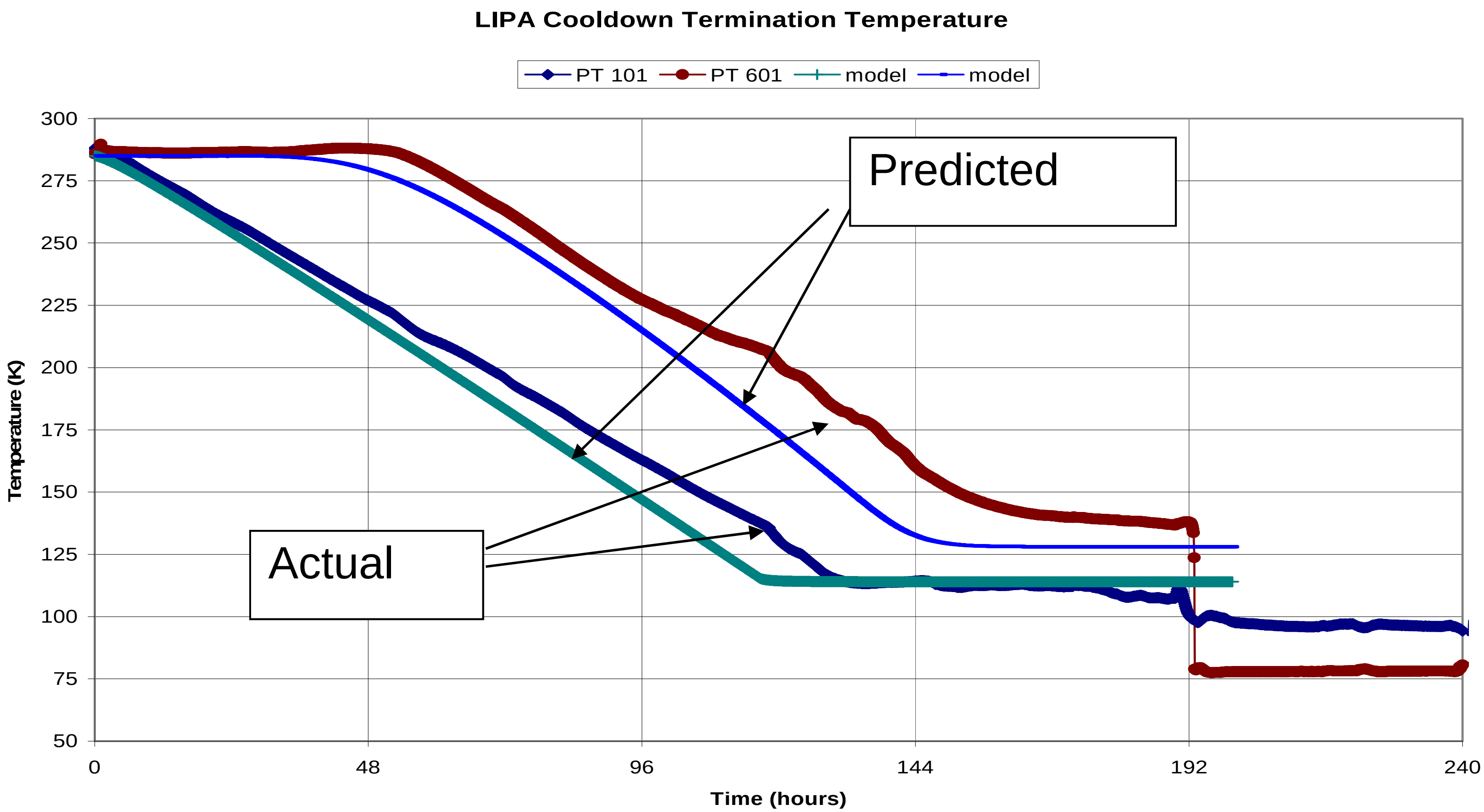
Cable cool down



Cable Issue After First Cool Down

- Cable capacitance measurement done after first cool down showed unexpected results
- Further analysis showed that a connection inside two of the terminations was missing
- Cable system was warmed again to analyze and solve the issue
  - Issues identified in the termination due to
    - Assembly procedure (not possible to detect issues before failure)
    - Manufacturing tolerance of some termination parts
  - Issue solved by
    - Change of assembly procedure (enabled checking the component before failure to see if it was operating correctly)
    - Change of some components (in all terminations)

Termination design improved based on analysis of experienced issue

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Cable System On Site Testing

- Prior to energization the installed cable system was tested after cool down
- AC-high voltage test
  - Test performed using a series AC-resonant test set
  - Voltage of 1.5 U0 applied for one hour on each phase separately
  - Cable system successfully passed the test
- Partial Discharge Measurement
  - During AC-high voltage test PD was measured by external consulting company to identify possible dielectric issue
  - PD-sensitivity check was done resulting in sensitivity of approximately 15 pC
  - PD was measured at the two cable ends simultaneously using a measurement device suited for on site testing
  - Second measurement system (one end only) was used to double check the measurement result
  - No PD from the cable system could be detected

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Cable Energization

- AC-High Voltage test completed successfully
  - 1.5 U0 applied at each phase for one hour
  - PD measurement completed No partial discharge detected
- 24 hour dielectric soak test completed successfully
  - Cable connected to LIPA grid at one end
- Cable connection at both ends completed on April 22nd
  - Operation with parallel over-head line for 24 hours
  - Operation without parallel path afterwards

Cable Commissioning Successfully Completed

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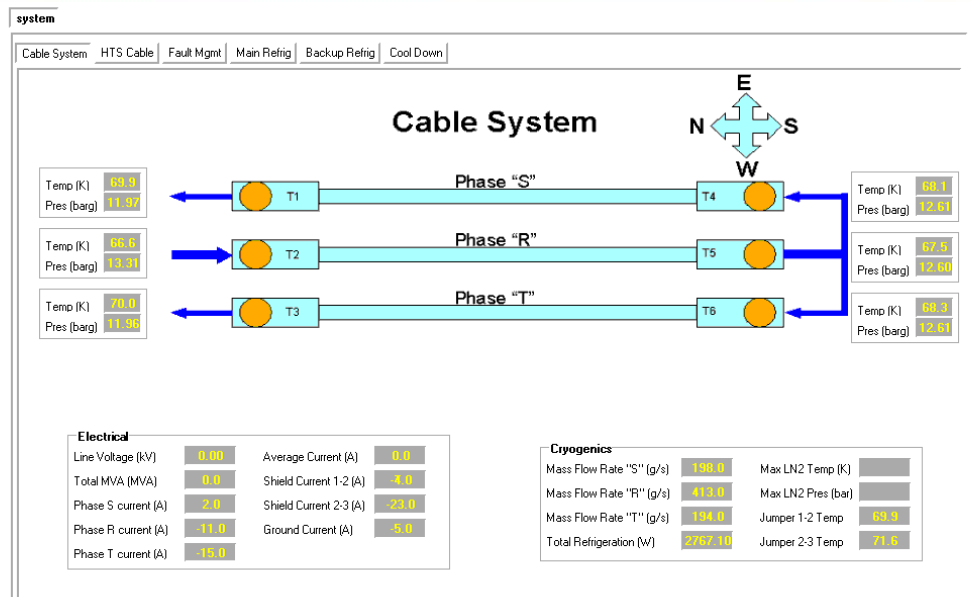
Cable Operation - Measurements

- The cable system is monitored regarding a variety of parameters to
  - Ensure safe operation
  - Gain measurement data to compare with design results
- Measurement data analyzed so far:
  - Cable cool down behavior
  - Cable cryostat thermal loss
  - Nitrogen pressure drop
  - Temperature increase due to dielectric loss
  - Temperature increase due to AC-loss
  - Thermal behavior of termination (bushing)
  - Cable system time constants



Cable System Measurements in very good Agreement with Design Results

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Refrigerator Status – Performance

Shawn Bratt, Air Liquide

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Progress Update

- Performance testing completed Nov. 30th 2007
- Cable Cool-down completed March. 1st 2007
- Operation & Maintenance Ongoing

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REVIEW- Final Design-Refrigerator Subsystem

- Refrigerator Design Summary
  - Re-use of Detroit refrigerator from previous Pirelli SPI Cable Program
  - Upgrades to system were necessary to adapt it to LIPA project and include:
    - Upgraded cooling capacity (+38%) for primary and back up systems
    - New system for the cable cool down “Cool Down Skid”
    - New buffer for fault reaction and recovery “Distribution Box”
    - Telemetry to allow remote monitoring and control “Control/Command Cabinet”
    - New 13,000 Gal tank for LN2 supply
  - Operated 6 months prior to cable commissioning

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Final Design Performance Criteria

- Primary System Refrigeration: 5.65 kW @ 65K – 72K, 375 g/s LN2, 78 g/s GHe
  - 5.066 kW cable cryostat/termination loss
  - 333 W refrigeration system loss
  - 251 W extra capacity (5% Margin)
- Backup System Refrigeration: 6.77 kW (20% Margin)
  - Existing Backup System: 4.27 kW
  - New Added LN2 Module: 2.5 kW
- LN2 Consumption
  - Existing Backup System: 30 g/s (135 L/hr)
  - New LN2 Module: 13.4 g/s (60 L/hr)
  - A 13,000 gal Tank to Provide at minimum 3 Day Supply (4000 gallon heel)

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Performance Testing

Final Testing Period (without cable) – Sept 21st to Oct 30th

- Performed Primary Refrigerator maximum load performance testing
- Performed Backup Refrigerator maximum load performance testing

Results

- Primary refrigerator performed to **5.74 kW, 400 g/s, 65-72,2K**
- Backup refrigerator performed to **6.26 kW, 375 g/s, 64.9-73.1K**

Performance Testing

Performance Testing period (with cable) – Nov 23rd to Nov 30th

- Measured Primary Refrigerator load performance while connected to cable
- Measured Backup Refrigerator load performance while connected to cable

Results

- Primary refrigerator performed at **4.04 kW, 405 g/s, 65.5-70.5K**
- Backup refrigerator performed to **4.06 kW, 395 g/s, 65.3-70.4K**

LN2 Consumption Measured

- Backup Refrigerator System total: ~200 L/hr

Performance Testing

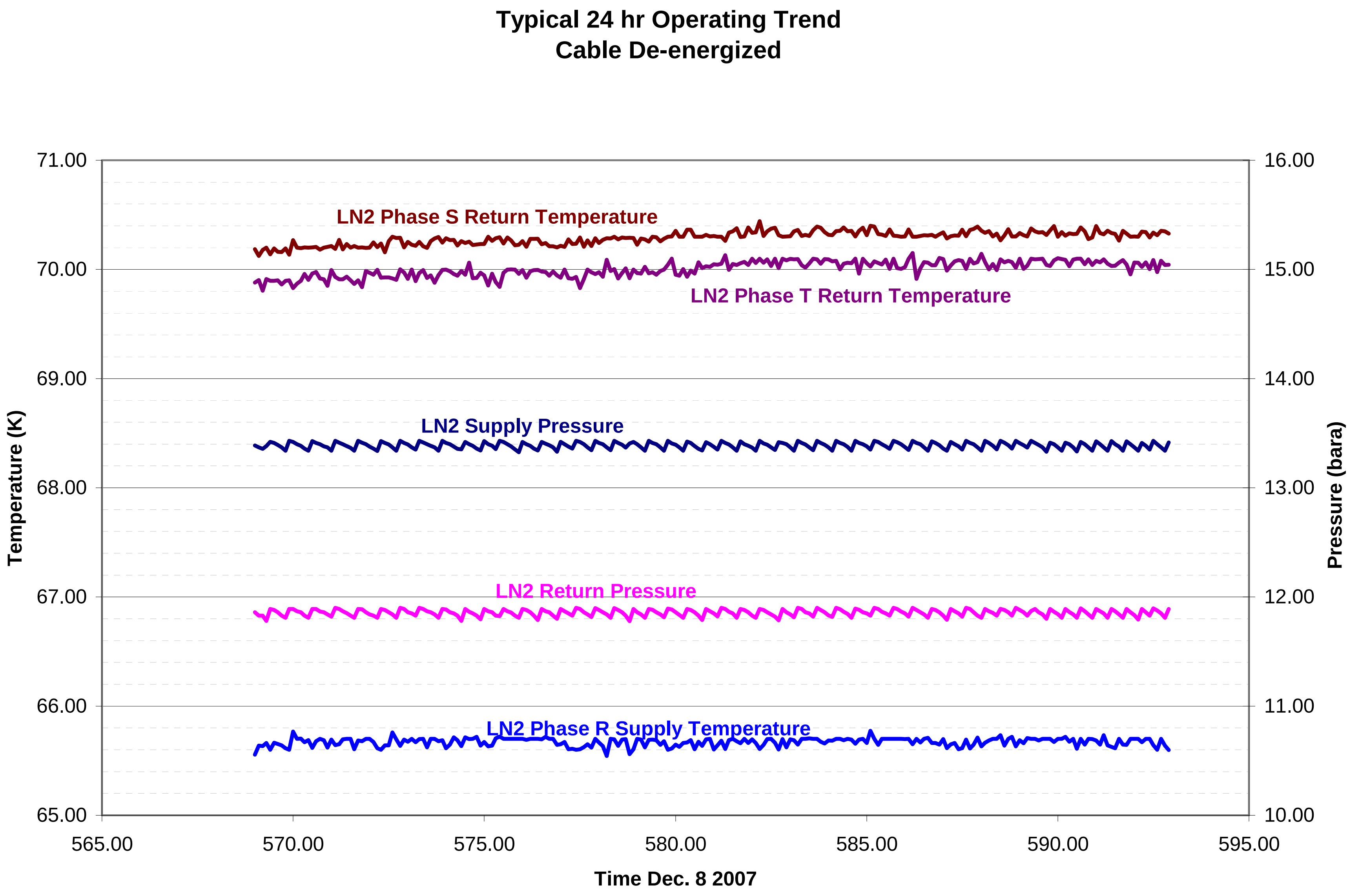
Performance with cable energized – April 23rd

- Measured Primary Refrigerator load performance while cable energized

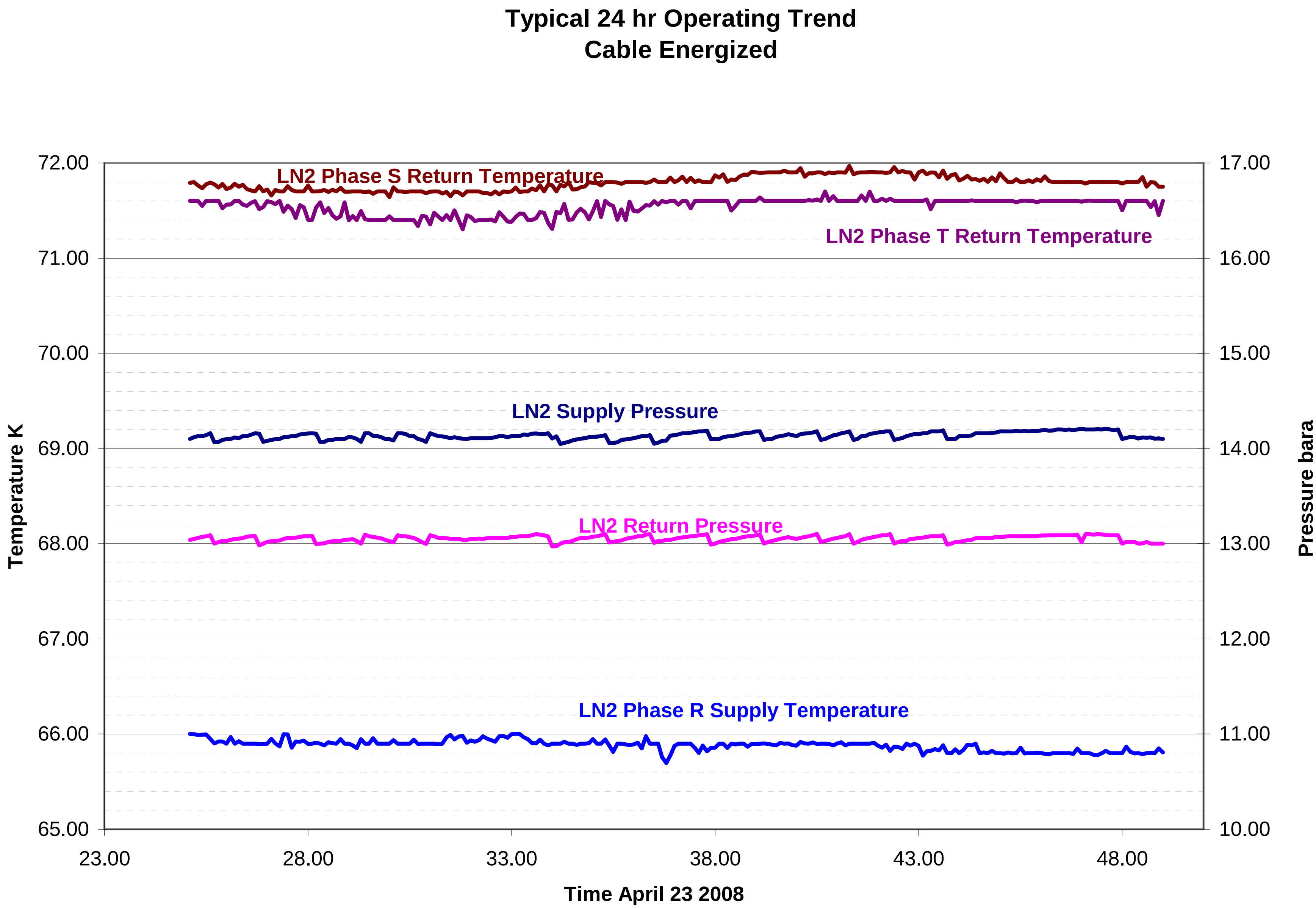
Results

- Primary refrigerator performed at **5.56 kW, 415 g/s, 65.3-72K**

Operation


Typical 24 hr Operating Trend
Cable De-energized
LN2 Phase S Return Temperature
LN2 Phase T Return Temperature
LN2 Supply Pressure
LN2 Return Pressure
LN2 Phase R Supply Temperature
71.00
70.00
69.00
68.00
67.00
66.00
65.00
Temperature (K)
16.00
15.00
14.00
13.00
12.00
11.00
10.00
Pressure (bara)
565.00
570.00
575.00
580.00
585.00
590.00
595.00
Time Dec. 8 2007

Operation



Typical 24 hr Operating Trend
Cable Energized
LN2 Phase S Return Temperature
LN2 Phase T Return Temperature
LN2 Supply Pressure
LN2 Return Pressure
LN2 Phase R Supply Temperature
Temperature K
Pressure bara
Time April 23 2008
72.00
71.00
70.00
69.00
68.00
67.00
66.00
65.00
17.00
16.00
15.00
14.00
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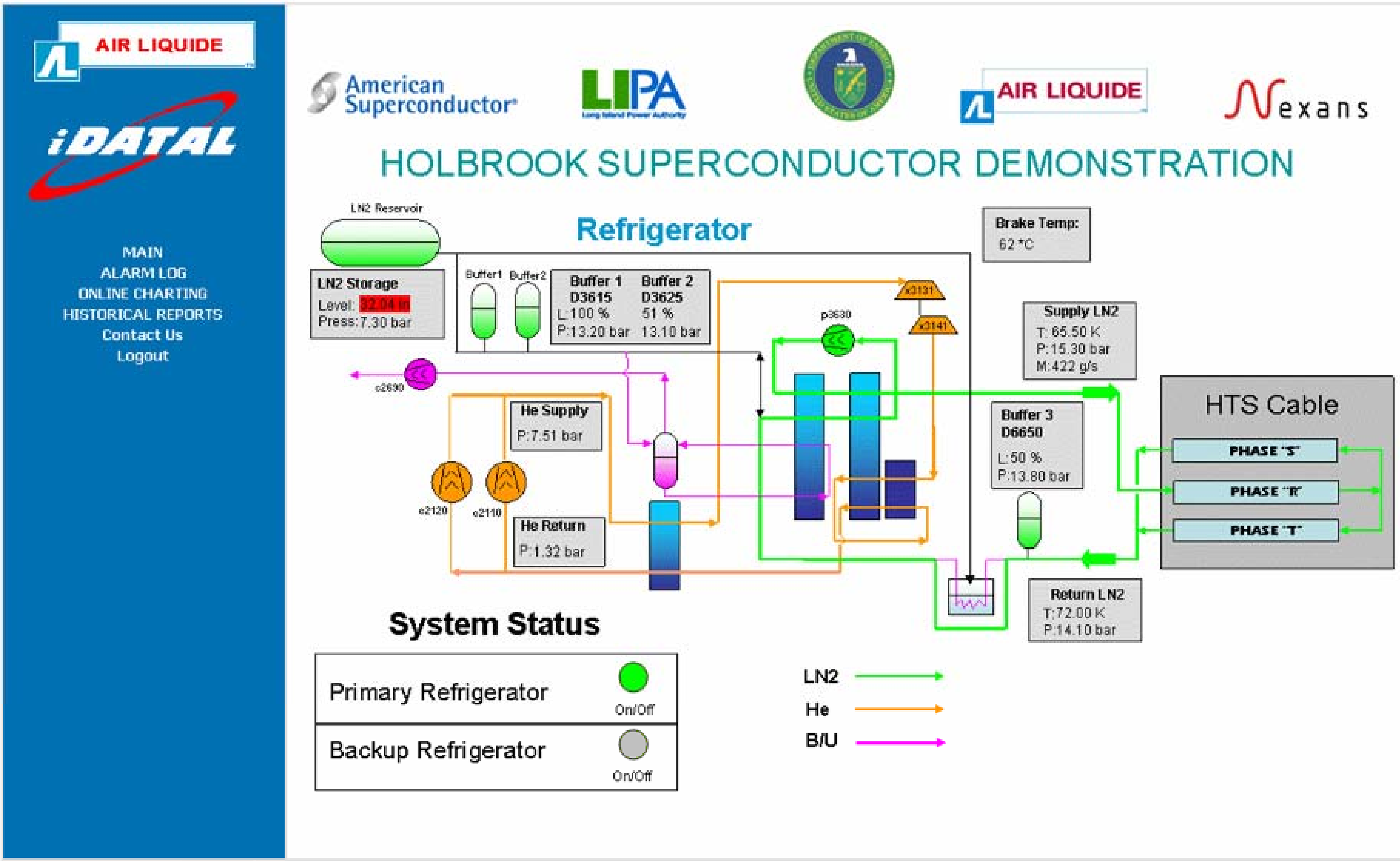
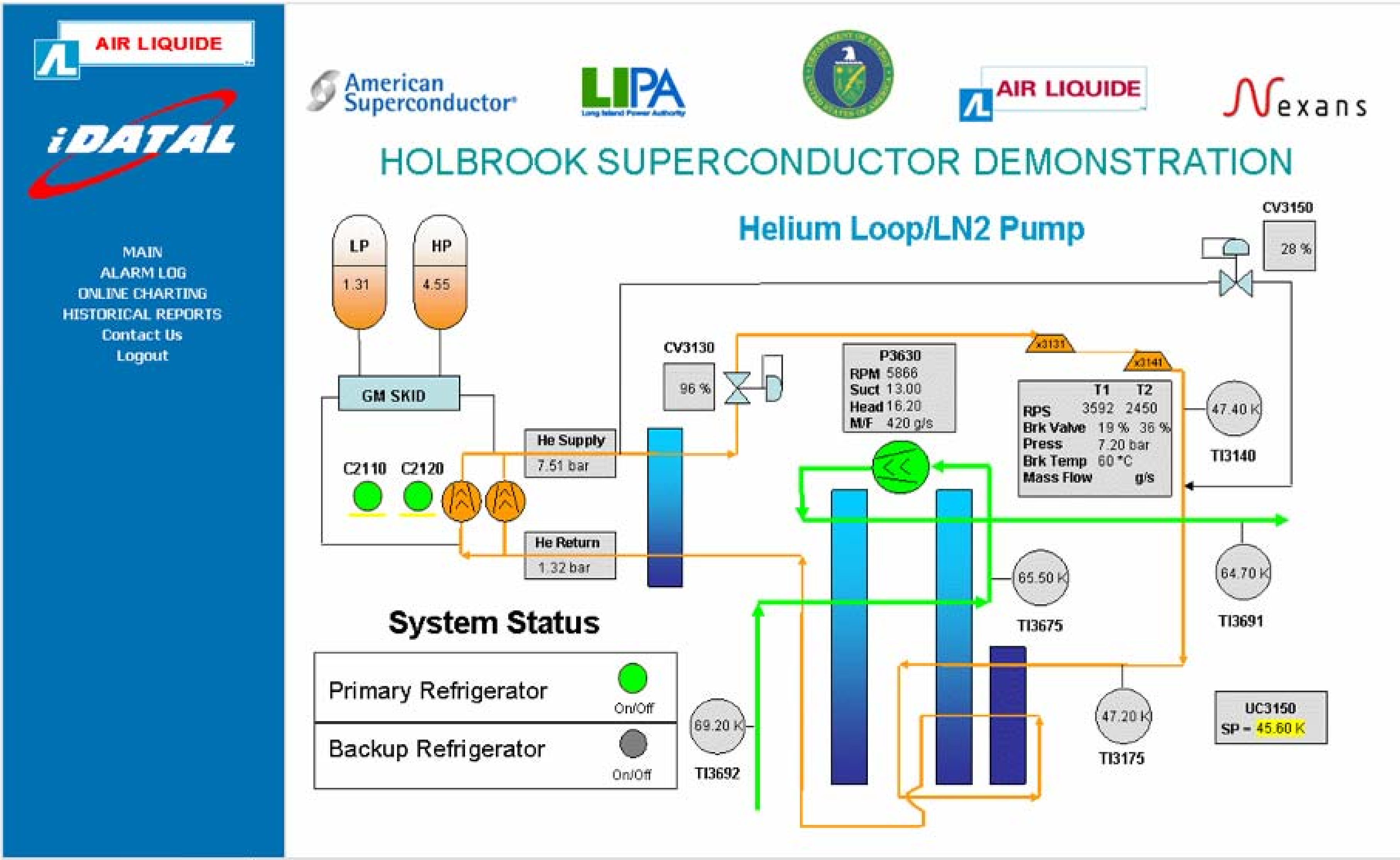
Operation

Remote Supervision – Main Synoptic



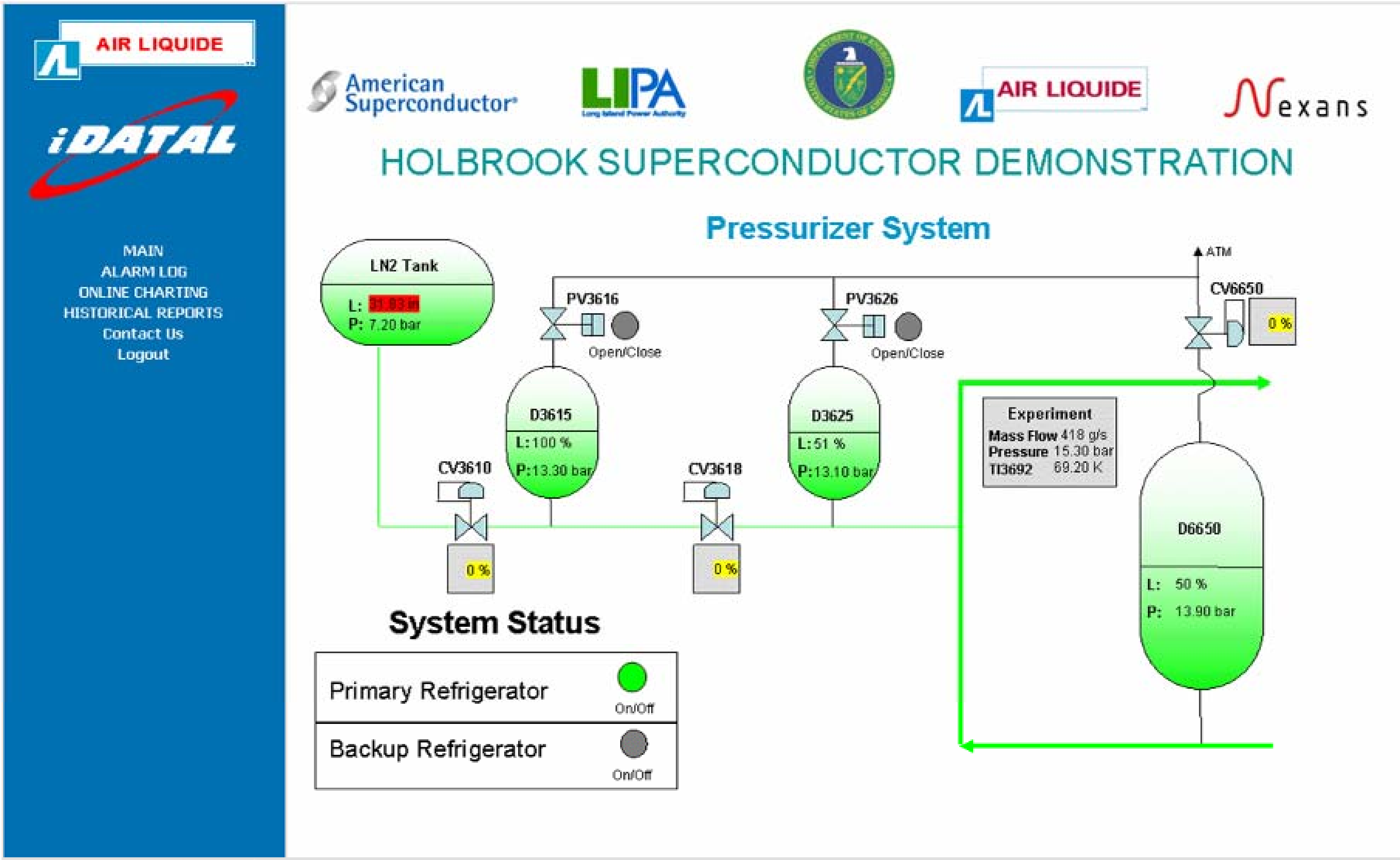
Operation

Remote Supervision – Gas Management Synoptic



Operation

Remote Supervision – Pressurizer System Synoptic



Operation Statistics

- 3824 Operating Hours Nov 24, 2007 – July 25, 2008
- Several Trip Events
  - Pump VFD issues with network capacitor bank operation
  - Compressor issues due to supply voltage sag
  - Water Chiller issues with high ambient temperature, > 40°C
- Maintenance Activities Performed to date:
  - September 2007 –
    - Compressors' oil and filter change
    - LN2 Pump bearing replacement
    - LN2 and He cryogenic valve seat replacements
    - Recertification of relief valves
  - Ongoing –
    - Routine inspections and logs
    - Grease compressors' bearings
    - Clean compressor filters and exchangers

BI-WEEKLY TASKS
Advanced Parameters Check
1 x Distant
1 x Site Visit

	DECEMBER						JANUARY			FEBRUARY			MARCH					
	Week 1			Week 2			Week 3			Week 4			Week 5			Week 6		
	Value	Date	Init	Value	Date	Init	Value	Date	Init	Value	Date	Init	Value	Date	Init	Value	Date	Init
WEEKLY TASKS - ON SITE																		
He/LN2 Cryogenic Plant																		
Check Cooling Water Parameters	X	12/12	wak										X	3-Mar	wak	X	12-Mar	wak
Inspect all valves, flanges, and connections	X	12/12	wak										X	3-Mar	wak	X	12-Mar	wak
Check Pressure Drop of Turbines, adjust as req.	n/a	12/12	wak										X	3-Mar	wak	X	12-Mar	wak
Check rotary vacuum pump oil, change as req.	X	12/12	wak										X	3-Mar	wak	X	12-Mar	wak
Check diffusion pump fluid level	**CHG**	12/12	wak										X	3-Mar	wak	X	12-Mar	wak
Check level of D3625 and refill if not 100%*	n/a	12/12	wak										X	3-Mar	wak	X	12-Mar	wak
Compressor Station																		
Check cooling oil level	X	12/12	wak										X	3-Mar	wak	X	12-Mar	wak
Check and clean or renew filter mats	n/a	12/12	wak															
Distribution Box																		
Inspect all valves, langes, and connections	X	12/12	wak										X	3-Mar	wak	X	12-Mar	wak
Nexans' Terminations																		
General Visual Check (from outside fence)	n/a	12/12	wak										X	3-Mar	wak	X	12-Mar	wak
Additional LN2 Module																		
General Visual Check	X	12/12	wak				X	24-Jan	WAK	X	19-Feb	WAK	X	3-Mar	wak	X	12-Mar	wak
Monitor Gas Stocks																		
LN2 Tank + visual inspection	32'	12/12	wak	30'	12/18	wak							X	3-Mar	wak	X	12-Mar	wak
GN2 Bottles for instrument air	low	12/12	wak										X	3-Mar	wak	X	12-Mar	wak
GHE Buffer levels	low	12/12	wak				X	24-Jan	WAK				X	3-Mar	wak	X	12-Mar	wak
GHE bottles	low	12/12	wak				X	24-Jan	WAK				X	3-Mar	wak	X	12-Mar	wak

Holbrook Superconductor Site Status

Tom Welsh, Long Island Power Authority

LIPA Service Territory – New York State ~ Long Island

- LIPA is a NYS Authority established in 1998 as the primary electric service provider for LI
  - 1207 sq. mi. *(roughly 100 miles by 12 miles)*
  - Nassau, Suffolk and the Rockaway Peninsula
- Population of about 3 million
  - 1.1 million residential customers
  - 100,000 commercial customers
  - Since 1998, 5.7% population growth *(172,000 more people)*
- $2.0 billion invested in system upgrades and improvements
- LIPA owns the assets
  - All T&D operations and most IS systems are outsourced

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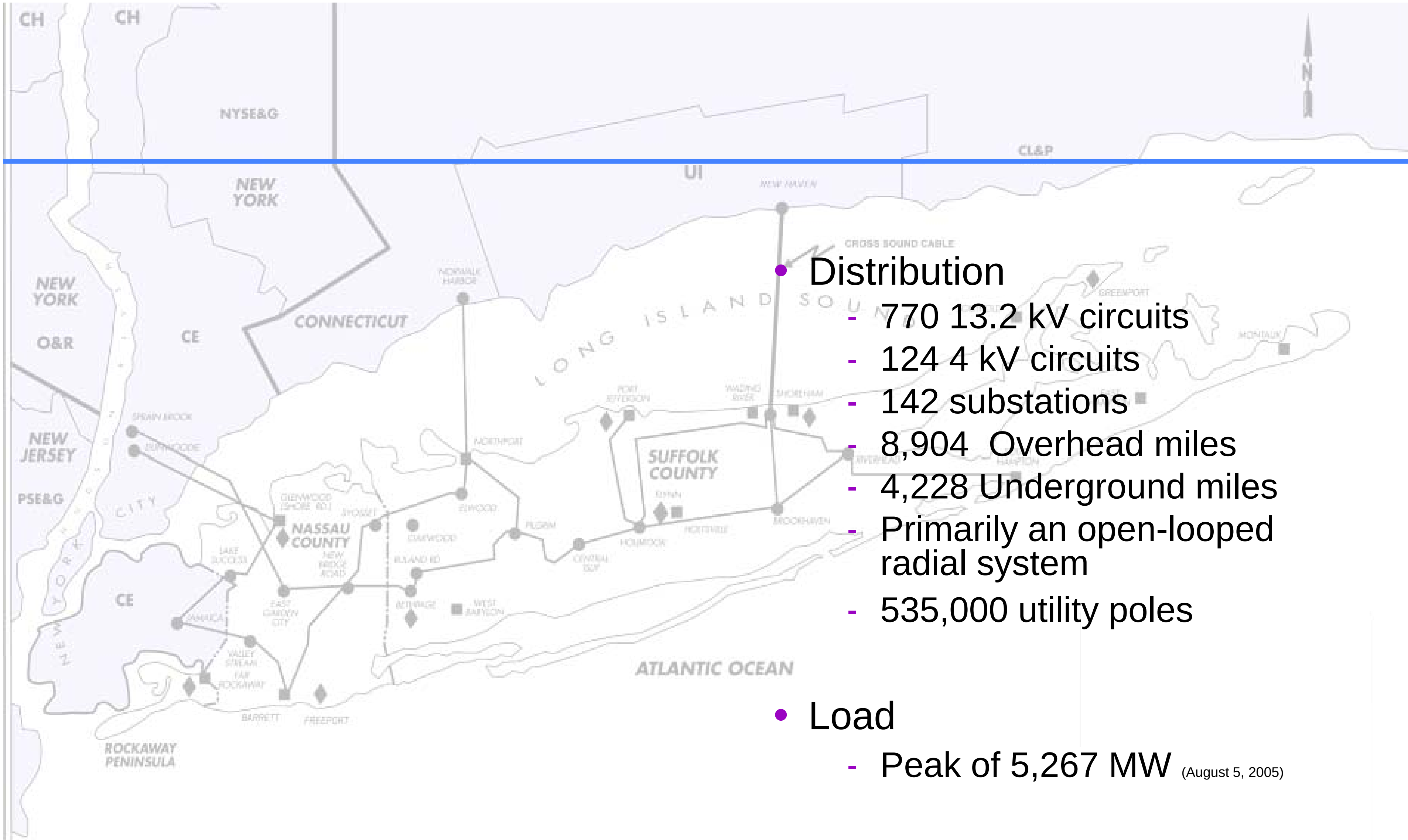

- Distribution
  - 770 13.2 kV circuits
  - 124 4 kV circuits
  - 142 substations
  - 8,904 Overhead miles
  - 4,228 Underground miles
  - Primarily an open-looped radial system
  - 535,000 utility poles
- Load
  - Peak of 5,267 MW (August 5, 2005)

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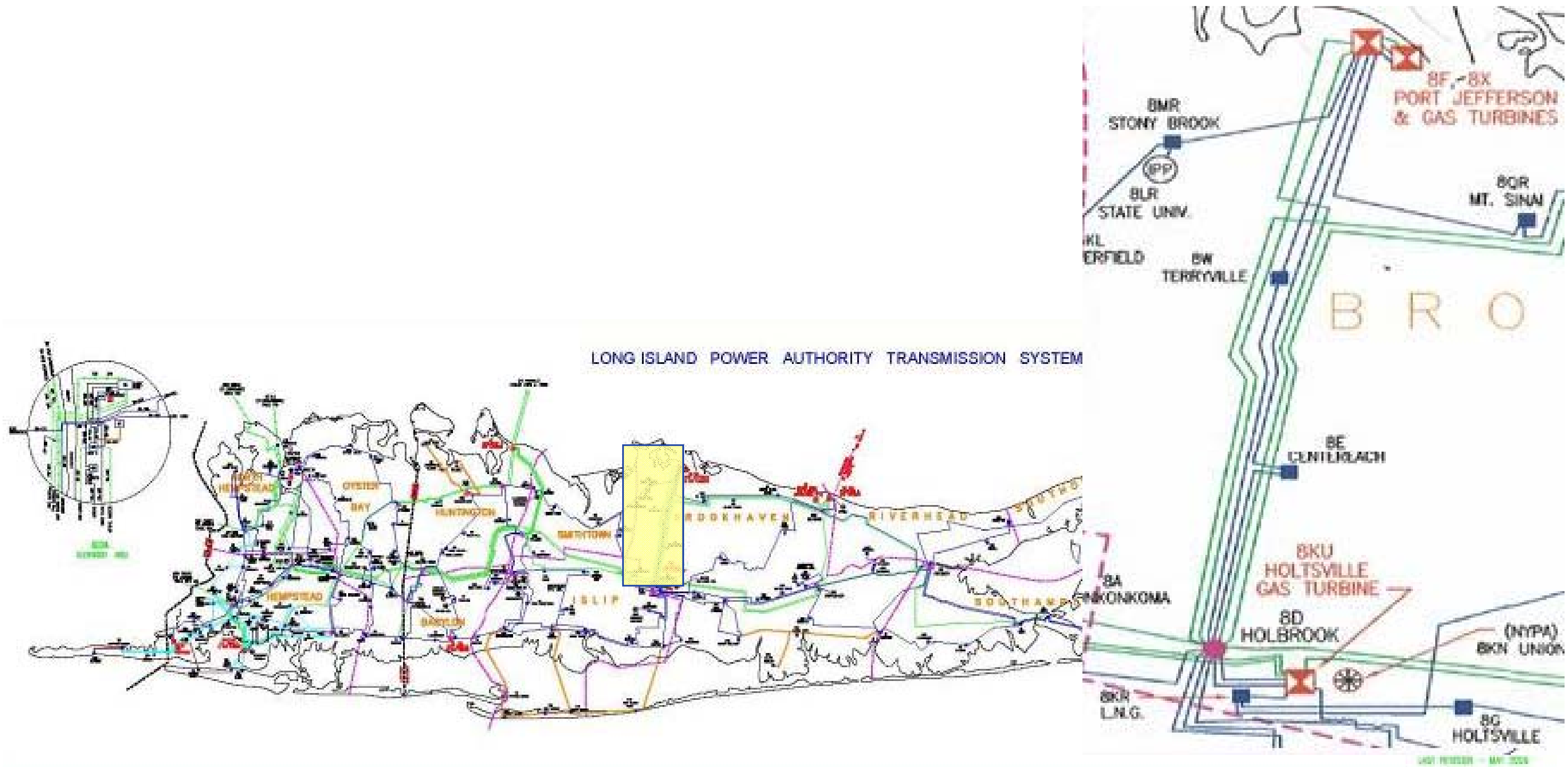
LIPA Transmission System



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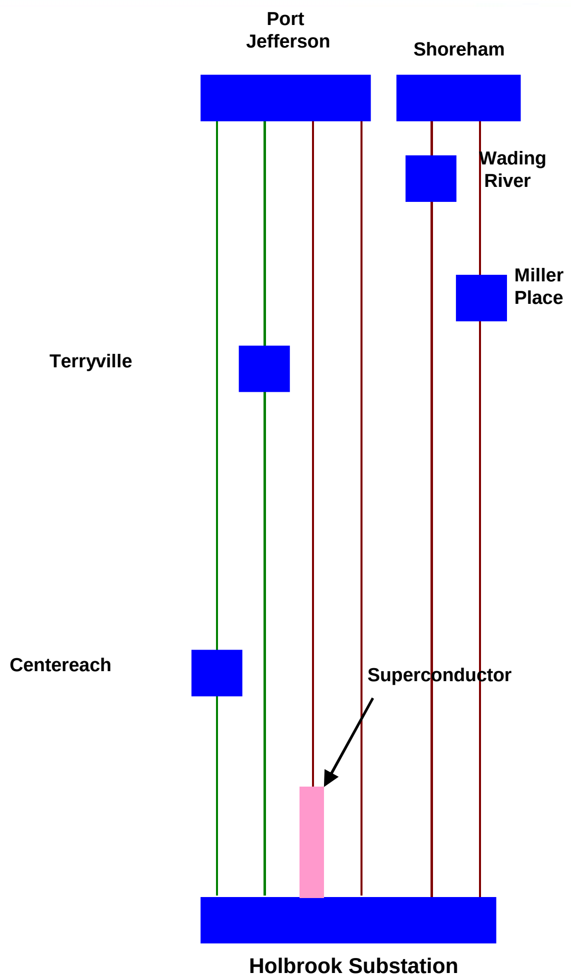
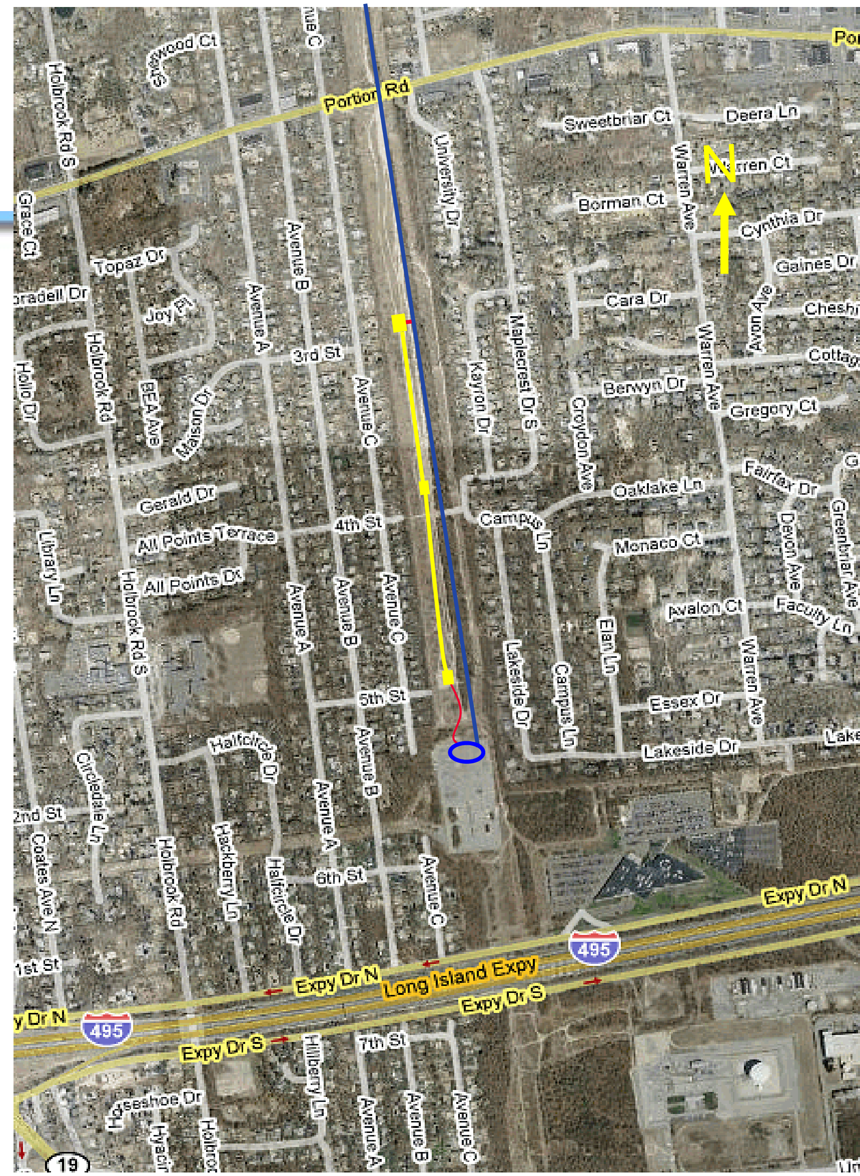
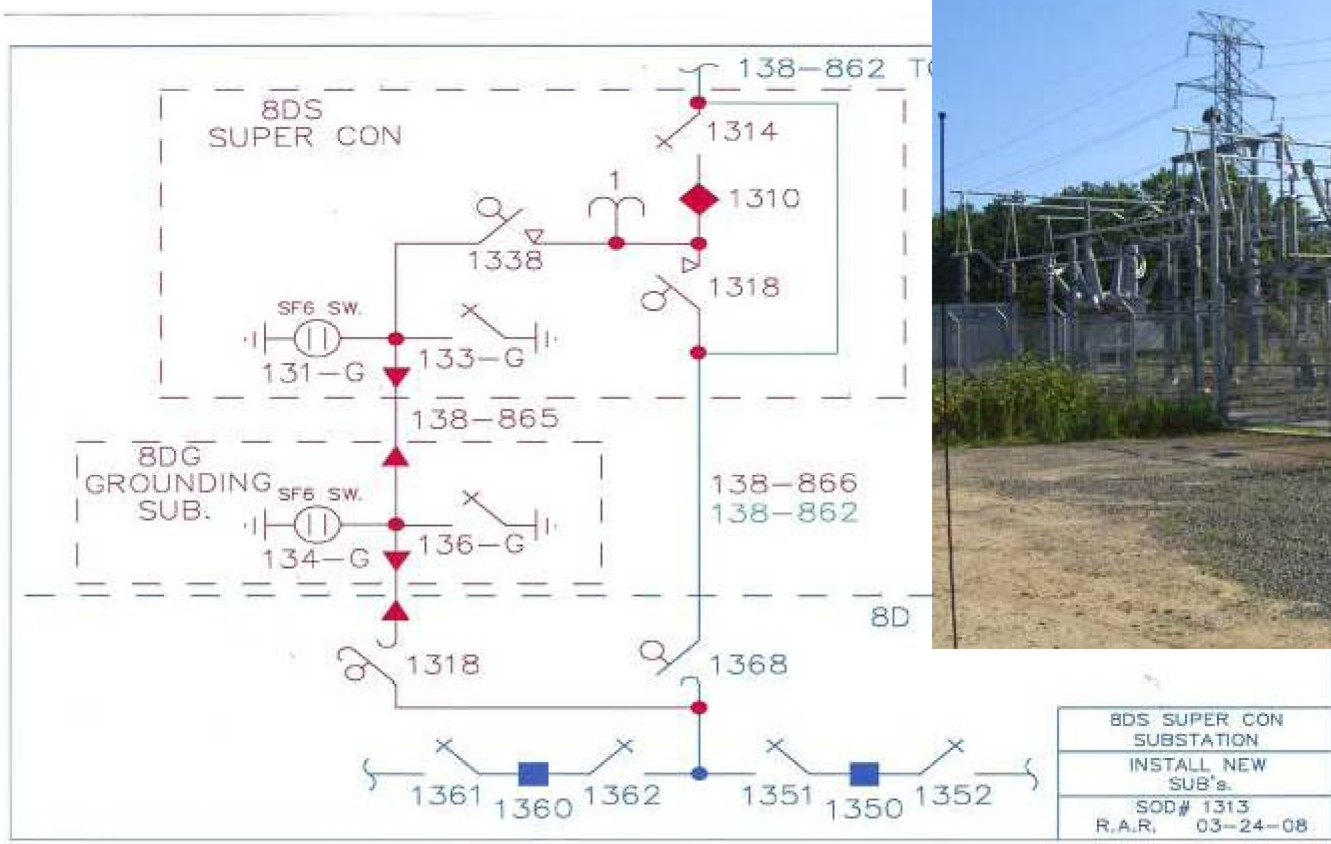
Land and Route





One Line


138–862 T
8DS
SUPER CON
1314
1
1310
1338
1318
SF6 SW.
133–G
131–G
138–865
8DG
GROUNDING
SUB.
SF6 SW.
136–G
134–G
138–866
138–862
8D
1318
1368
1361
1360
1362
1351
1350
1352
8DS SUPER CON
SUBSTATION
INSTALL NEW
SUB's.
SOD# 1313
R.A.R. 03–24–08

Pre-Construction

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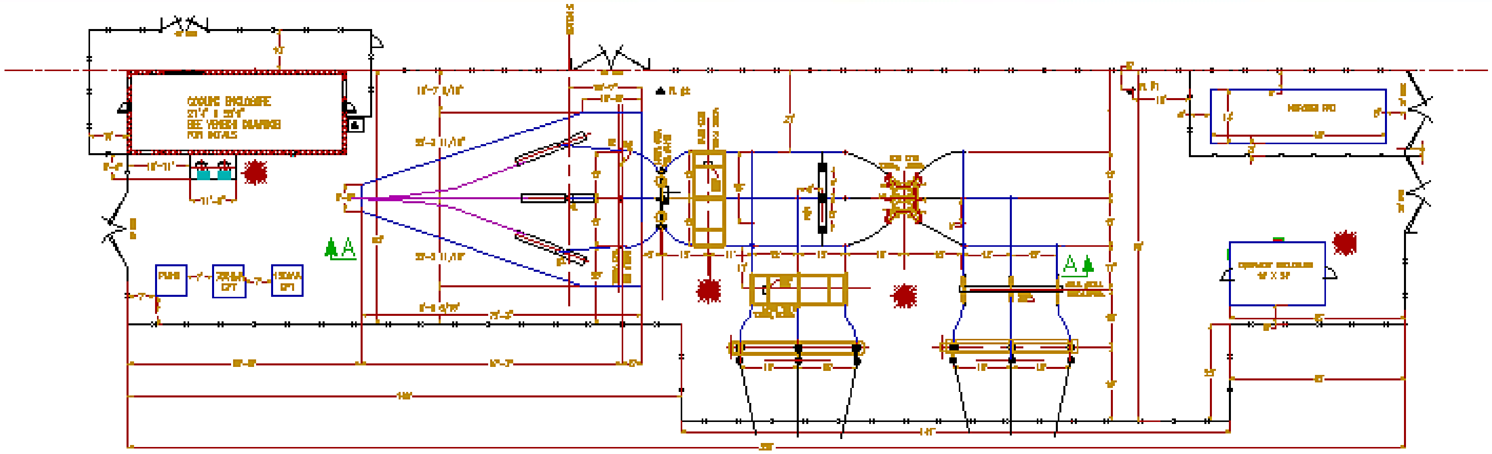
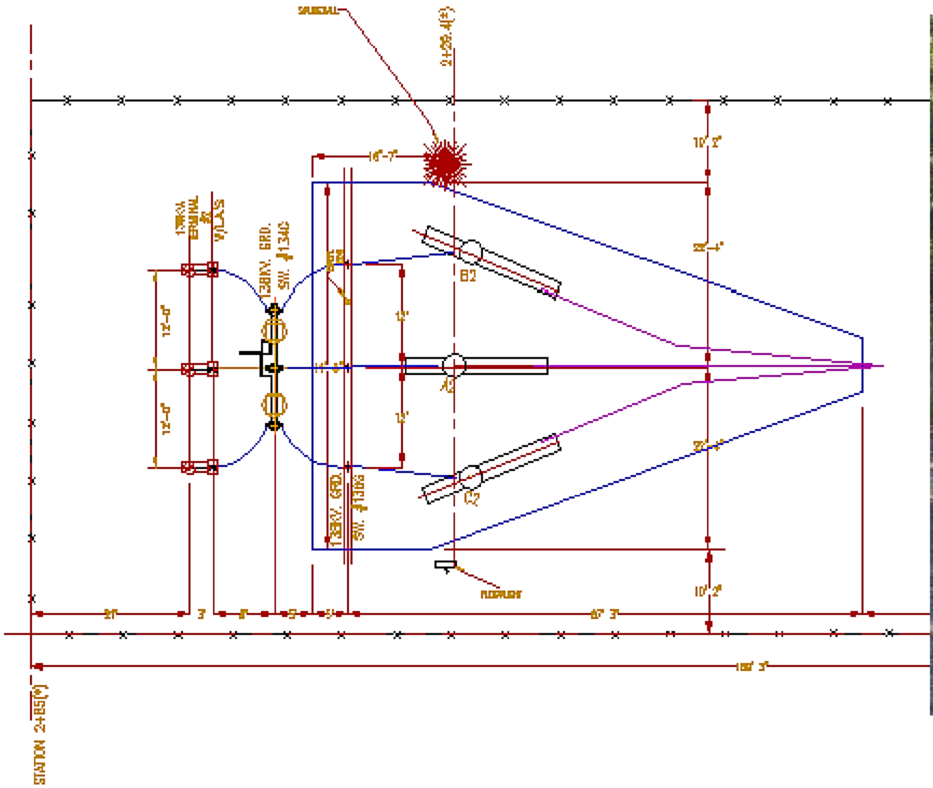
Refrigeration substation



Grounding Substation



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Sound Issues

- Several questions regarding noise at the site (during operation)
- Conducted sound study
    - 35 db at ambient
    - Source: refrigerator building
    - 50 db with refrigerator running
- Acoustical Louvers
    - Lowered sound signature during operation to 38 db (modeled)

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Sound & Site Mitigation

Why is LIPA Interested?

- Project Provides Potential Tool to Meet LIPA's Long Term Needs
  - ROW Congestion - HTS Cables provide increased power transfer capability within existing ROWs (2 - 5 times the capacity in the same space)
  - Overhead Permitting Problems
  - Potential cost savings compared to upgrading to 345 kV transmission system
- LIPA Long Term Needs
  - Must meet increasing power demands in existing ROWs
  - Load continues to increase
    - LIPA expects 1200 MW of new load by 2020 - Major transmission reinforcements will be required
- Site Specific
  - East / West transfer capability increase required by Caithness 1 & 2 and other potential power insertions

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Visitors are Welcome!

- Tom Welsh
- 516-545-3162
- twelsh@service.lipower.org

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Operating Experience

Jim Maguire, AMSC

System Operation

- The system was energized on April 22, 2008
  - Operation has proceeded well
  - There have been several “trips” where the refrigeration system has been shut down we believe may be due to dips in the supply voltage.
  - Issues are being resolved and system is currently back online

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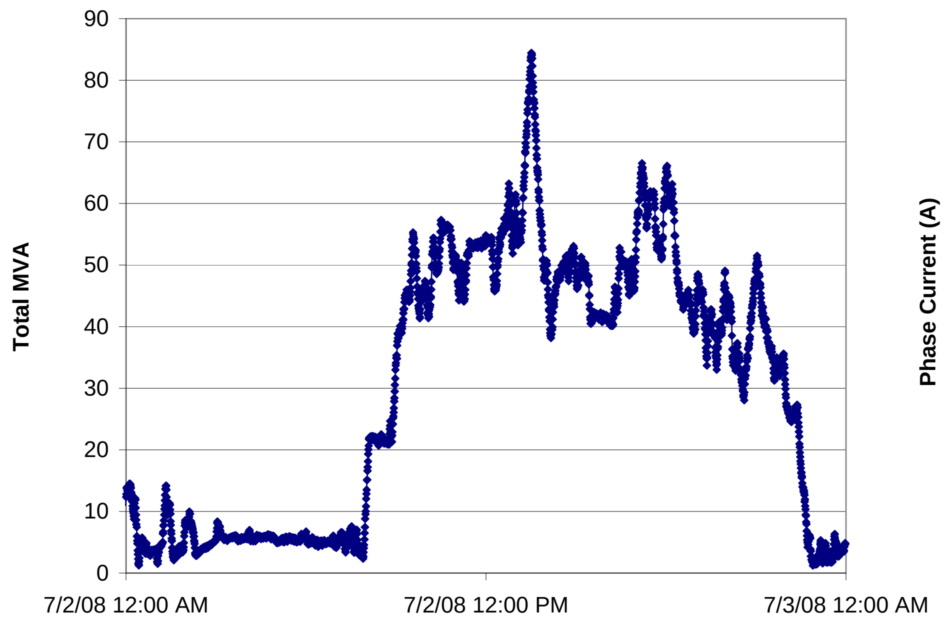
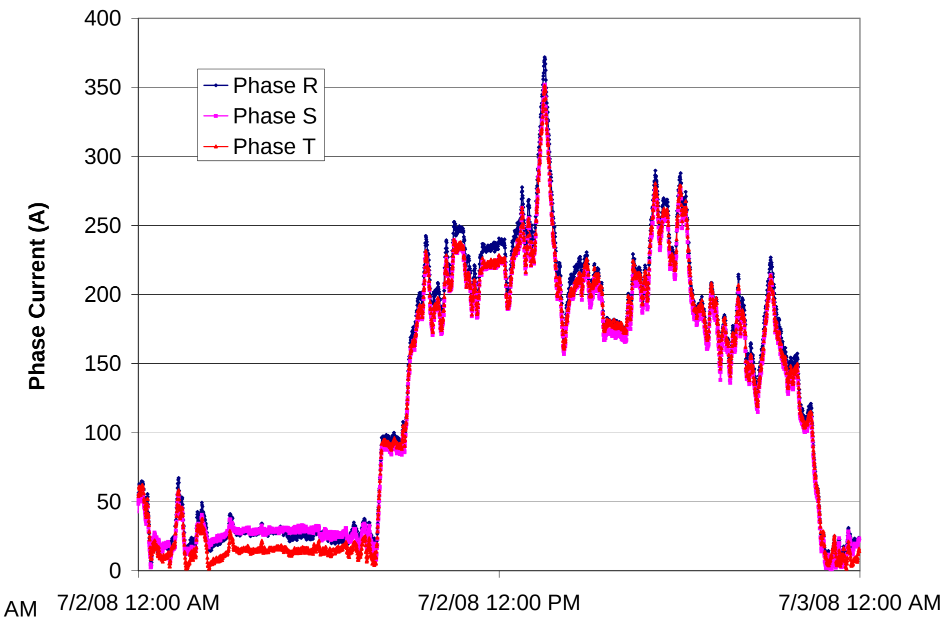
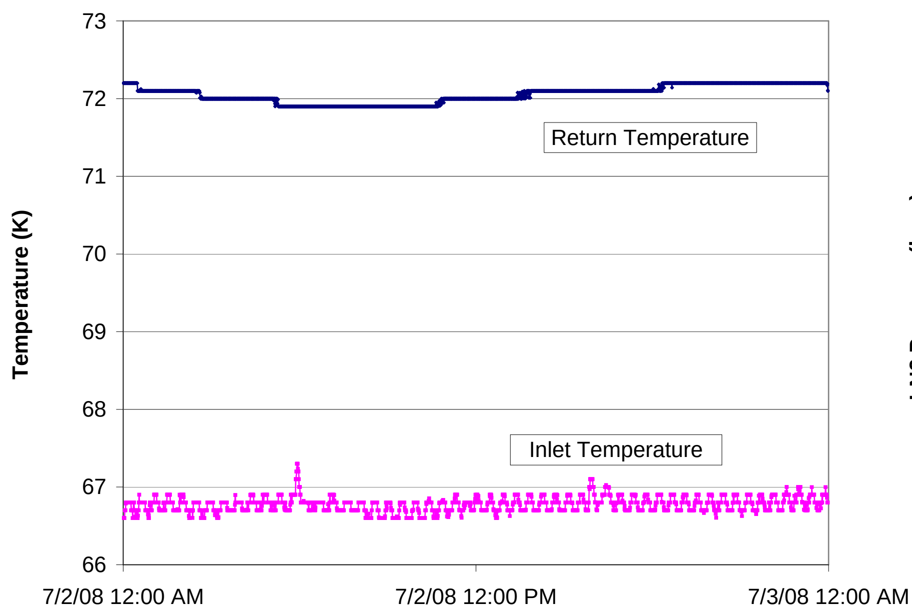
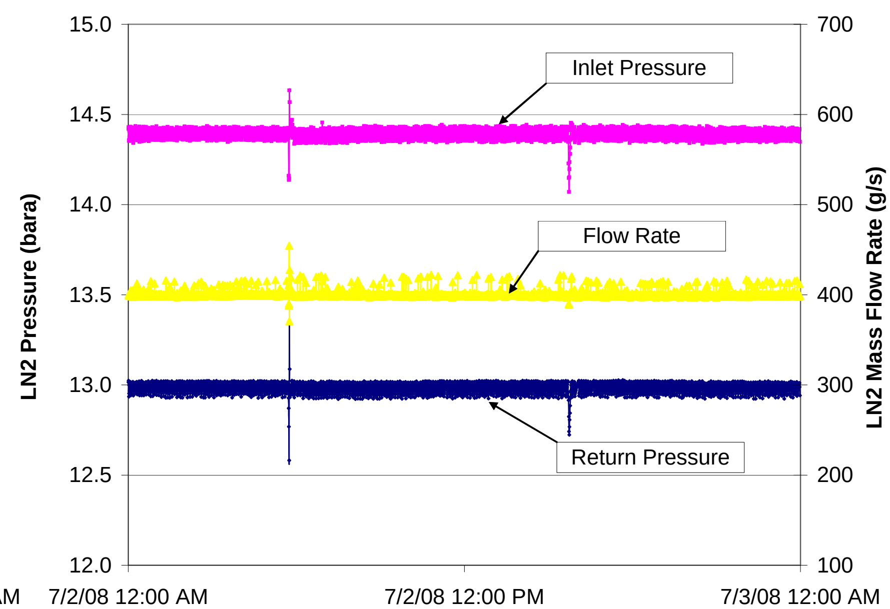
Steady State Operation (I)





Steady State Operation (II)





FY 2009 Plans

Jim Maguire, AMSC

Plans for GFY-09

- Operate for 1 year from April 22, 2008 minimum
- Monitor fault current waveforms
- Monitor refrigeration system performance
- Monitor cable thermal and electrical performance

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Demonstration of a Pre-Commercial Long-Length HTS Cable System Operating in the Power Transmission Network

DOE Peer Review Update
August 4-6, 2009
Alexandria, VA

Agenda

Introduction	**Jim Maguire, AMSC**
Project Overview	**Jim Maguire, AMSC**
FY 2009 Results and Performance	
LIPA 1 System Operational Experience	**Jim Maguire. AMSC**
LIPA 2 Design Status	**Jim Maguire. AMSC**
Cable	**Frank Schmidt, Nexans**
Refrigeration System Design	**Shawn Bratt, Air Liquide**
FY 2010 Plans	**Jim Maguire, AMSC**

Project Overview

Jim Maguire, AMSC

LIPA Project Overview

- Long Island Power Authority – Holbrook Substation
- Electrical Characteristics
  - Design Voltage/Current – 138 kV/2400 A ~ 574 MVA
  - Design Fault Current – 51,000 A @ 12 line cycles (200ms)
- Physical Characteristics
  - Length ~ 600 m
  - HTS Conductor Length ~155 km
  - Cold Dielectric Design
- Hardware Deliverables
  - Three ~600 m Long Phase Conductors
  - Six 138 kV Outdoor Terminations
  - One Refrigeration System
- Commissioning – Spring 2008

World's First Transmission Voltage HTS Cable is Operational!

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LIPA Project Goals and Objectives

- Demonstrate a Transmission Voltage Level HTS cable in an operational Power Transmission Grid
- Demonstrate 138 kV Outdoor Termination for Superconducting Cable
- Demonstrate a 2G HTS transmission cable and a cable joint in an operational power transmission grid.
- Demonstrate an FCL cable technology and repairable cryostat.
- Demonstrate modular refrigeration system.

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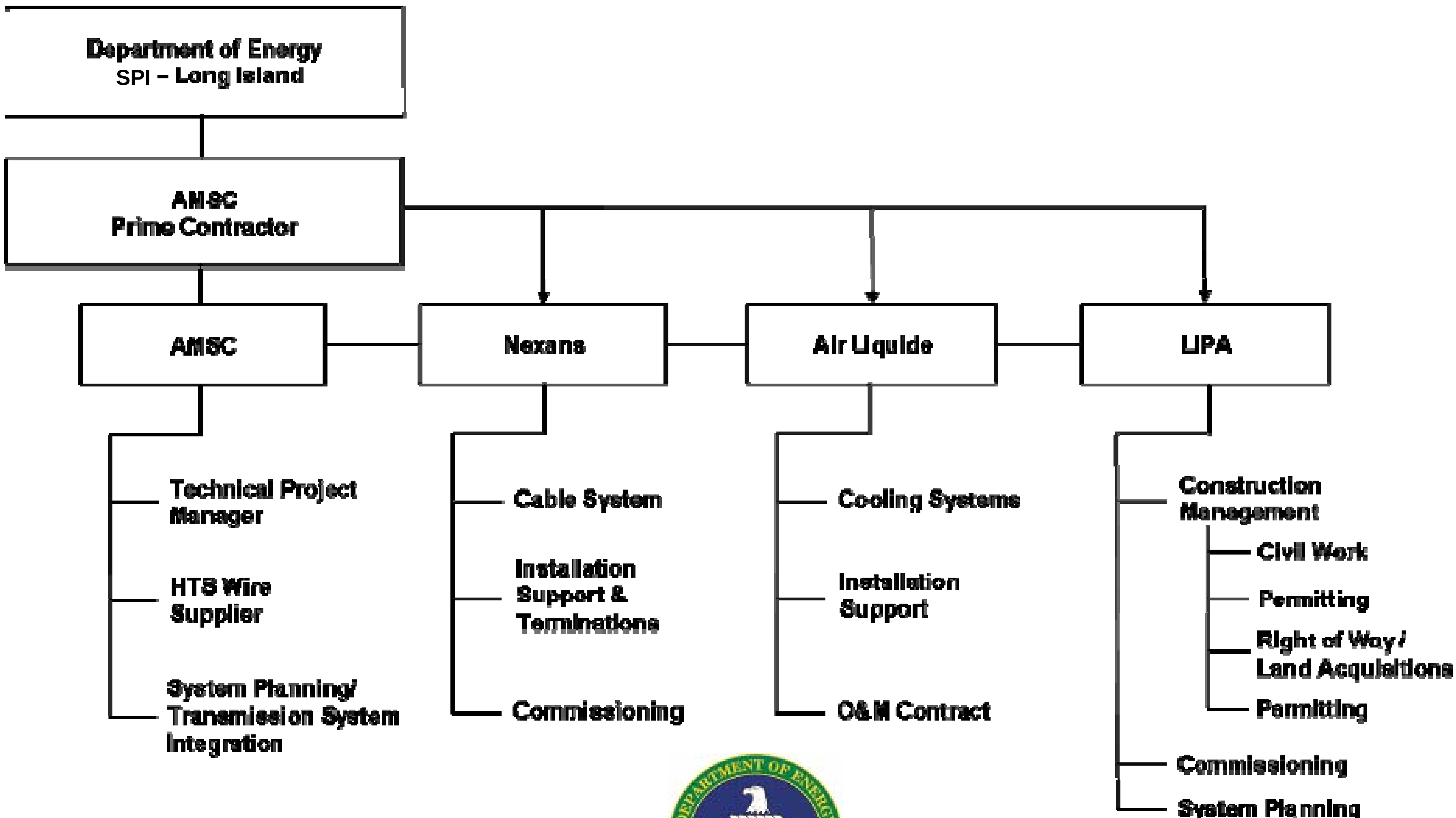
LIPA Cable Project and Project Team



Major Challenges of LIPA Project

- System Design
  - 138 kV, 2,400 amp operation
  - Survive 51 kA @ 200 ms fault & manage through-faults
- HTS Conductor Design
  - Handle real-world cabling stress using standard manufacturing equipment
- Cable and Termination Design
  - Qualify to 138 kV operation, 650 kV BIL
  - Safely manage voltage breakdown
  - Manage results from loss of cryostat vacuum
  - Manage thermal shrinkage independent of length
- Accessory Design
  - 138kV cable joint
  - Field repairable cryostat

Major Milestones in FY2009

- Cable and Termination
  - Modeling updated for 2G wire
  - Short length cable sections validated
  - Cryostat loss of vacuum and recovery event demonstrated
  - Thermal shrinkage test fixture completed and in use
- Refrigeration System Design
  - Design study complete
  - Configuration downselected
  - Key components designed

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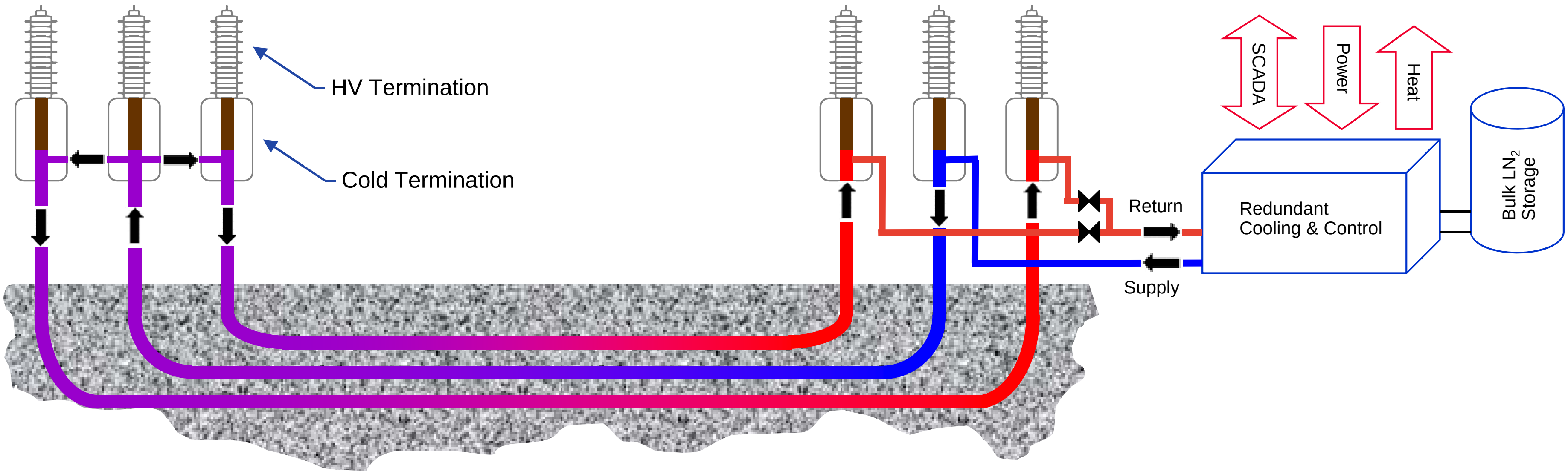
LIPA HTS Cable System



LIPA Project Status Update

- North End View
  - 3 terminations
  - Breakers
  - Grounding switches
  - 3 phase conductors

- South End View
  - 3 terminations
  - Grounding switches
  - 3 phase conductors

World's First Transmission Voltage HTS Cable Became Operational in 2008

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LIPA 1 System Operational Experience

Jim Maguire, AMSC

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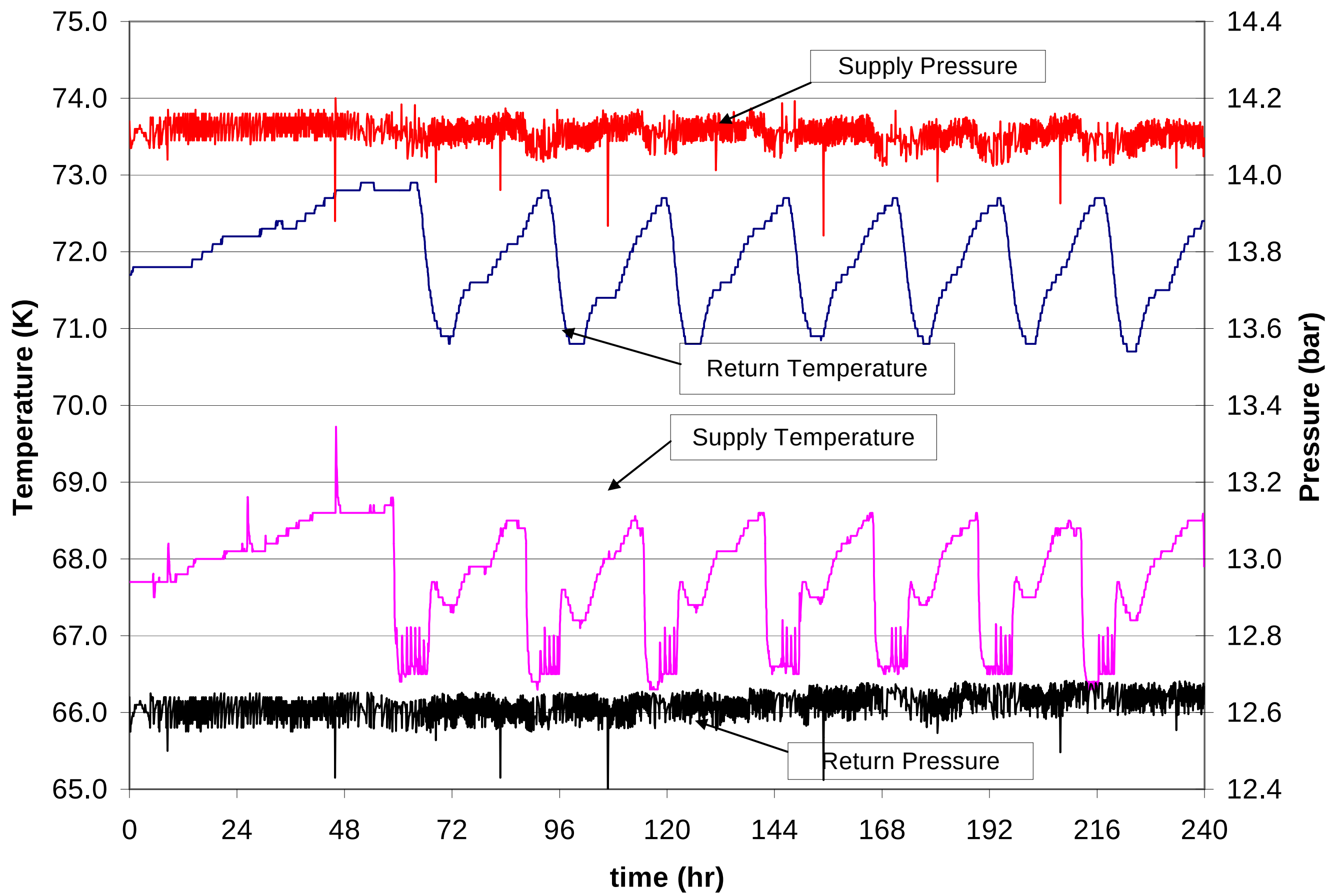
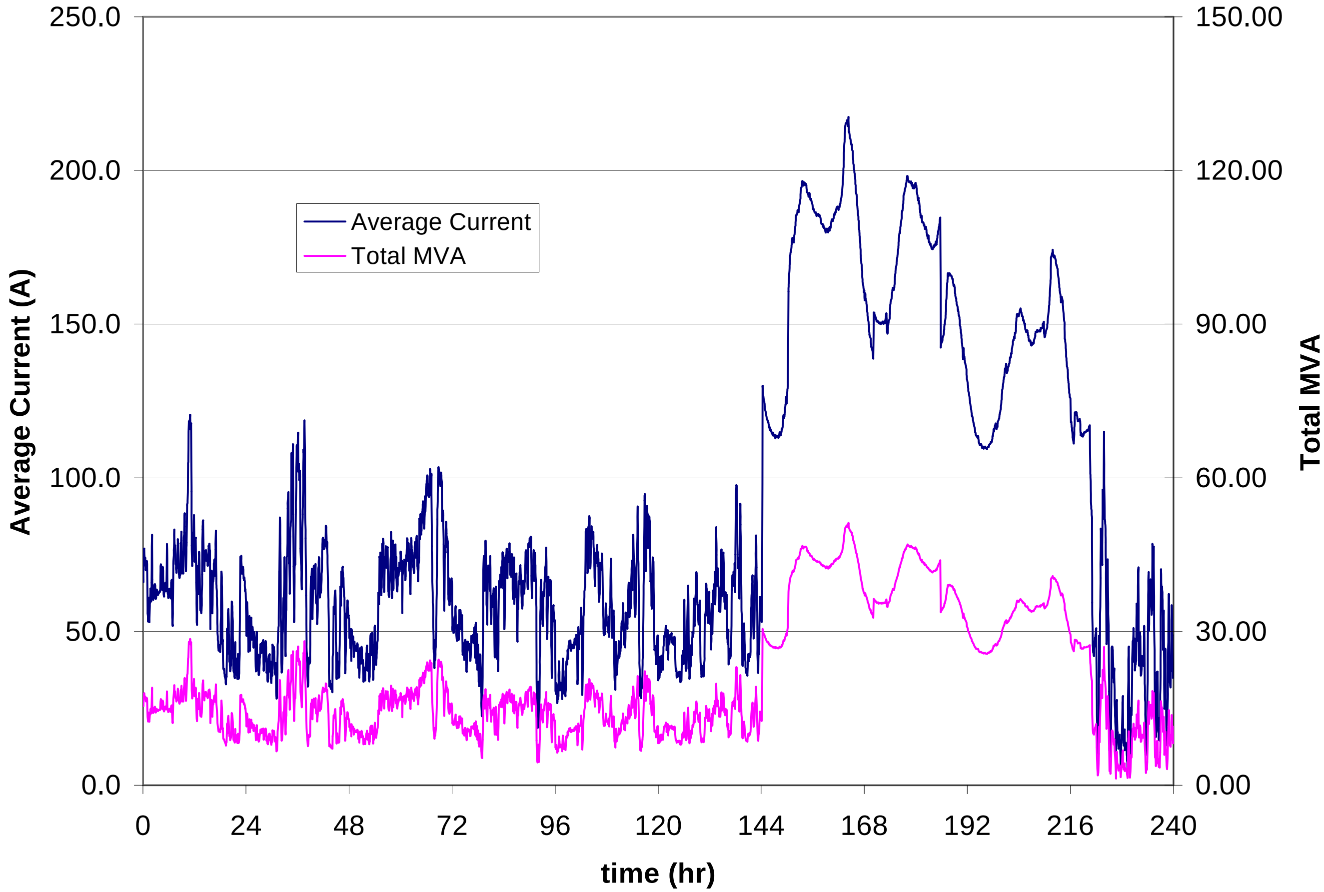
Normal Operation – Cryogenic System



Normal Operation – Cable



Cable Cryostat after One Year

Operation Condition		case 1	case 2	case 3
Load	MVA	0	16	82
Average I	A	0	75	350
Line Voltage	kV	0	138	138
total Thermal Load	W	3672	4301	4615
cable load	W	2358	2947.5	3144
Termination load	W	1314	1353	1471
Cable cryostat loss	W/m	1.31	1.31	1.31
Termination parasitic loss	W/termination	218.95	218.95	218.95
Cable electric loss	W/m	0.00	0.33	0.44
Termination electric loss	W/termination	0	6.55	26.2

No significant changes in performance after 1 year of operation

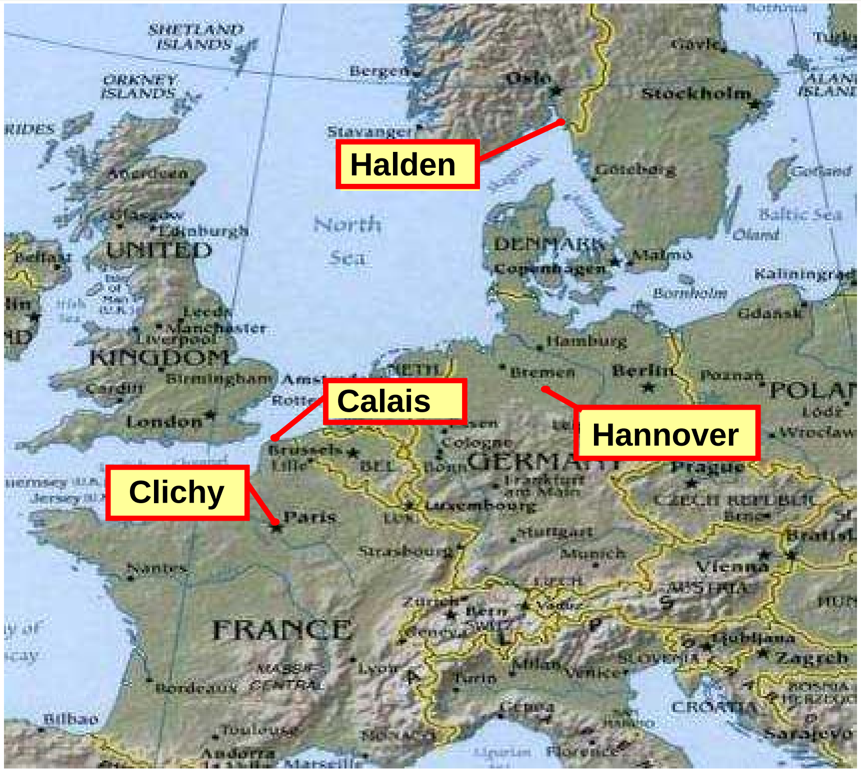
LIPA 2 Project
Cable and Terminations

Frank Schmidt, Nexans

Nexans Main Objectives of LIPA 2

- Fault current limiting and fault current tolerant cable design
- Thermal contraction handling technique independent of cable length
- Repairable cryostat - Cryostat design that can be repaired after damage
- Cable Joint
- Demonstration of a 600 meter long 2G wire cable in the LIPA network

Nexans Sites Involved



- Clichy (France)
  - Project controlling
  - Cable installation
- Hannover (Germany)
  - Project management, design and engineering
  - Cable testing
  - Cryostat development and manufacturing
- Halden (Norway)
  - Cable core manufacturing
- Calais (France)
  - Termination adaptation
  - Cable joint development

Nexans team for LIPA 2 unchanged to ensure the best continuity for the development

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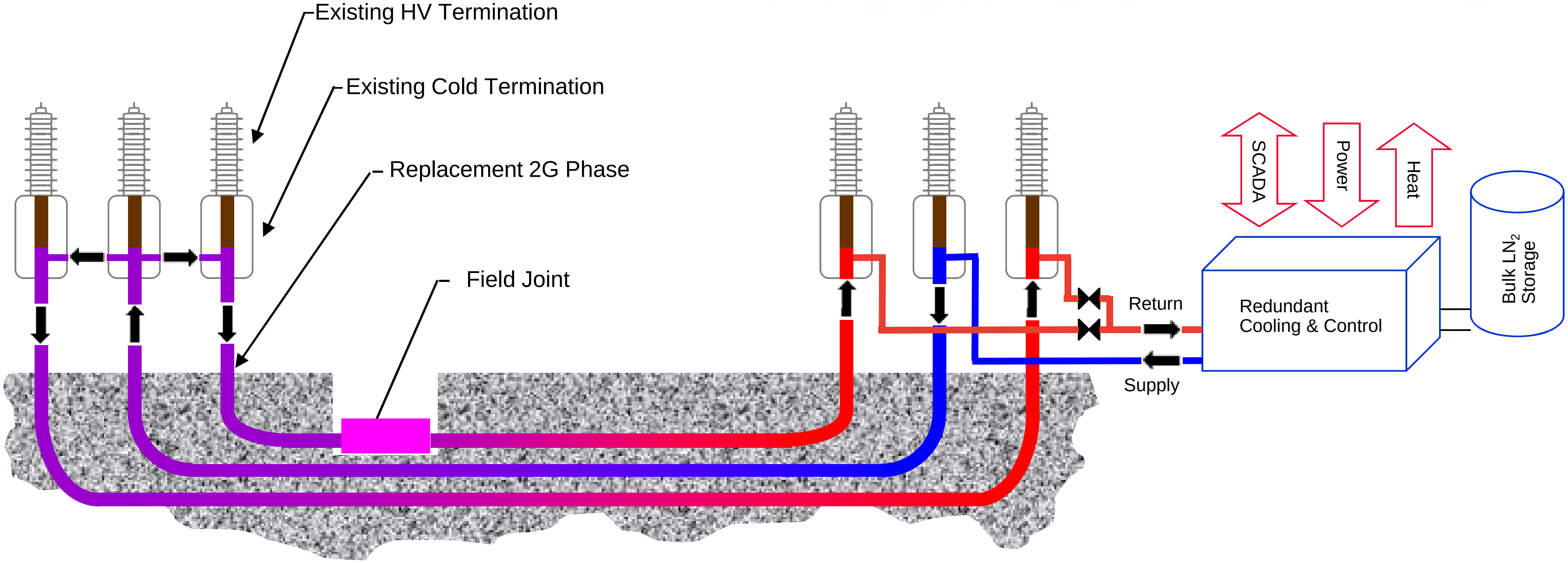
LIPA II HTS Cable System



- To be installed in LIPA grid
  - Single phase of stabilized 2G cable to survive short circuit currents
  - New cryostat (2 pieces)
  - Cable joint

Cable Design

- Update of the existing modeling tools to be able to develop a cable design that
  - Meets the required specification
  - Is able to either limit the fault current energy deployed into the cable during a fault current in the grid or to tolerate the fault current without getting damaged
  - Provides low losses in normal operating conditions
  - Is able to compensate thermal shrinkage during cool down

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Improvements for Modeling Tools within Lipa 2

- Include 2 G wire properties for the current distribution calculation
  - ☑Done for the current distribution calculation based on fixed μr
- Include or estimate the magnetic substrate losses in the loss calculation
  - Work in progress
  - UCD model used for the moment including a fixed loss value per tape as additional AC losses generated by the substrate
- Review the AC loss calculation and verify through short sample measurements
  - Work in progress
  - First measurements obtained

Short sample manufacturing

- Short samples with two phase layers, one screen layer being manufactured in Hannover
- 2 m of ‘good sample length’
- First measurement results obtained
- Coordination with AMSC regarding loss theory

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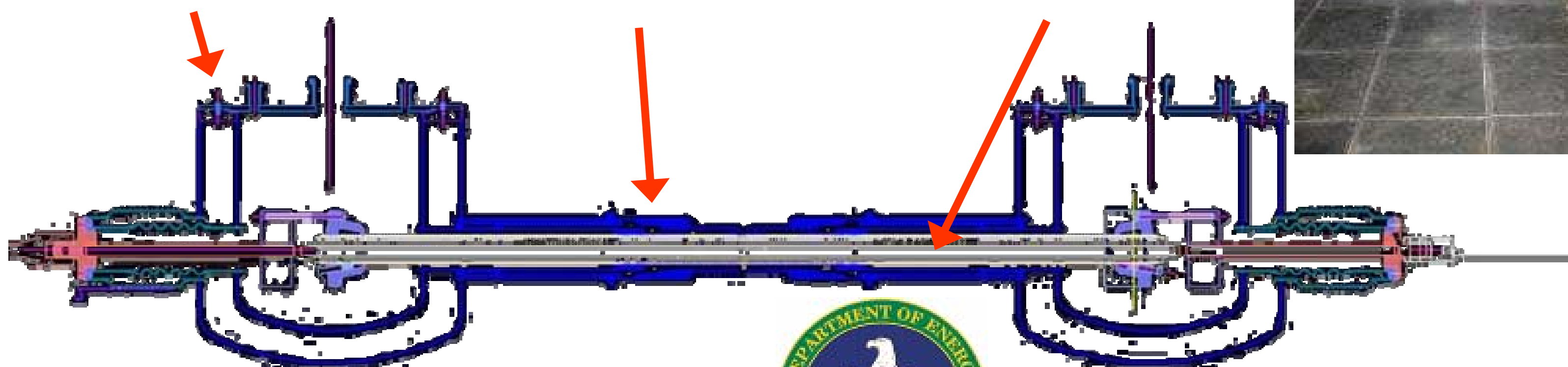
Thermal Shrinkage Testing

- Thermal shrinkage handling technique has to take into account
  - Cable thermal shrinkage properties
  - Termination connection components
  - Joint components
  - Cryostat properties
- Several approaches are possible and currently investigated
- Final approach requires verification testing using a specific test setup

Thermal Shrinkage Testing

- Mechanical test rig has been set up to perform shrinkage management tests
- Modular setup for samples of 10 meter (can be extended)
- Setup also suitable for other measurements
  - AC losses on longer samples
  - Ic measurements
  - Fault current tests on 10 meter samples
- Measurement of displacement implemented and "no force"-testing possible



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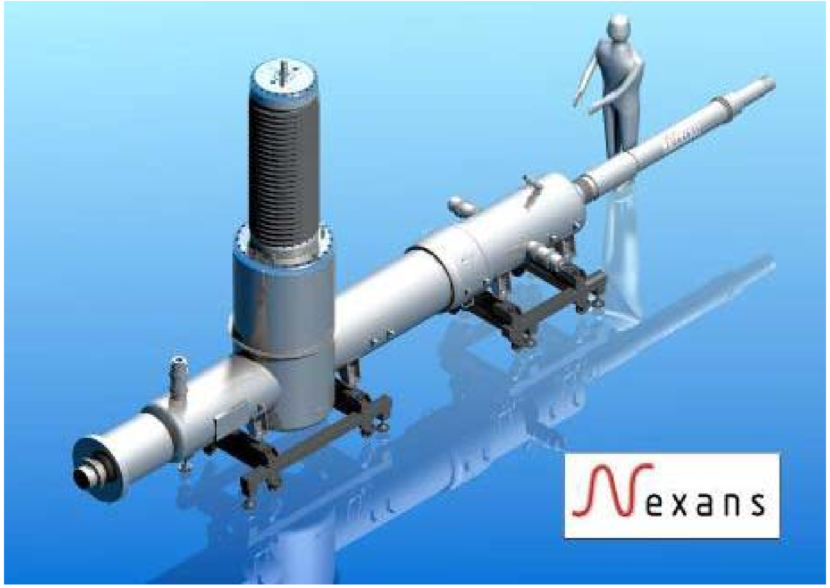
Thermal Shrinkage Testing

- Several tests were performed to date in cables partially populated with HTS (dummy) cables
- Fault current limiting cable design (dummy 1)
  - Cool down and force measurement
  - Cool down and displacement measurement (no force)
- Fault current tolerant design (dummy 2)
  - Cool down and force measurement
- Results contribute to the further planning and development of the thermal shrinkage handling technique
- Verification tests on final cable design and termination components to be done

High Voltage Termination

- LIPA 1 terminations design is kept for this project but adapted for the new YBCO HTS cable:
  - Removal of the cable shrinkage management by full length motion in termination (~1m)
  - Adaptation of the cable connection for 2G wires



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High Voltage Termination

- **<u>Connection adaptation to LIPA 2 cable:</u>**

  - Test & validation of specific brazing alloys for 2G tapes
    - No superconducting properties degradation

  - Connection design adapted for new cable with hollow former

  - Design validation with dummy cable:
    - Thermal distribution in liquid nitrogen with nominal current
    - Electrical resistance measurement at cryogenic temperature
    - Mechanical resistance with pulling force

  - Connection resistance improved by 40 to 50% regarding LIPA 1 project

High Voltage Joint

- **A first joint prototype has been assembled and tested in NEXANS Hanover testing laboratory during summer 2008**
  - Full-scale joint prototype, assembled in a 30m testing loop
  - LIPA 1 cable design with 2G tapes
  - Electric field distribution equal or higher than the joint design based on Lipa 2 cable
- **This first prototype was fully validated regarding high voltage**
  - AC withstand test 190 kV / 30 min
  - Lightening impulse test 650 kV (+/-)
  - Partial discharge measurement

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High Voltage Joint

- **Cable connection of the joint was adapted for LIPA 2 cable:**
  - New connection design for hollow former & 2G tapes
  - Validation on dummy cable
    - Mechanical resistance
    - Electrical resistance in cryogenic conditions
    - Expected thermal distribution with nominal current
  - **Last joint connection design presents an electrical resistance improvement by a factor 3 regarding design already validated in 2008 (LIPA 1 design)**

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High Voltage Joint

- **Joint cryostat was designed according to the cable joint design developed:**
  - Length: about 2.6m (external)
  - Diameter: about 350mm (outer)
  - Prototype ready for type test

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Repairable Cryostat - Overview

- TARGET: Develop a field repairable cryostat for HTS cables
- Task 1 (finished)
  - Subdivide the vacuum space into shorter sections
  - Design of vacuum barriers along the length of the cryostat
- Task 2 (ongoing)
  - Optimize the subdivided vacuum space length
  - Determine the optimum spacing between barriers. (Balance cost of barriers with replacing damaged sections and additional cold power costs for operating with degraded vacuum)
- Task 3 (finished)
  - Technique for drying the vacuum space
- Task 4 (finished)
  - Optimize cable insulation geometry for drying and re-evacuation
- Task 5 (ongoing)
  - Field repairable cryostat concept demonstration
  - Laboratory demonstration of a cryostat with vacuum barrier, evacuation and drying technique
  - Report with recommendations

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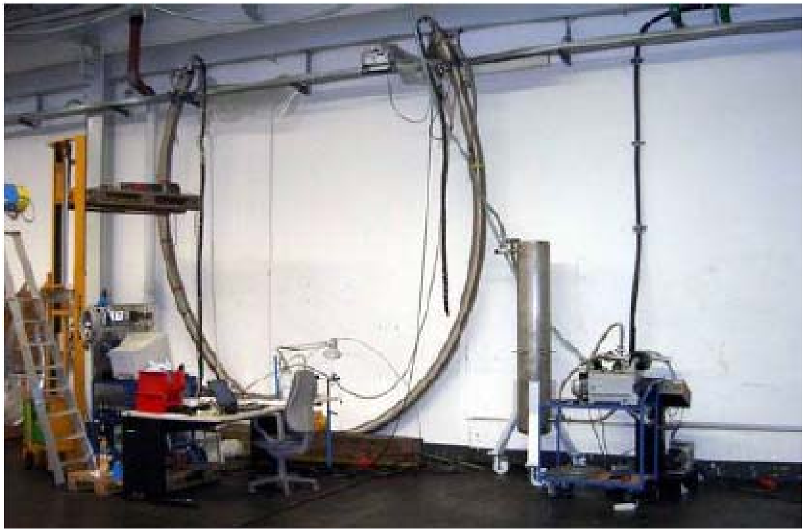
Repairable Cryostat

- Drying test of a 10 meter transferline was finished
  - Initial vacuum level – $1*10^{-4}$ mbar
  - Heat inleak was measured prior to vacuum loss – 1,2 W/m
  - Vacuum was vented with water steam and left open with filled transferline for 24 hours
  - Repumping using developed drying technique



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Heat Inleak of repaired Cryostat

- Measurement of Heat inleak of the repaired cryostat was done
- Result in the same range as before – roughly 1,2 W/m
- Higher heat load measurements at the beginning are due to the end effect (higher filling level of the line)

LN2 Filling (m)	Gas Flow (l/s)	Gas Temperature	Room Temperature	Vacuum	Heat Inleak (W/m)
9,31	0,085	18°C	18°C	1,0x10-4	2,11
9,07	0,075	18°C	18°C	1,0x10-4	1,90
8,41	0,041	18°C	18°C	1,12x10E-4	1,13
8,33	0,040	18°C	18°C	1,2x10E-4	1,11
6,32	0,031	18°C	18°C	2,6x10E-4	1,12
6,28	0,031	18°C	18°C	2,6x10E-4	1,12

- Next steps
  - Confirm the measurement on a 40 meter long line
  - Conductance measurement on 40 meter line to be measured
  - Analysis of results to estimate optimum vacuum space

Cryostat repair test was completely successful on a 10 meter line

Repairable Cryostat – Demonstration on 40 m line

- A new 40 m pipe with vacuum barriers and weldable terminations on both sides has been manufactured.
- This pipe will be damaged at the outer cryostat tube with vacuum loss and humidity loading.
- Test program
  - Heat inleak measurement of undamaged line
  - Damage with humidity load
  - Repair with developed repair method
  - Drying
  - Heat inleak measurement of repaired line

Test on longer line will allow estimation of behaviour of longer lengths

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Cable Manufacturing Process

- Same equipment as for LIPA 1
  - Stranding Machine
    - Stranding of superconducting tapes using industrial process – existing machines adapted to meet specific requirements of the superconducting material
    - Machine modified with magnetic hysteresis brakes for tight control over winding tension
  - Dielectric Lapping Line
    - Dielectric manufacturing on conventional machines
    - Specific dielectric design to meet demands on bending properties and high voltage insulation properties

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LIPA 2 HTS Cable Concept

- Former (various designs tested)
- Copper stabilization layer
- 2 layers of 2G tape in cable conductor
- Lapped high voltage insulation
- Single layer of 2G tapes in screen
- Copper stabilization layer

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LIPA 2 Dummy 1

- Manufactured late 2008
- Built according to fault current limiting design
  - Current limiting, thus no copper
  - Stainless steel corrugated tube former
- Design concept successful
  - No Ic degradation visible
    - Significant scatter in original Ic data
    - Physical appearance OK

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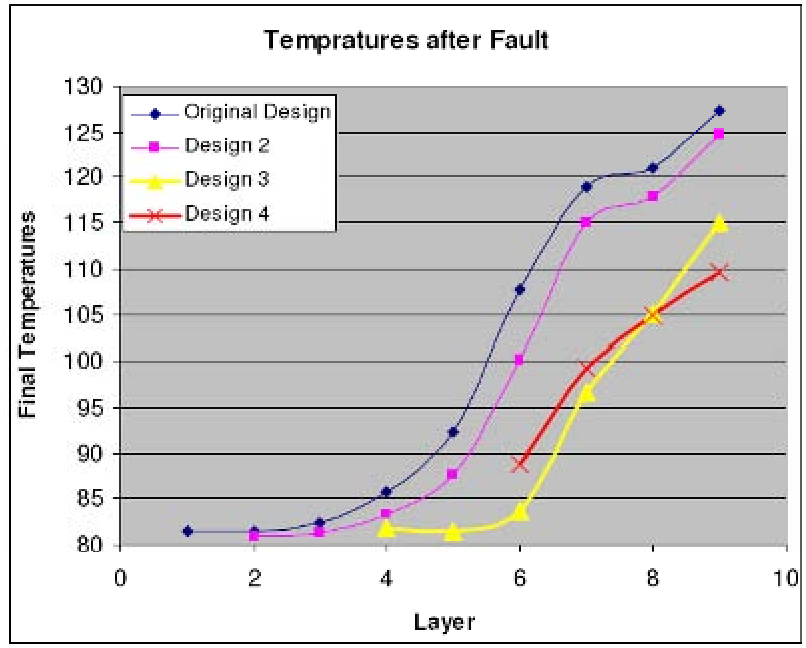
LIPA 2 Dummy 2

- The cable design used for Dummy 02 needs to be fault current tolerant
- Copper stabilization material required
- Optimized former layout developed to reduce the temperature increase in case of fault current
- Dummy 2 manufacturing was finished mid 2009
- Testing of 2G wires to be finished



Dummy 3 planned based on results from Dummy 1 and 2

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Conclusions

- Modeling indicates that both designs (FCL and FCT) are feasible and designs are being pursued
- Thermal contraction work to date indicates various possible solutions
- Cryostat repair work results to date are very promising and are expected to fulfill the project objectives
- Very good results of high voltage cable joint development
    - Remaining work just needs to address adaptation to final cable design when available
- Cable manufacturing and testing is going very well
    - Manufacturing process under control to be refined with final cable design

Projects proceeding well – all development tasks addressed with solutions available

LIPA 2 Project
Refrigeration System Design

Shawn Bratt, Air Liquide

Refrigeration System Objective

- Develop a new refrigeration technology dedicated to long-length HTS cable with the main characteristics below

  - **Low operation cost**
    - High efficiency
    - Low maintenance
  - **Low refrigerator cost**
    - Simple design
    - Modular design
  - **High reliability**
  - **Long life time**

Refrigeration System Objective

- Develop a new Refrigeration technology dedicated to long-length HTS cable with the following main characteristics:

Cooling air temperature range for rejecting heat:	50°C max (30°C nominal)		
LN2 temperature at cable interface:	**74 - 72 K**	**or**	**76 - 72 K**
Cold power required at cable interface:	**20 kW**	**or**	**20 kW**
(net refrigerator capacity excluding "house" loads)			
LN2 mass flow:	5 kg/s	or	2.5 kg/s
Refrigerator LN2 pressure increase:	1.2 bars	or	2.4 bars
LN2 minimum pressure at cable inlet:	16.3 bara	or	18 bara
Efficiency:	> 20% Carnot		
Manufacturing cost target:	<$100/cold W series production		

Heat load from LN2 pump

< 2 kW

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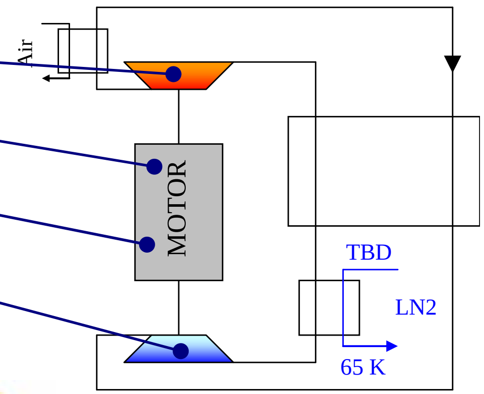
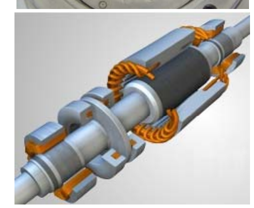
Refrigeration System Objective

- Find an new refrigerator technology able to achieve the objectives
  - **Previous** high power refrigerators system are based on a Reverse-Brayton cycle using a screw compressor and a cryogenic expander without power recovery (LIPA 1)
  - **Innovating Reverse-Turbo-Brayton Process**
    - This cooler uses a He / Ne reverse turbo-Brayton process.
    - The essential innovation concerns the assembly of all active elements on a single shaft
      - centrifugal compressor
      - high-speed motor
      - Magnetic bearings
      - cryogenic turbo expander





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Refrigerator Development Status

- Progress made thus far
  1. Select several refrigerator configurations
  2. Comparison of the refrigerator configurations' performance
  3. Select the best refrigerator configuration
  4. Preliminary design of this refrigerator configuration
  5. Calculate the refrigerator's performance and validate the refrigerator stability during off-design modes (cool down, partial load …)
  6. Design the critical components (motor + magnetic bearings)

Refrigerator Development Status

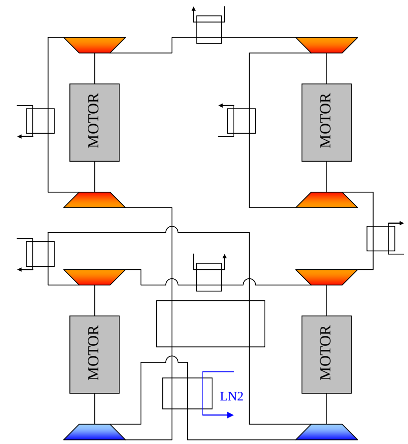
2. Comparison of the refrigerator configurations' performance

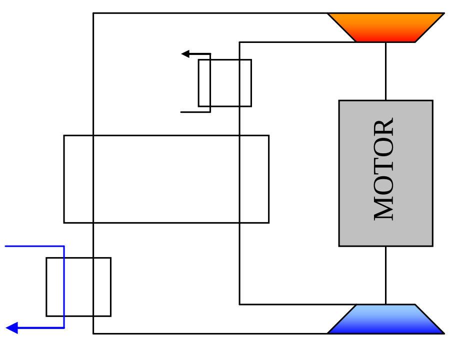
   - In order to compare the 5 refrigerator configurations, 5 refrigerator numerical model have been developed
   - These 5 models are made of several validated sub-component numerical models: Centrifugal compressor, Centripetal expander, Synchronous motor, Heat exchangers…
   - The 5 refrigerator configurations have been optimized at the nominal working point using the numerical models
   - These results allow us to select the most favorable configuration for the cooler specification below
     - Air temperature for rejecting heat: 30°C (nominal)
     - LN2 temperature at cable interface: 74 - 72 K
     - Cold power required: 20 + 2 kW
     - Efficiency: > 20% Carnot

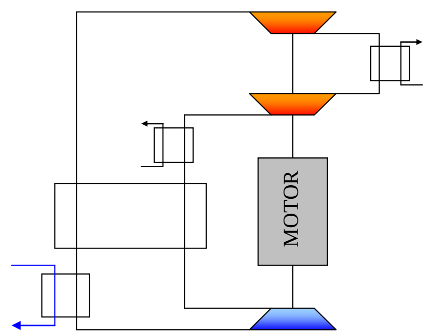
Refrigerator Development Status

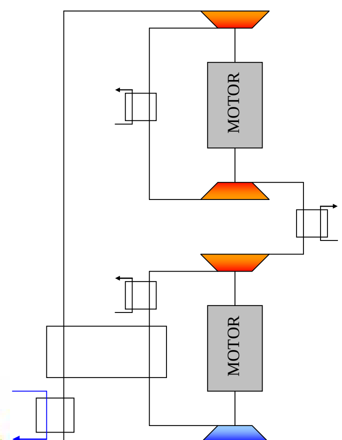
1. Select several refrigerator configurations

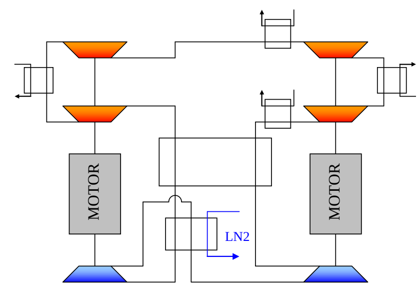
   - 5 configurations were selected following the thermodynamic analysis
     - 1 Compressor + 1 Motor + 1 Expander
     - 2 Compressors + 1 Motor + 1 Expander
     - 3 Compressors + 2 Motors + 1 Expander
     - 4 Compressors + 2 Motors + 2 Expanders
     - 6 Compressors + 4 Motors + 2 Expanders











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Refrigerator Development Status

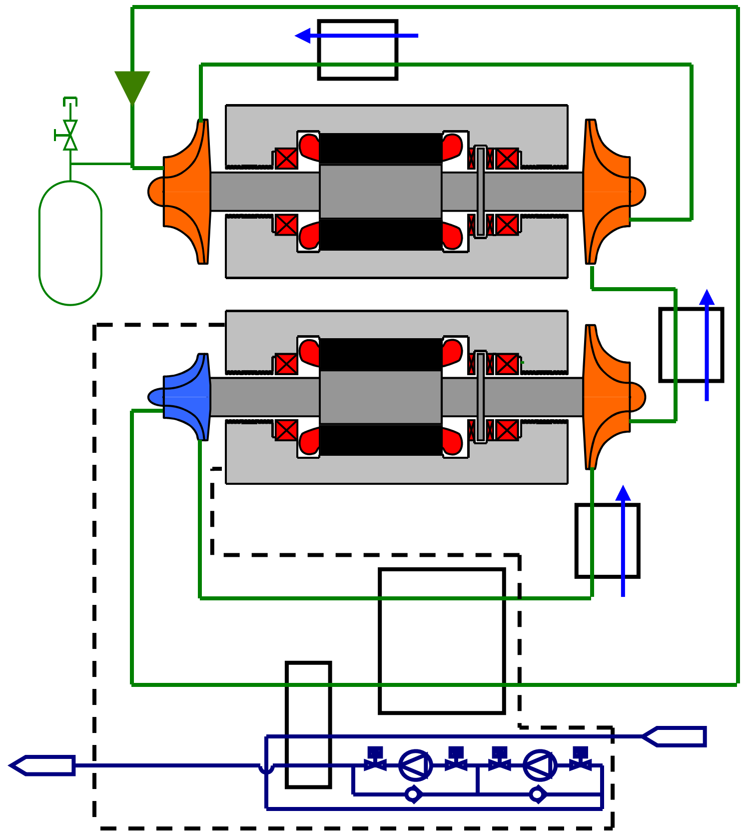
3. Select the best refrigerator configuration

Configuration	Electrical consumption	Capital cost	Remarks
1 Compressor 1 Motor 1 Expander	-	-	High load on the axial magnetic bearings. Not adapted to the requirement. **Well suited for higher cold temperature.**
2 Compressors 1 Motor 1 Expander 4m³ CC HEX	16.37 We/Wc 133%	Low	Design with reasonable heat exchanger is not possible. Compressors wheels are not optimized and difficult to develop and improve Shaft design is difficult: 2 compressors and 1 cryogenic expander wheel on the same shaft. Mass flow is high. **Well suited for lower cold power.**
3 Compressors 2 Motors 1 Expander 2m³ CC HEX	12.34 We/Wc 100 %	Medium	Compressor and expander wheels are optimized and easy to improve. Cryogenic system is simple. Only 2 wheels on the same shaft. **Well suited for this application**: Best cost-performances ratio.
4 Compressors 2 Motors 2 Expanders 2m³ CC HEX	11.00 We/Wc 89.1%	High	Good effectiveness. However, high capital cost for a poor increase in global efficiency. Cryogenic system is complex. this configuration needs more compressor wheels.
6 Compressors 4 Motors 2 Expanders 2m³ CC HEX	10.09 We/Wc 81.8%	Very high	Very good effectiveness, however high capital cost. **Well suited for lower temperature. Well suited for higher cold power.**

Refrigerator Development Status

4. Preliminary design for this refrigerator configuration

    - Process & Flow Diagram



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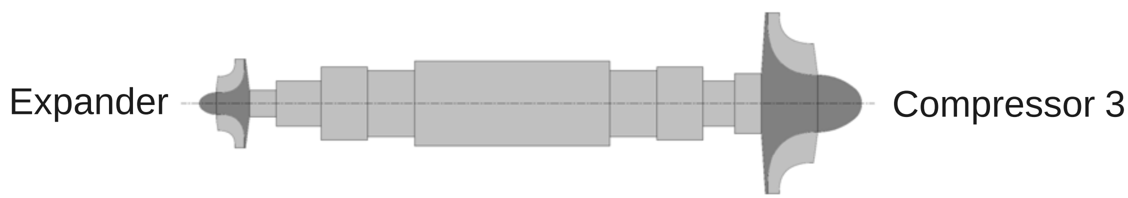
Refrigerator Development Status

4. Preliminary design for this refrigerator configuration
   - Two-stage Moto-Compressor characteristics
     - Motor nominal mechanical power: 185 kW
     - Nominal rotation speed: 40000 rpm

   - Moto-Turbo-Compressor characteristics
     - Motor nominal mechanical power: 72 kW
     - Nominal rotation speed: 58000 rpm



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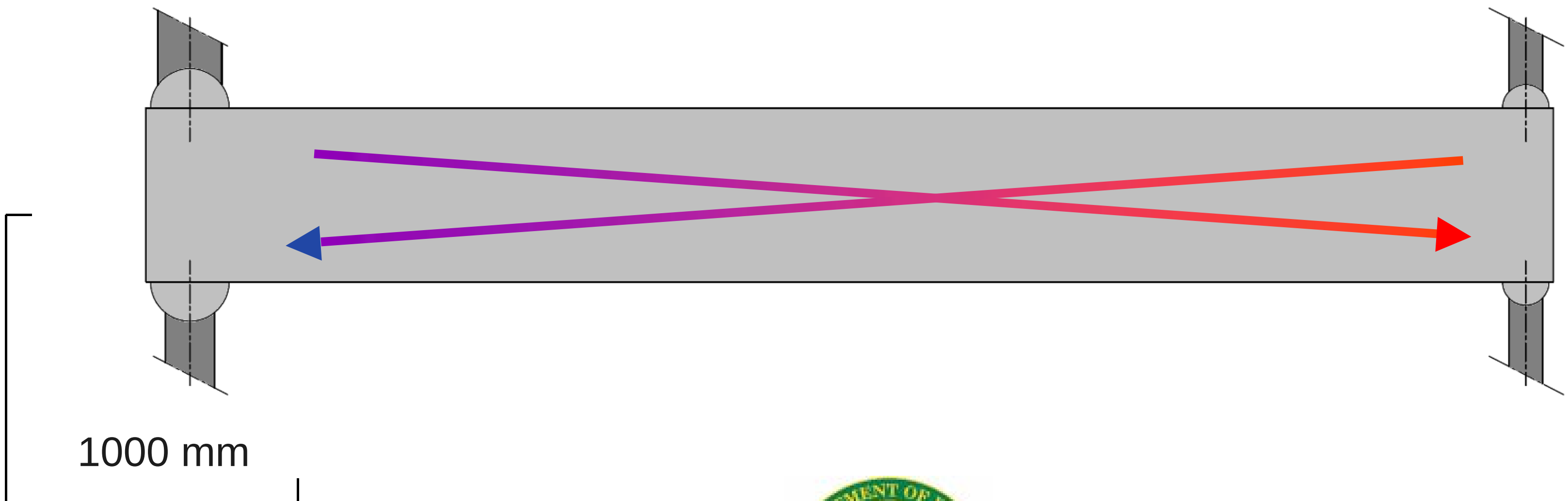
Refrigerator Development Status

4. Preliminary design for this refrigerator configuration

   - Counter-flow heat exchanger

     - Block size: 4.9 m x 0.6 m x 0.68 m
     - Duty: 480 kW
     - Thermal efficiency: 98.5 %



Refrigerator Development Status

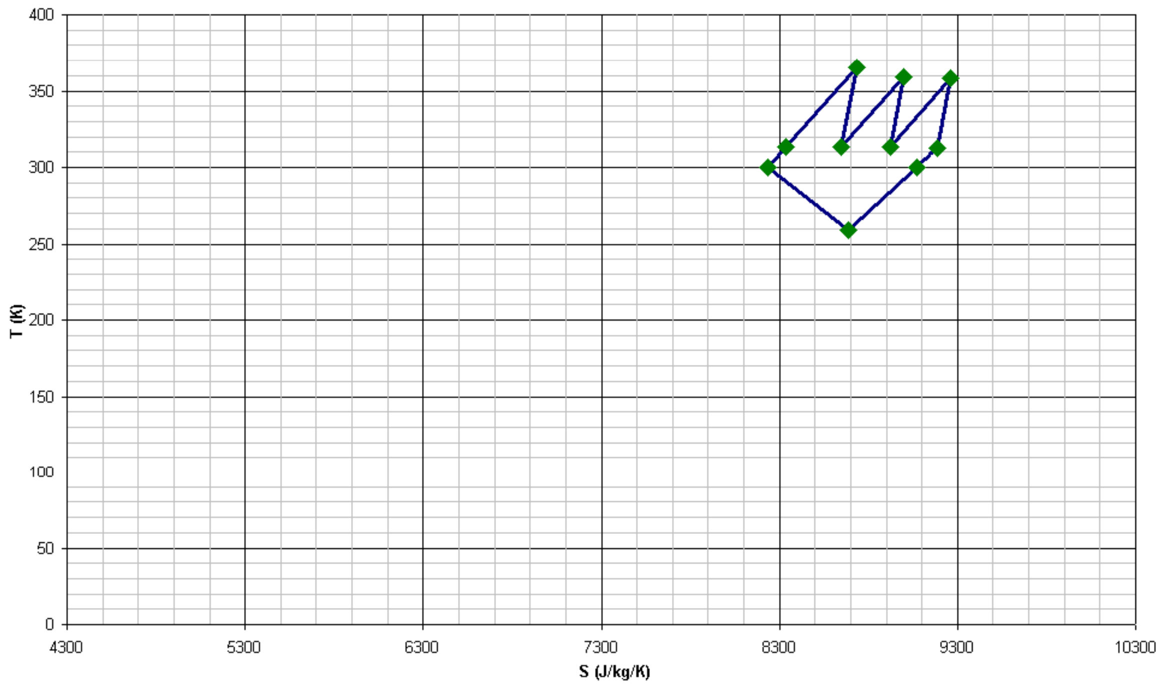
5. Calculate the refrigerator's performance during off-design modes
   - A complete off-design numerical model was realized for the chosen configuration. This model allows to simulate:
     - A complete cooler cool-down
     - Cooler operation for different cold temperatures
     - Cooler operations for the specified air temperature range
     - Cooler operation at partial load

Refrigerator Development Status

5. Calculate the refrigerator's performance during off-design modes

   - Cooler cool-down simulation at nominal rotation speed

     - At 300 K: Cold power = 38700 W; 0.3% of Carnot efficiency



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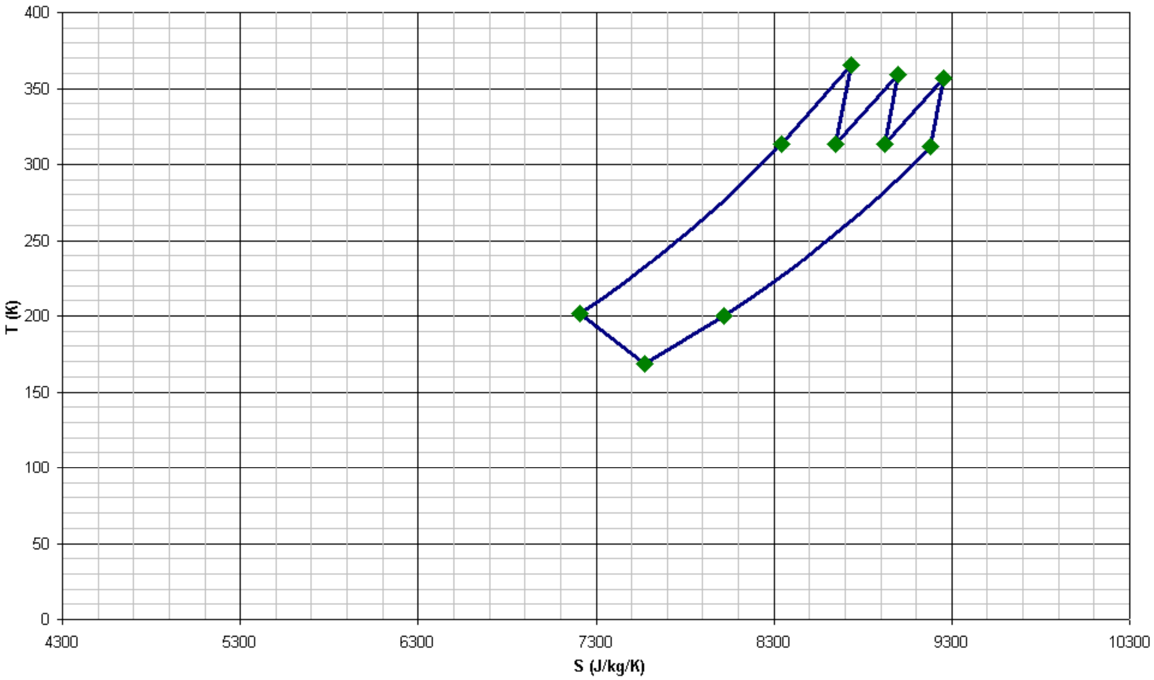
Refrigerator Development Status

5. Calculate the refrigerator's performance during off-design modes

   - Cooler cool-down simulation at nominal rotation speed

     - At 200 K: Cold power = 36300 W; 8.7% of Carnot efficiency

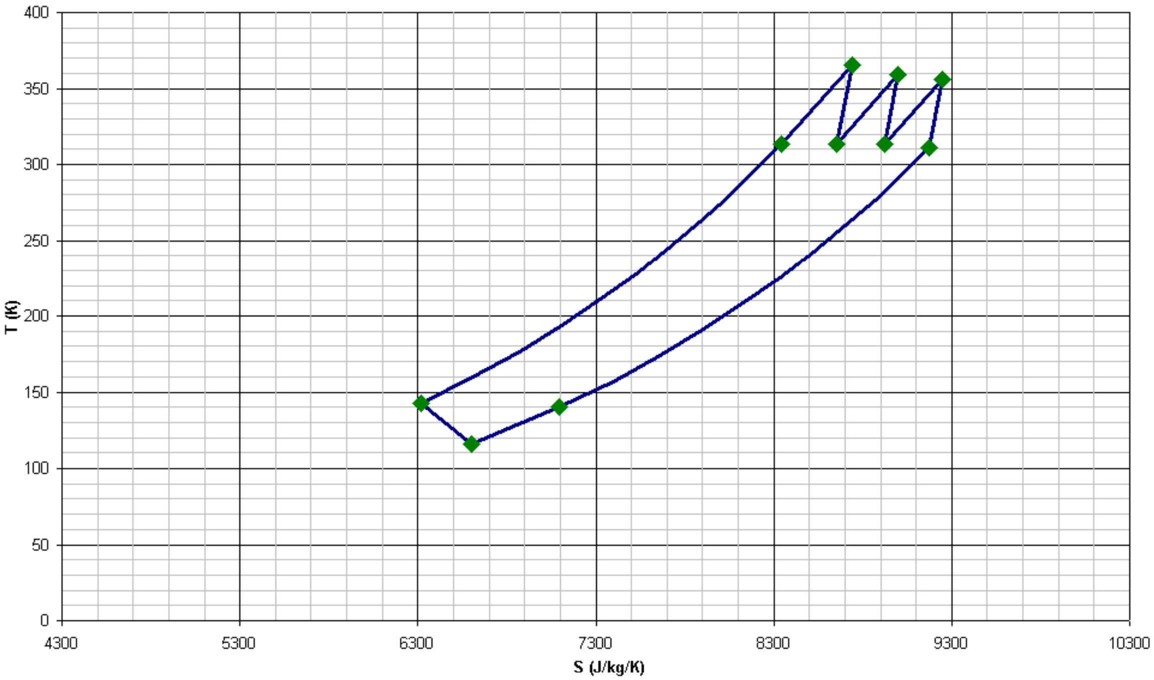


Refrigerator Development Status

5. Calculate the refrigerator's performance during off-design modes

   - Cooler cool-down simulation at nominal rotation speed

     - At 140 K: Cold power = 33100 W; 17.7% of Carnot efficiency

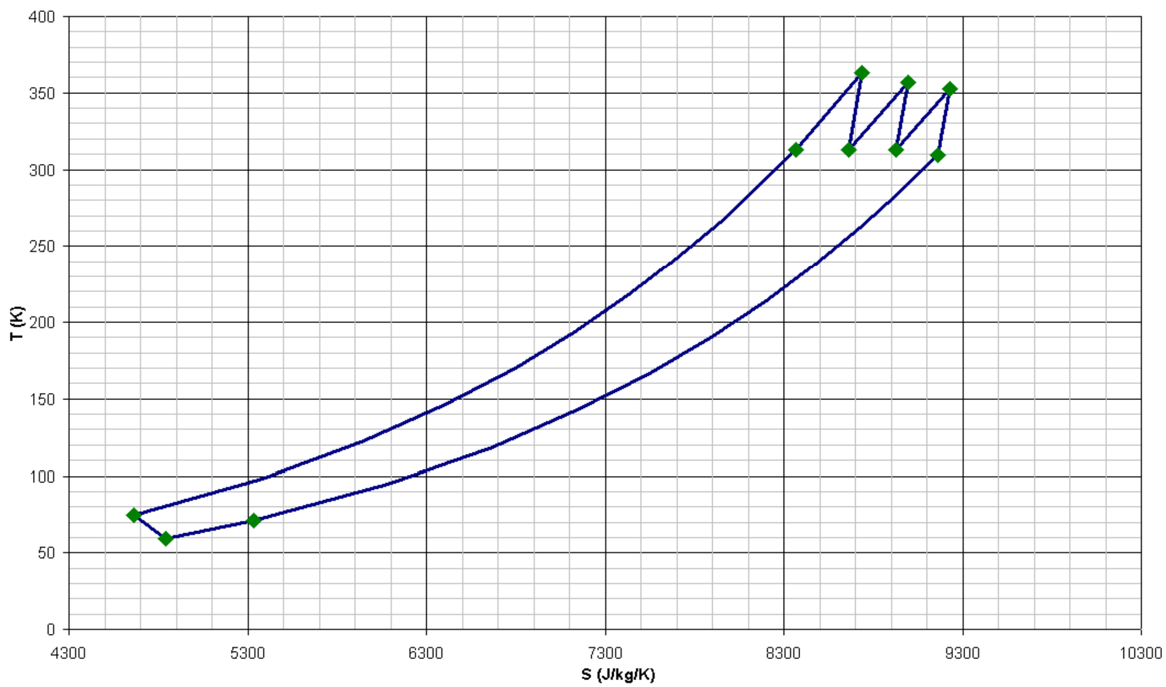


Refrigerator Development Status

5. Calculate the refrigerator's performance during off-design modes

   - Cooler cool-down simulation at nominal rotation speed

     - At 72 K: Cold power = 22000 W; 27.6% of Carnot efficiency (12.34 We/Wc)



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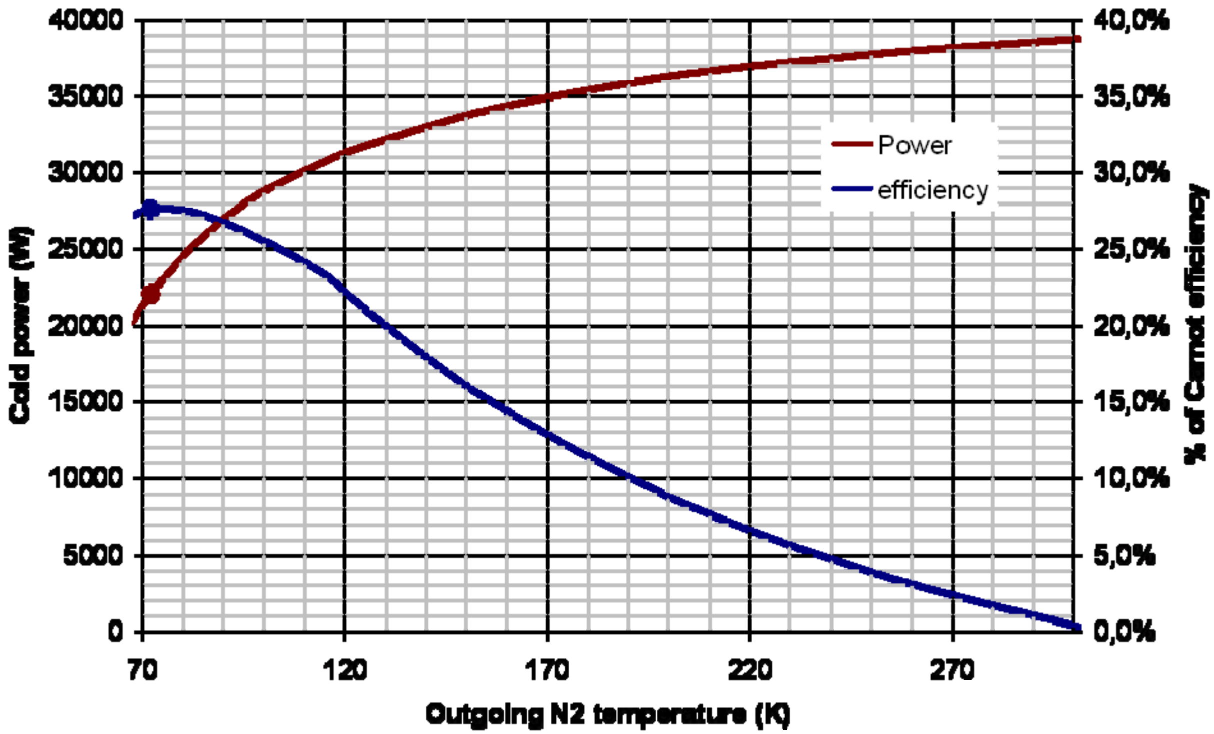
Refrigerator Development Status

5. Calculate the refrigerator's performance during off-design modes

   - Cooler cool-down simulation at nominal rotation speed

     - Cold power and % of Carnot efficiency during cool-down

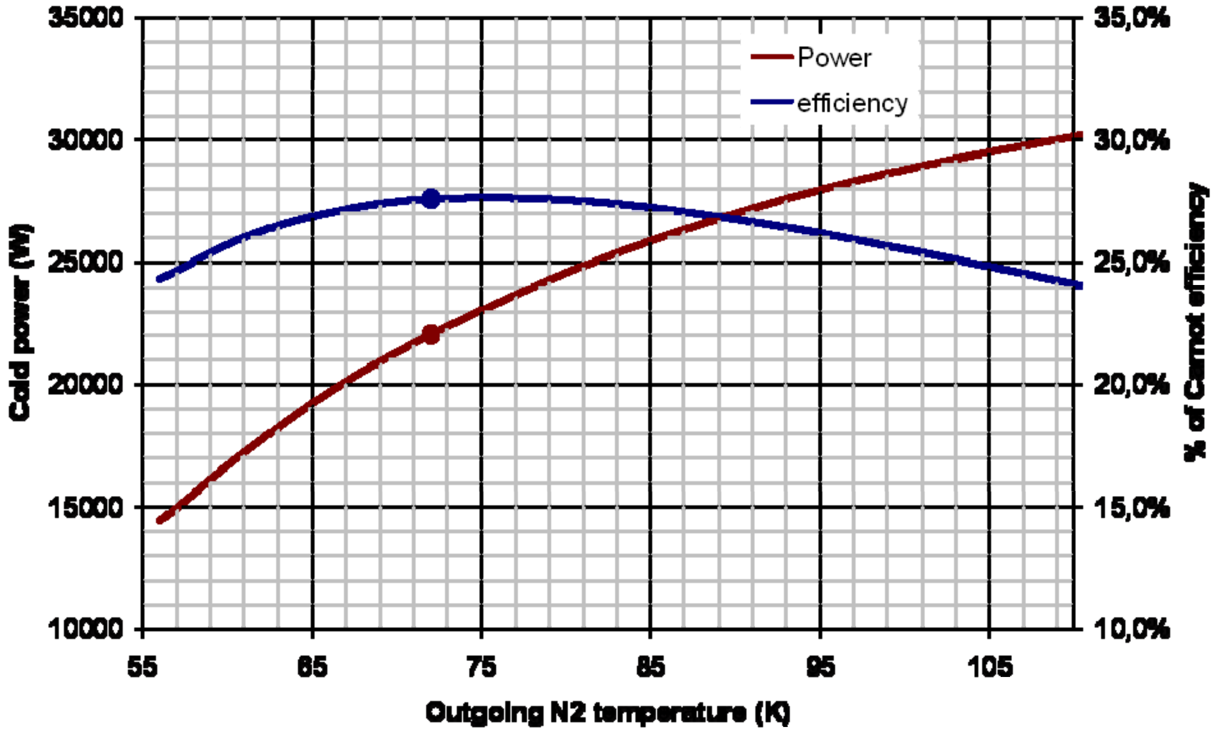


Refrigerator Development Status

5. Calculate the refrigerator's performance during off-design modes

   - Operation for different cold temperatures at nominal rotation speed

     - A cooler simulation was performed from 55 to 110 K (assuming no N2 freezing)



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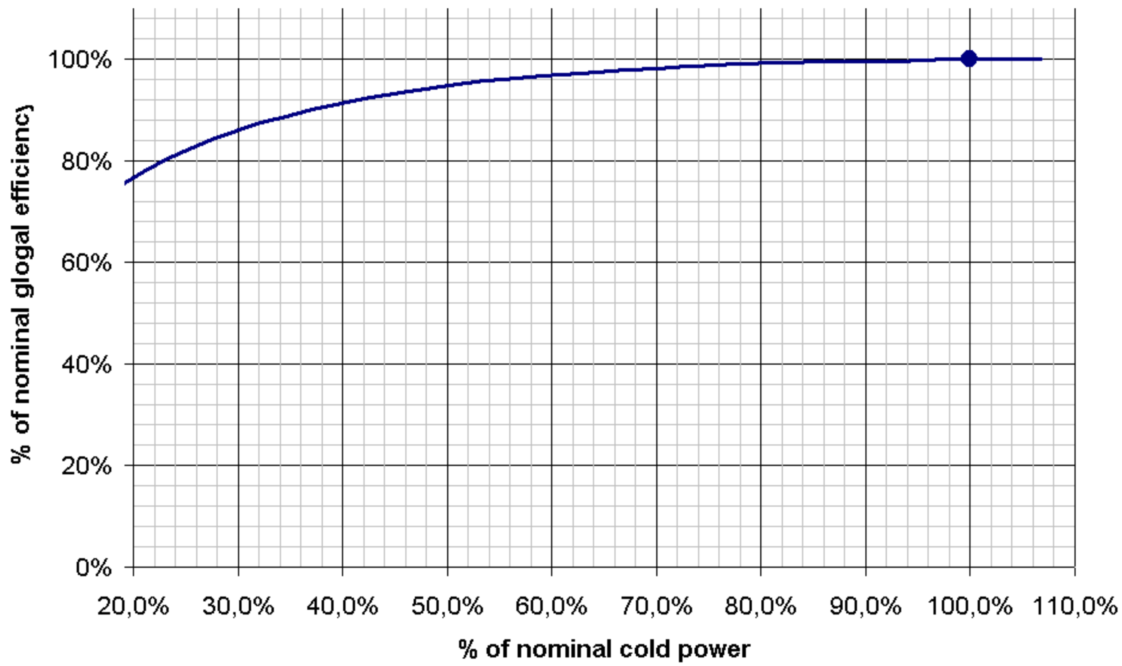
Refrigerator Development Status

5. Calculate the refrigerator's performance during off-design modes

   - Cooler operation at partial load, nominal cold temperature

     - At **50% of nominal cold power**, global efficiency is decreased only by **5.3%**



Refrigerator Development Status

5. Calculate the refrigerator's performance during off-design modes

   - Conclusions

     - Compared to the previous process the Turbo-Brayton process is highly flexible
       - Centrifugal compressors and expander are stable for all conditions
       - 17% to 50% of nominal cold power → 20 to 26% of Carnot efficiency
       - 50% to 100% of nominal cold power → 26 to 27.6% of Carnot efficiency
       - 55 and 115K of cold temperature → 24 to 27.6% of Carnot efficiency (14 to 30 kW)
       - With cooling air at 50°C the system is able to reach the specification
     - Compared to the previous process the Turbo-Brayton process is simple and therefore reliable
       - System control is simple, only 1 parameter to modify: % of nominal rotation speed for motor 1 and 2
       - Compressors and expander do not need variable inlet guide valves: Variable rotation speed is sufficient in all operating conditions

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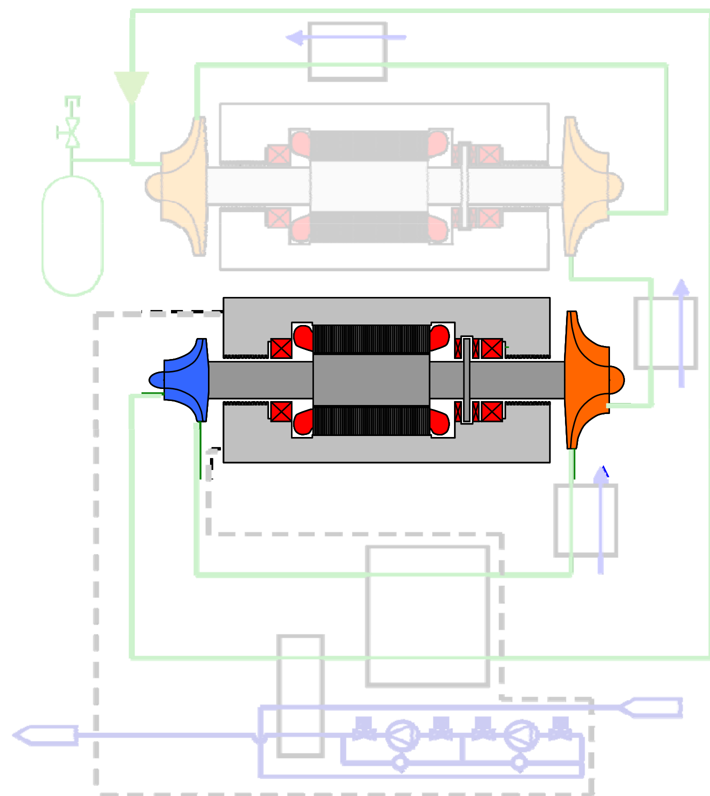
Refrigerator Development Status

6. Design the critical components: Moto-Turbo-Compressor design (Motor + Magnetic bearing + electronics)

- The Moto-Turbo-Compressor represents the refrigerator's critical components
- Therefore, the Moto-Turbo-Compressor has been designed in detail



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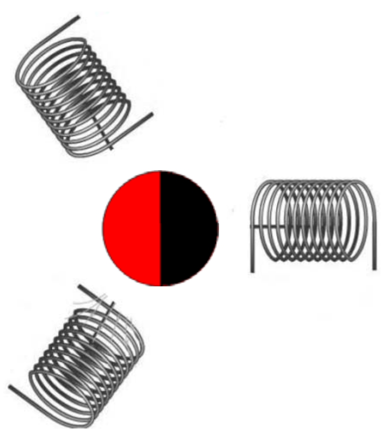
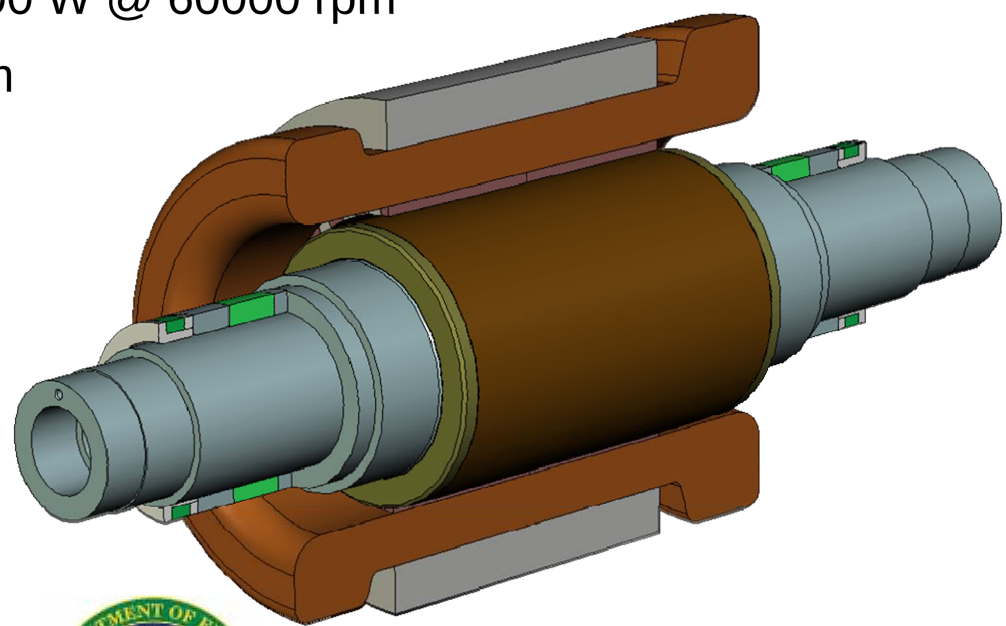
Refrigerator Development Status

6. Design the critical components: Moto-Turbo-Compressor design (Motor + Magnetic bearing + electronics)

   - Motor design
     - 2 poles – 3 phase High speed permanent magnet synchronous motor
     - Mechanical power = 80000 W @ 60000 rpm
     - Stator diameter = 152 mm
     - Motor efficiency = 98 %





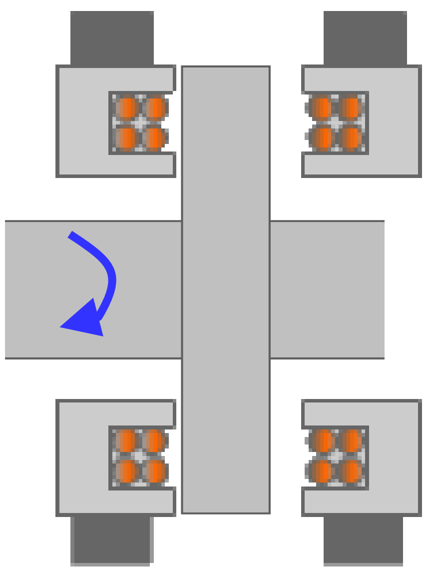
Refrigerator Development Status

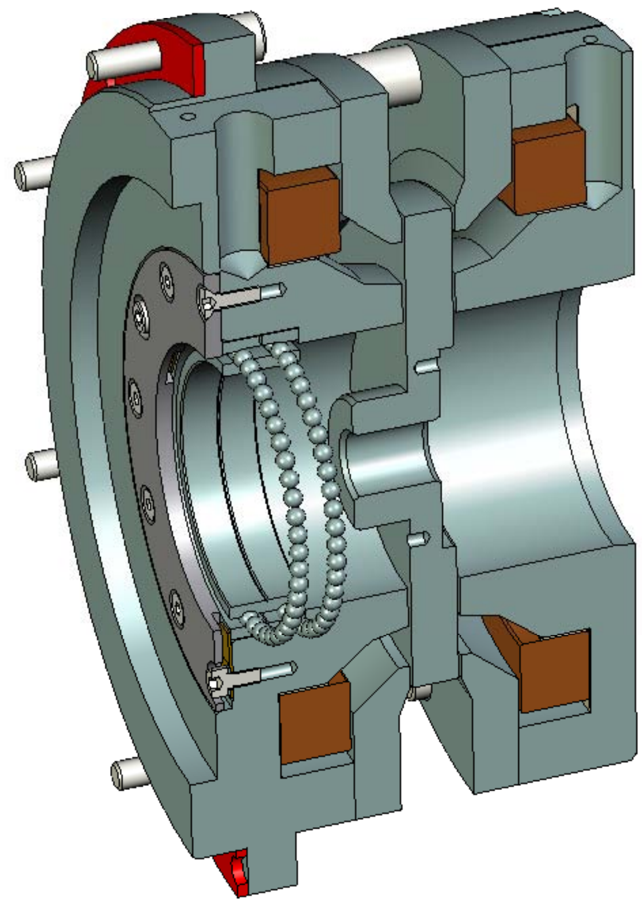
6. Design the critical components: Moto-Turbo-Compressor design (Motor + Magnetic bearing + electronics)

  - Axial magnetic bearing design

    - Maximum axial load = +/- 1400 N

    - Power consumption = insignificant





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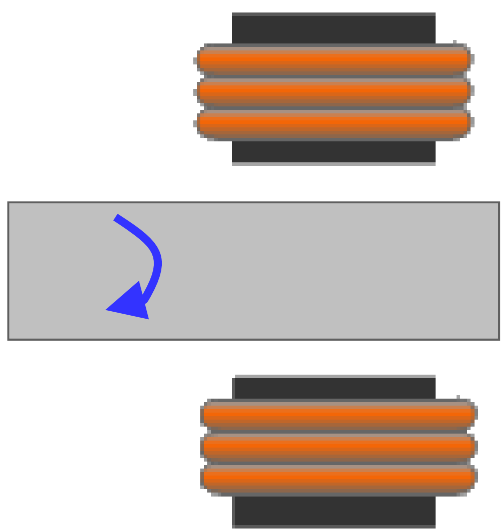
Refrigerator Development Status

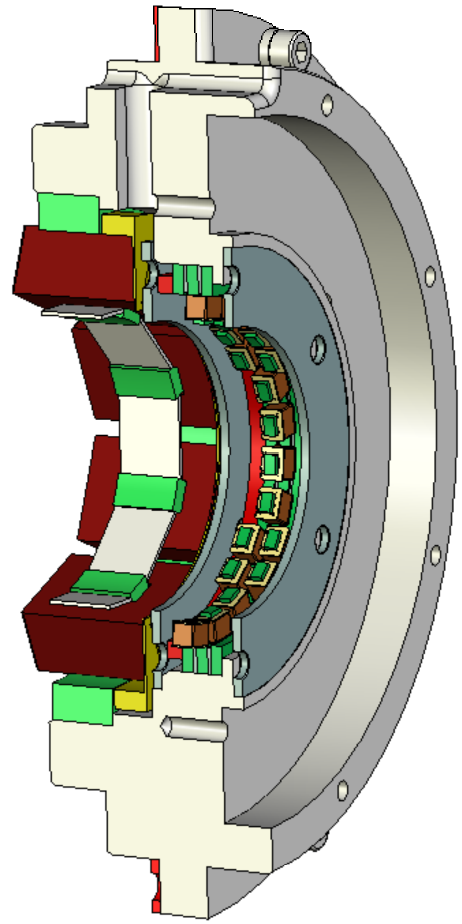
6. Design the critical components: Moto-Turbo-Compressor design (Motor + Magnetic bearing + electronics)

   - Radial magnetic bearing design

     - Maximum radial load = +/- 110 N per bearing

     - Power consumption = insignificant





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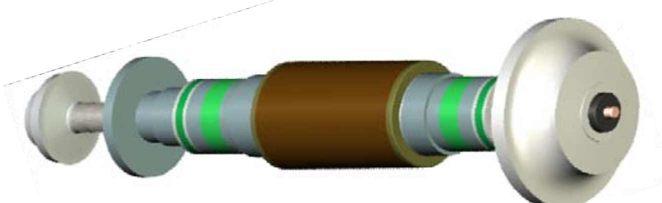
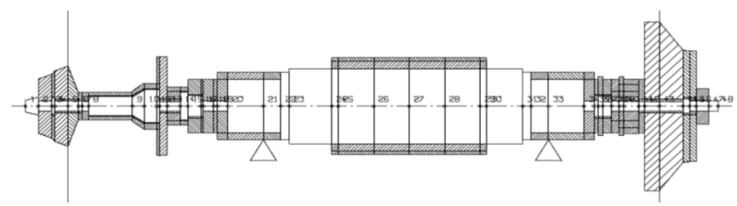
Refrigerator Development Status

6. Design the critical components: Moto-Turbo-Compressor design (Motor + Magnetic bearing + electronics)

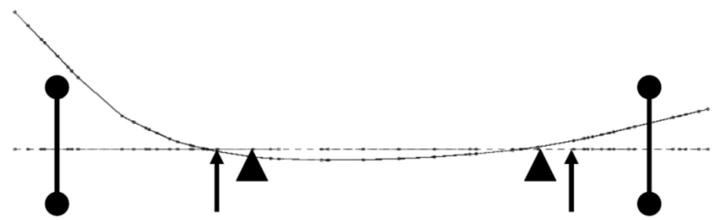
   - Rotor dynamics analysis

     - In a rotor dynamics analysis, the system's critical speed is particularly important. The critical speed corresponds to a rotation speed that is equal to the modal frequency. Because the critical speed is the speed at which the system can become unstable, we must be able to accurately predict those speeds.





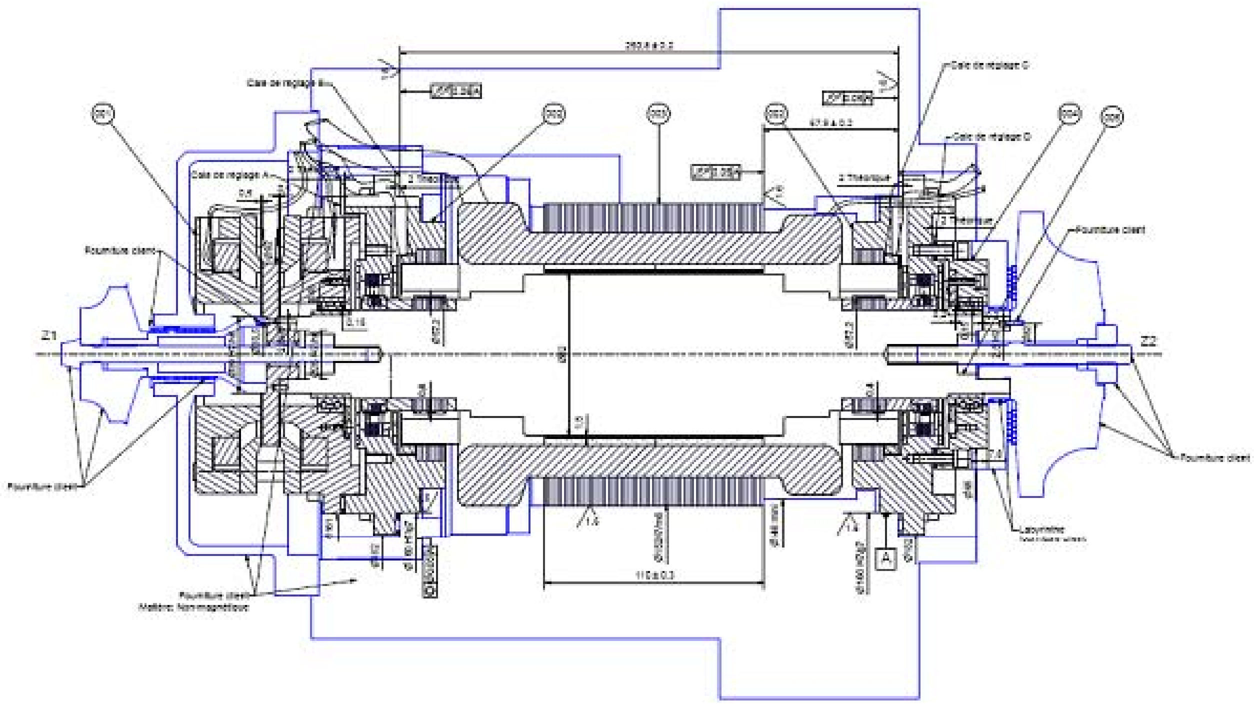
     - 1st bending mode
       - 1226 Hz @ 60000 rpm
       - The separation margin = **22.6 %** (acceptable)



Refrigerator Development Status

6. Design the critical components: Moto-Turbo-Compressor design (Motor + Magnetic bearing + electronics)

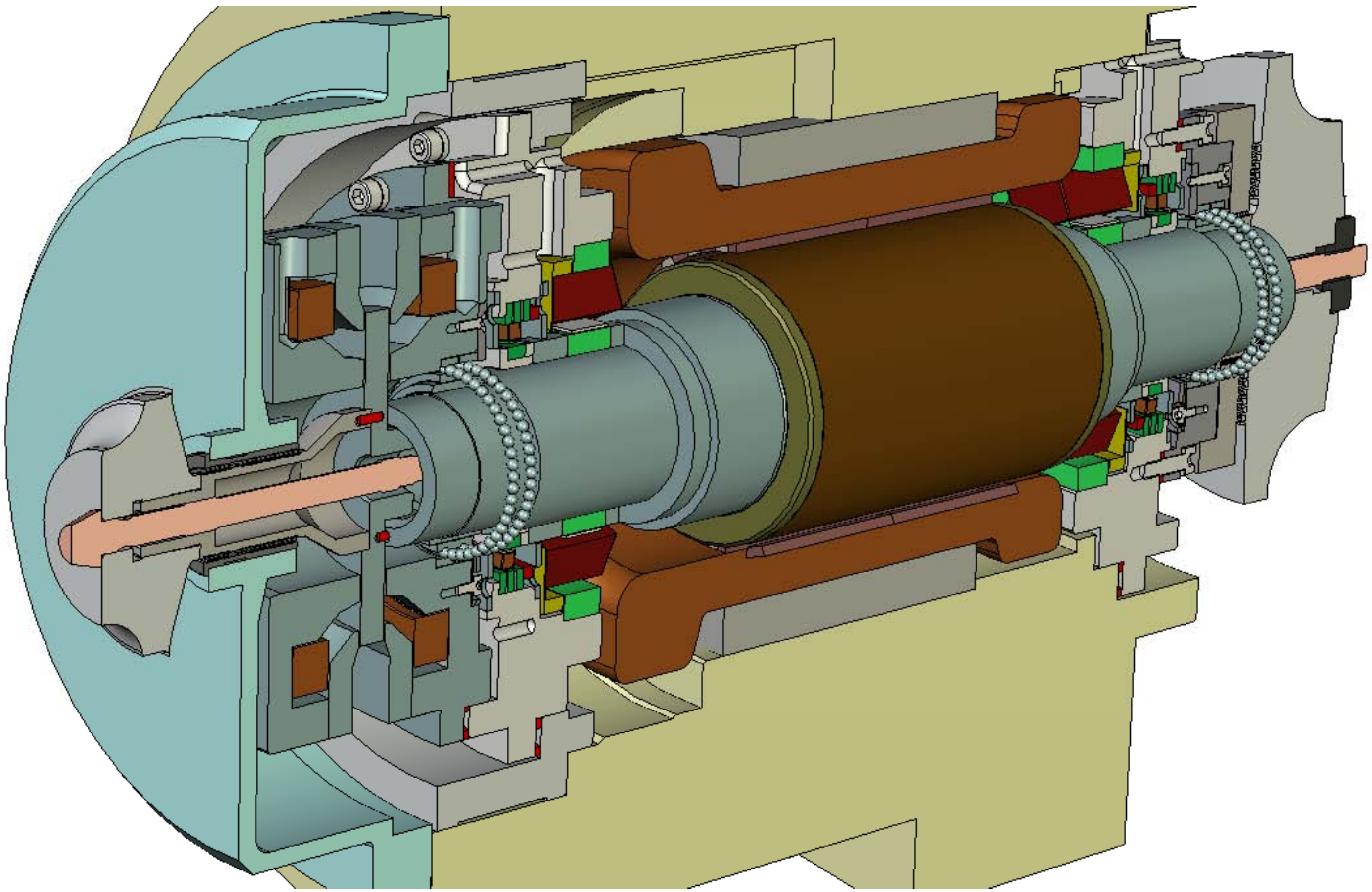
   - Motor + magnetic bearing assembly drawing



Refrigerator Development Status

6. Design the critical components: Moto-Turbo-Compressor design (Motor + Magnetic bearing + electronics)

   - Moto-turbo-compressor assembly 3D model

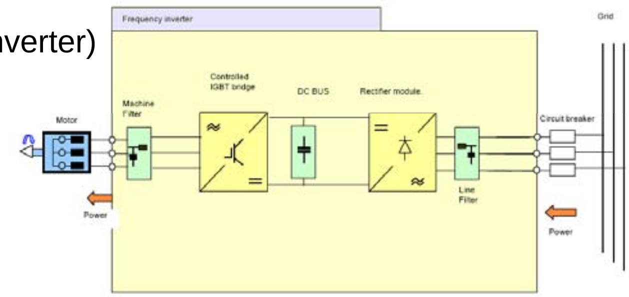


Refrigerator Development Status

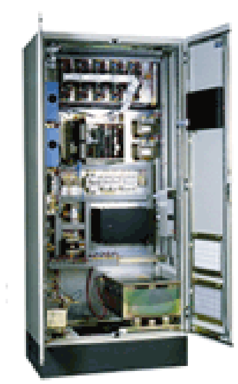
6. Design the critical components: Moto-Turbo-Compressor design (Motor + Magnetic bearing + electronics)

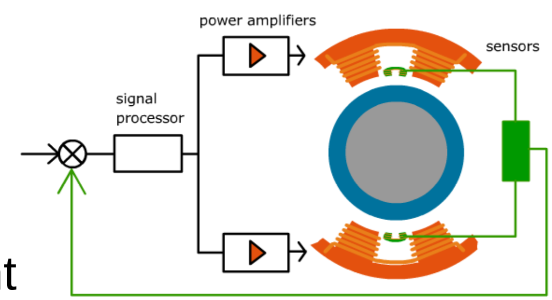
   - Power electronics sizing and design

     - High frequency motor power supply (power converter)
       - Outlet frequency = 1000 Hz
       - Outlet electrical power = 82000 W
       - Efficiency = 96 %



     - magnetic bearings controller
       - Number of active axes = 5
       - Power amplifiers voltage = 150 V
       - Power amplifiers current = 4 Amps
       - Average power consumption = insignificant





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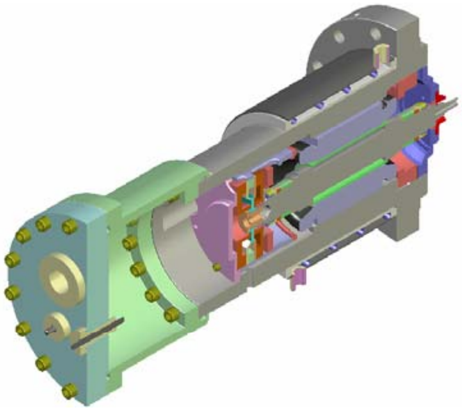
Nexans

Refrigerator Development Status

- Windage losses measurements
  - In high-power reverse-turbo-Brayton applications the windage losses could be significant because of the high rotation speeds and the high rotor cavity pressure levels.
  - Therefore, a numerical model has been developed for windage losses calculation in high speed synchronous motors. This model has been validated with data from published references.
  - Nevertheless, some specific tests have been necessary in order to validate this model with high density surrounding gases. A windage losses test bench was designed and manufactured specifically for these tests.



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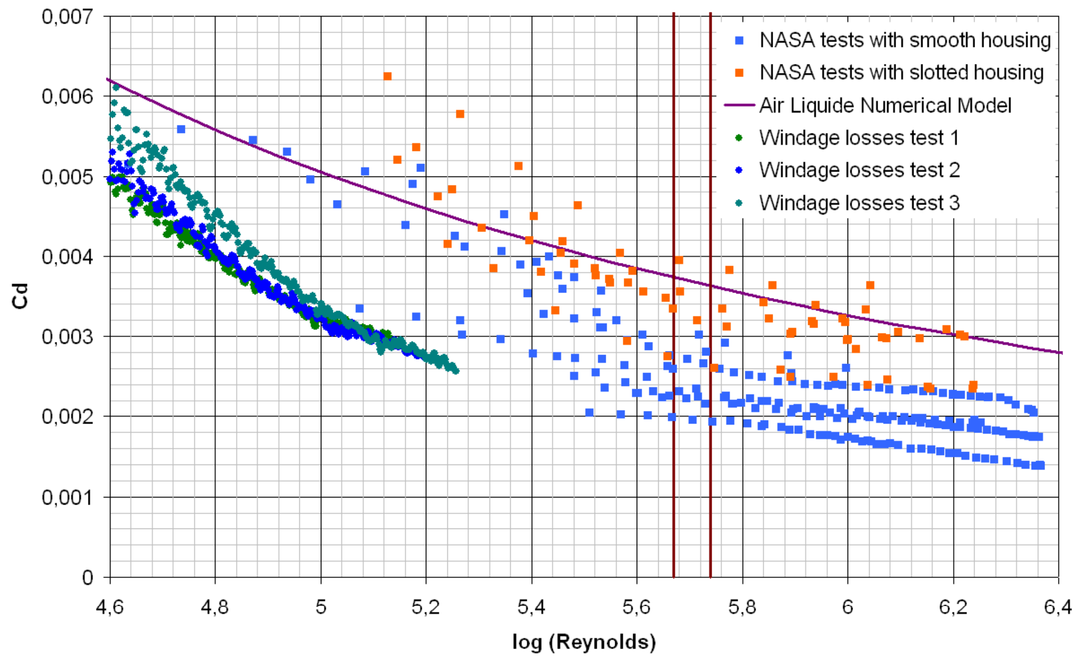
Refrigerator Development Status

- Windage losses measurements
  - Several tests have been realized at variable Reynolds numbers. For each test, the drag coefficient was measured. The main objective of these tests is to validate that the measured drag coefficients are always lower than the calculated drag coefficients (Air Liquide numerical model). This is the case as showed in the graph below:

➢ *In conclusion the Air Liquide numerical model is validated.*



Conclusions

- **Project is performing well**
- **Good progress on all technical objectives**
- **Current LIPA project operation experience supports the need for next generation refrigerator**

Plans for GFY-10

- Manufacture all 2G HTS wire for demonstration
- Manufacture and qualify 30 meter test cable
- Detailed design and manufacture of key refrigeration components
- Manufacture conductor core for 600 meter cable

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DEVELOPMENT AND DEMONSTRATION OF A LONG LENGTH TRANSMISSION VOLTAGE COLD DIELECTRIC SUPERCONDUCTING CABLE TO OPERATE IN THE LONG ISLAND POWER AUTHORITY GRID

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ABSTRACT

The US Department of Energy is funding the world´s first cold dielectric superconducting power cable demonstration project at transmission level voltage, to be installed at the Long Island Power Authority (LIPA) grid in 2007. The cable is designed to carry 574 MVA at a voltage of 138 kV. It will remain installed as a permanent part of the LIPA grid. The project team is comprised of American Superconductor, Nexans, Air Liquide and LIPA. This paper will give an overview of the technical goals of this project as well as the project status. It will describe the cable design and development process, the refrigeration system and the site installation status. An overview will be given about some system-specific operational characteristics influencing the cable system design such as fault currents.

KEYWORDS

Superconducting cable, Superconductor, high voltage

INTRODUCTION

High-capacity, underground HTS power cable has long been considered an enabling technology for power transmission. Power cables using HTS wires have been developed to increase the power capacity in utility power networks while maintaining a relatively small footprint. Over the past decade, several HTS cable designs have been developed and demonstrated. All HTS cables have a much higher power density than copper-based cables. Moreover, because they are actively cooled and thermally independent of the surrounding environment, they can fit to much more compact installations than conventional copper cables, without concern for spacing or special backfill materials to assure dissipation of heat. The Lipa HTS cable project is funded by the US Department of Energy. The project goal is to design, develop and demonstrate the first long length, transmission level voltage, cold dielectric, high temperature superconductor power cable. The cable is designed for permanent installation in the Long Island Power Authority (LIPA) grid and will be able to carry 574 MVA at a voltage of 138 KV. This paper gives a project overview and discusses aspects of the cable design, refrigeration system and site design. Detailed test results of a prototype 30m cable and upgrades of refrigerator system will also be given.

PROJECT DESCRIPTION

The project is a Superconductivity Partnership Initiative (SPI) between the United States Department of Energy (DOE) and industry to develop a long length transmission voltage high temperature superconductor power cable. American Superconductor Corporation is the prime contractor as well as the manufacturer of the high temperature superconducting wires. Nexans is providing the design, the development and manufacturing of the cable and cryostat and Air Liquide is providing the cryogenic refrigeration expertise. The host utility, LIPA, is providing the site, civil work, controls and protection, transmission planning and the operation of the HTS cable. The cable system will be integrated into the LIPA grid and ready for energization in 2007.

CABLE SYSTEM SPECIFICATIONS

The cable system to be installed in the Long Island Power Authority grid is the worlds first to operate at the transmission level voltage of 138 kV. This cable is designed to carry 2400 A rated current resulting in 574 MVA of total power carrying capacity. The 600 meter long system is able to withstand 51 kA rms fault currents for 12 line cycles. In addition to that the system is designed to withstand lower level through faults while staying in operation.
The system will be installed in the Holbrook Substation area of the LIPA grid heading north for a distance of 600 meters where a new switching station is installed. This new station will house the cryogenic refrigerator, the HTS cable terminations, liquid nitrogen storage and the necessary controls for operation and control of the cable system, The power for this line will be taken from an existing 138 KV overhead circuit which will remain in parallel as a backup.

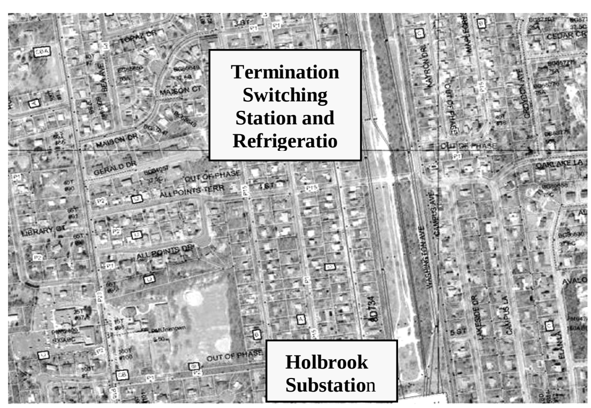

Fig.1. Aerial view of the cable route

CABLE SYSTEM DESIGN

General description

The cable used in the LIPA project is a cold dielectric design. The cable system contains three individual HTS cables and six terminations. The cable configuration consists of a copper former, two HTS conductor layers, an high voltage insulation layer, an HTS screen layer, a copper screen stabilizer and a cryogenic envelope. Fig.1 shows a schematic of cable cross section. During the normal operation, the cable core is maintained at operating temperature by circulating sub-cooled liquid nitrogen.

Fig. 2. Structure of superconducting cable phase

Each cable phase is linked to an outdoor termination at both ends located in the substation areas that will connect the cable to the LIPA grid. The terminations provide both a connection to the cable and interface to the cable cooling system.
In order to enable the appropriate opposite current flow in the superconducting shield layers the screens of the individual cable phases are connected at both cable ends. This is done through a cryogenic jumper cable located and connected at the cable terminations. The termination also contains a bursting disc to protect against transient overpressure generation inside the cable system and particularly inside the termination. A termination sketch can be seen in Fig. 3.

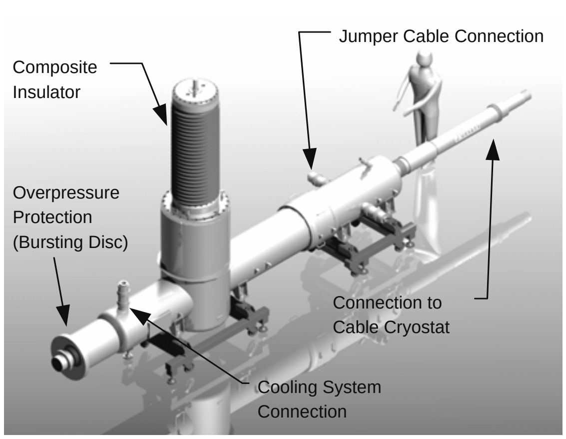

Fig. 3. Superconducting cable termination

Cable Operating Parameters

The selection of the cable operating parameters is driven by coolant properties, Ic characteristics of the wire, the cable core characteristics and the fault conditions of the installation site [5]. The selection process usually takes a few iterations due to coupling of various parameters. The fault current carrying capability of the cable is one of the strongest drivers for the cable design in both, hydraulic layout as well as geometry through the required cross section of the copper former and screen layers. Since nitrogen is used as coolant, the minimum operating temperature of approximately 65 K is selected, which is close to the solidification point. With the different constraints mentioned the maximum operating temperature, the maximum operating pressure and the diameter of the cable cryostat are determined. As a result of this design process, the operating pressure of 18 bar, LN2 flow rate of 0.375kg/s, the cryostat diameter of 88mm and maximum operating temperature of 72K are selected. The cryostat losses of 1.3 W/m/phase and a total pressure drop over the entire cable of 2 bar are expected. Fig.4 illustrates a final system thermal budget with various operating conditions.

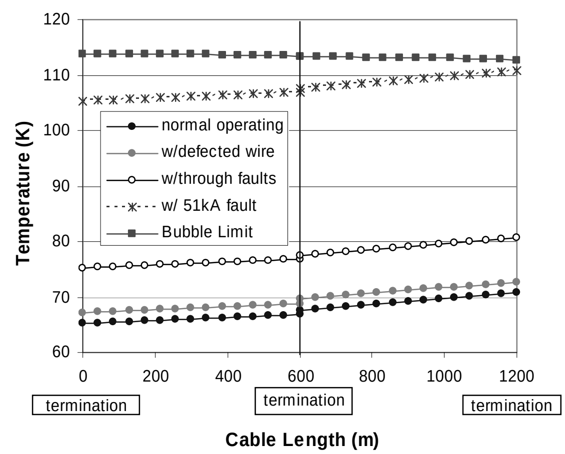

Fig. 4. Lipa cable thermal budget

Fault Management

As with conventional cable, HTS cables must be safe and reliable when abnormal conditions, such as local and through faults, occur in the power grid. Typically, the through faults are those that are generated at other locations but affect the power flow on the superconductor cable, while the local faults are those which happen directly on superconductor cable or related peripherals and in general require repairs, maintenance or replacement of equipment by utility operating personnel. After a through fault it may or may not be required to take the cable out of service depending on the amount of energy dissipated in the system, the fault history, the cable thermal behaviour and layout and the cooling system capabilities.
During a local fault, a large current many times greater than the rated current of the cable is created for a brief period of time until the circuit breakers can be opened. As a result, a tremendous amount of energy is dissipated into the cable core in a relatively short time. This dissipated energy drives not only cable system design but also cooling system design.

To provide proper system protection, it is necessary to have a general fault protection scheme that can be used to handle both local faults and through faults. Such a scheme has been developed during the course of this project and implemented in the Lipa grid protection environment.

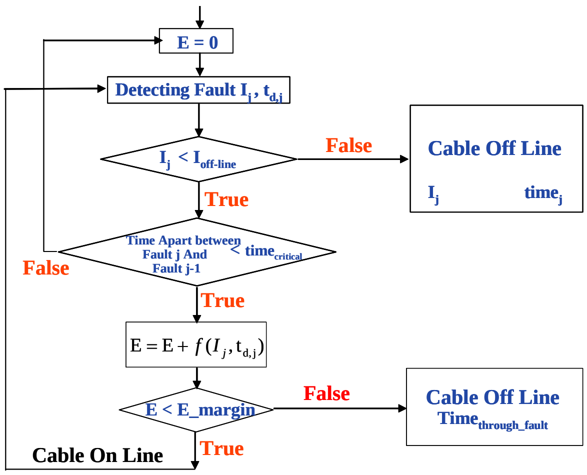

Fig. 2. Fault management scheme

The protection scheme for the current cable project is illustrated in Fig.5, where E is the energy stored in HTS cable core due to faults; I_j is the fault current of fault j; $t_{d,j}$ is the time duration of fault j; $f(I_j,t_{d,j})$ is the function to calculate energy dissipated into HTS cable core due to fault j; I_{off_line} is the single off-line current at which the cable must be taken off line; $time_{critical}$ is the time period during which the effect of the previous fault is entirely diminished and E_{margin} is the pre-determined threshold at which the cable must be taken off line. The Cable Off Line table shows how long the cable must be taken off line for a specific fault current I_j when the fault current is larger than single off-line current I_{off_line}. The off-line time is a function of refrigeration power and coolant flow rate. Even though, the scheme is designed for the current cable project, it could be used for the other cold dielectric cable design

REFRIGERATION SYSTEM DESIGN

General description

The refrigeration system used in the LIPA project is a turbo-Brayton Helium refrigerator that circulates subcooled 65K LN2 through the cable cryostat. A 100% capacity backup system comprised of two vacuum bath LN2 subcoolers and a 13000 gallon bulk storage tank supports the reliability of the system. The refrigeration capacity of the system in Primary mode is 5.65 kW and backup is 6.77 kW. If required both the primary and backup can be run together to augment the refrigeration capacity.

13,000 Gallon LN2 Bulk Storage tank

The 65K LN2 is supplied to the cable cryostat via a distribution valve cold box and vacuum insulated piping.

Distribution Cold Box

The cooling down of the cable is performed via a specialized mixing skid that allows the cable cryostat to be cooled in a controlled manor.

Cool Down Skid

Current Status

The refrigeration system installation was completed the end of January 2007. Startup and pre commissioning activities were performed through to mid March with many successful starts and stops and switchovers between primary and backup.

Helium Compressor

Final commissioning and performance testing is scheduled to be completed by the end of May, with all performance aspects of the refrigeration system critical to cable operation characterized and validated against design values, i.e. refrigeration power, LN2 flow rate at design pressure drop, LN2 temperature, overall system effects on change of operation. Adjustments, if required, to the operating logic of the refrigeration system will be done at this time.