Cryogenic Moderator System Performance

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Moderator System Overview

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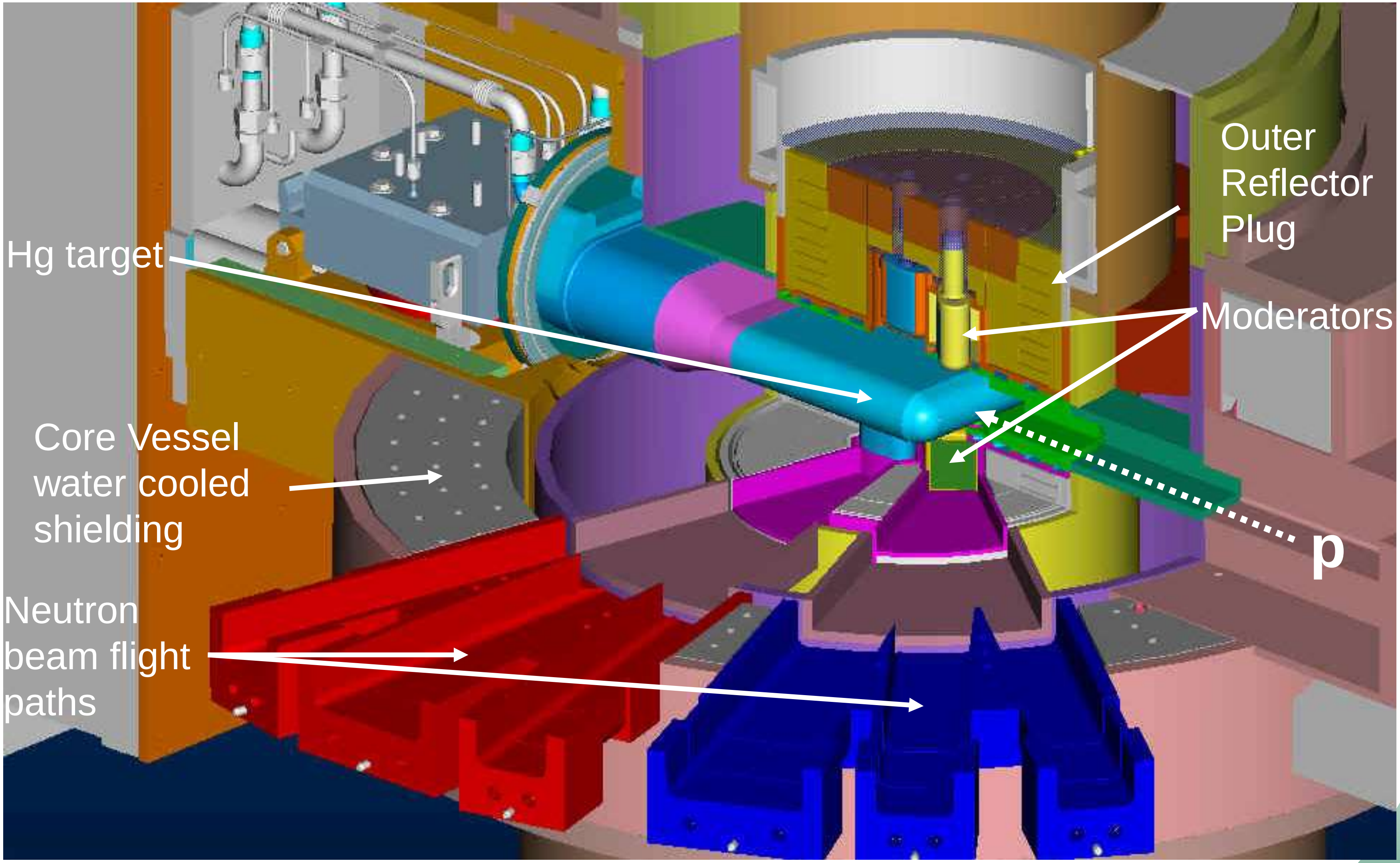
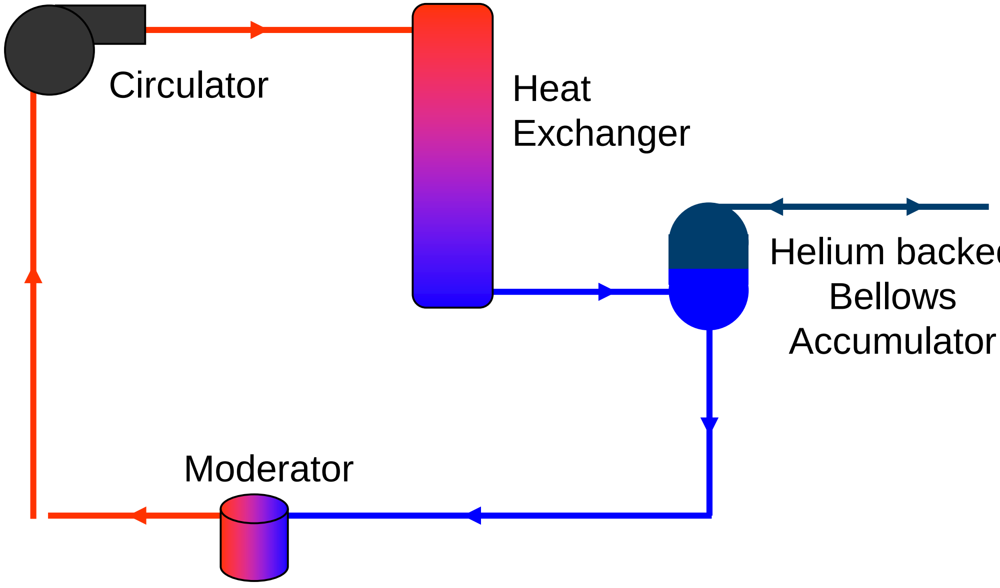
Target – Moderator Configuration



Hydrogen System Description

- The Hydrogen Moderator System is a series of three independent cryogenic loops each consisting of:
  - Moderator
    - load
  - transfer lines
  - Circulator
    - Flow control
  - Heat exchanger
    - Thermal control
  - Accumulator
    - Pressure control

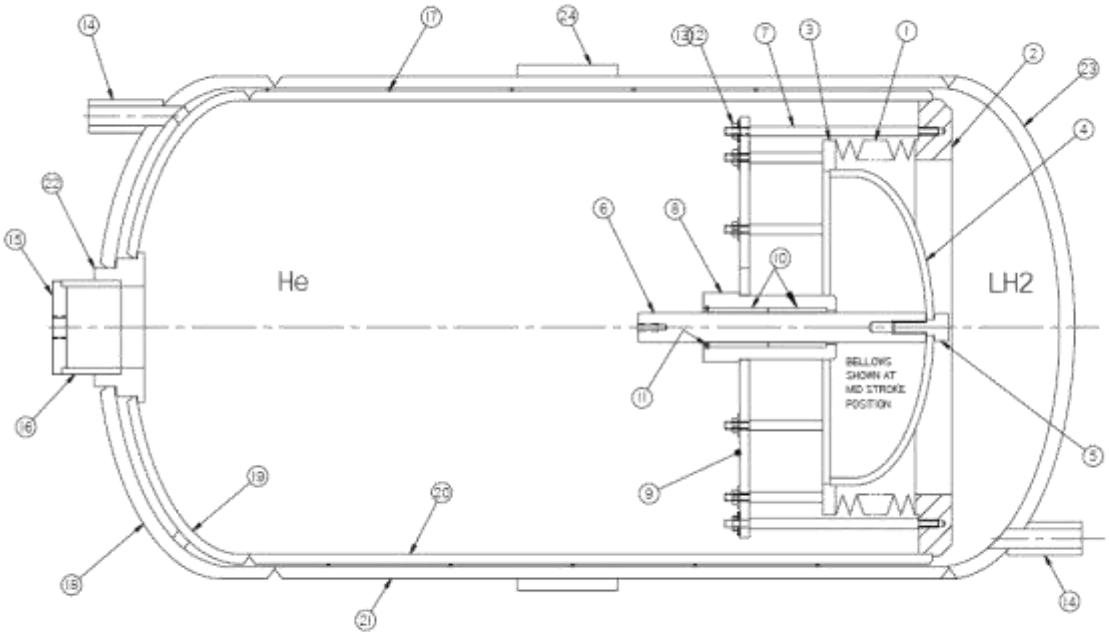


Normal Operating Conditions

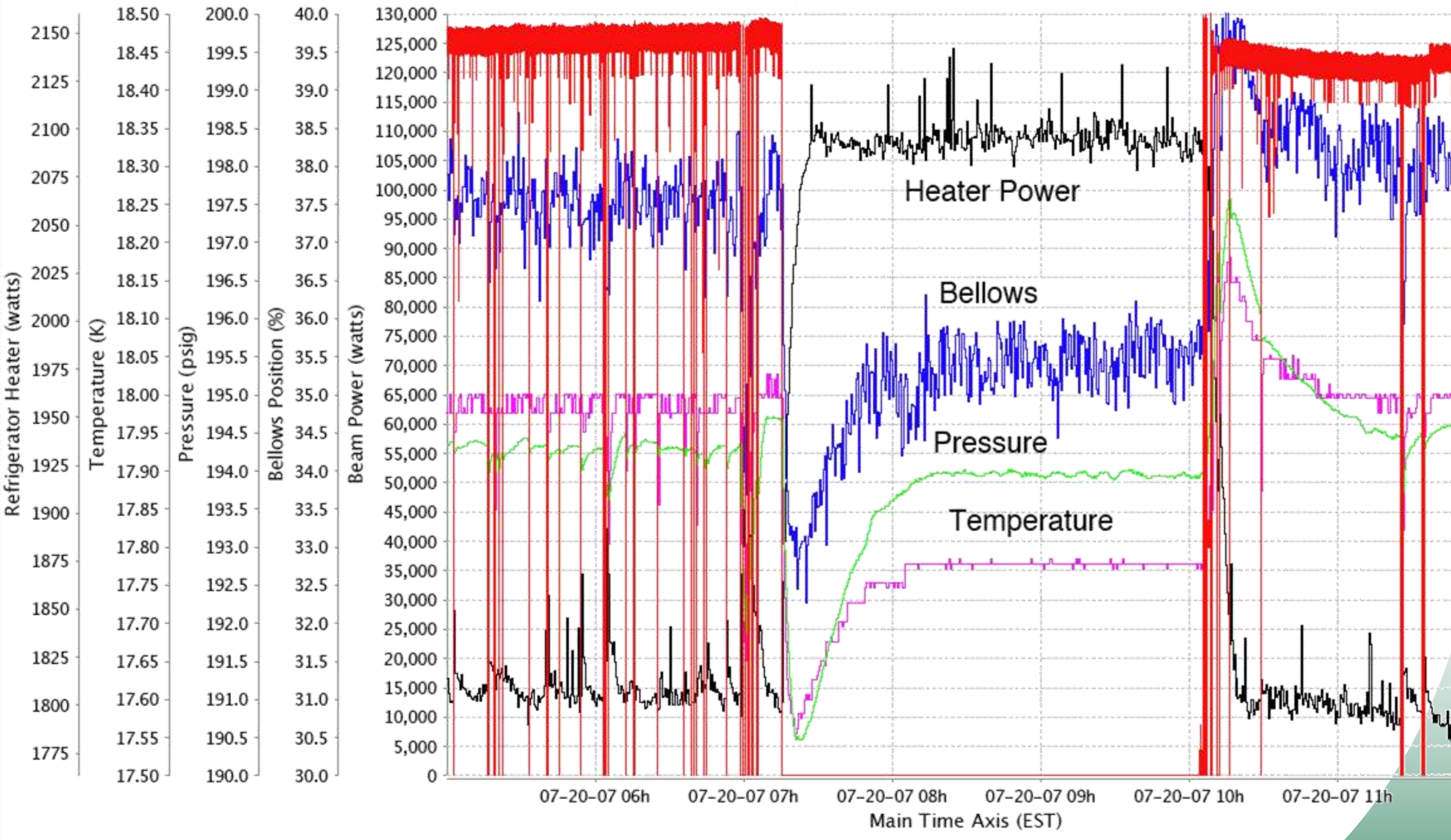
- **The hydrogen system operates at supercritical conditions at all times to avoid phase change complications.**
  - **Minimum loop pressure is maintained at 14 bar.**
    - **Provides a 1 bar margin above the critical pressure.**
- **The system operates in a constant mass mode thus it must accommodate a certain degree of pressure perturbation resulting from frequent beam interruptions.**
  - **Beam off pressure ranges from 14 to 15 bar.**
    - **Circulator capable of a delivering a maximum of 1 bar differential.**
  - **Beam on pressure ranges from 15 to 16 bar.**
- **Hydrogen supply temperature is controlled to maintain an average moderator temperature of 20 K.**
  - **Temperature throughout the loop ranging from 17.5 K to 22.5 K.**
- **Heat exchangers are designed with a very tight approach.**
  - **0.5 K**

Pressure Control Philosophy

- **Pressure is controlled passively by a cryogenic accumulator.**
- **The accumulator is a double walled design with an all stainless steel construction.**
  - **Helium backed bellows**
- **The accumulator vessel is actually surrounded by the flowing hydrogen.**
  - **Approaches isothermal expansion and compression of the helium.**
  - **Ensures adequate cool down.**



Cryogenic Accumulator in “Action”



125 kW Beam Heating

- Refrigeration heater load response to beam heat indicates a nuclear load of ~300 W.
  - ~2.4 W per 1 kW beam
- Hydrogen temperature is controlled within 0.25 K.
- Hydrogen pressure is controlled to within 0.6 psig.
- Pressure controlled passively by accumulator as recorded by ~2% shift in bellows position.

Helium Refrigerator Requirements

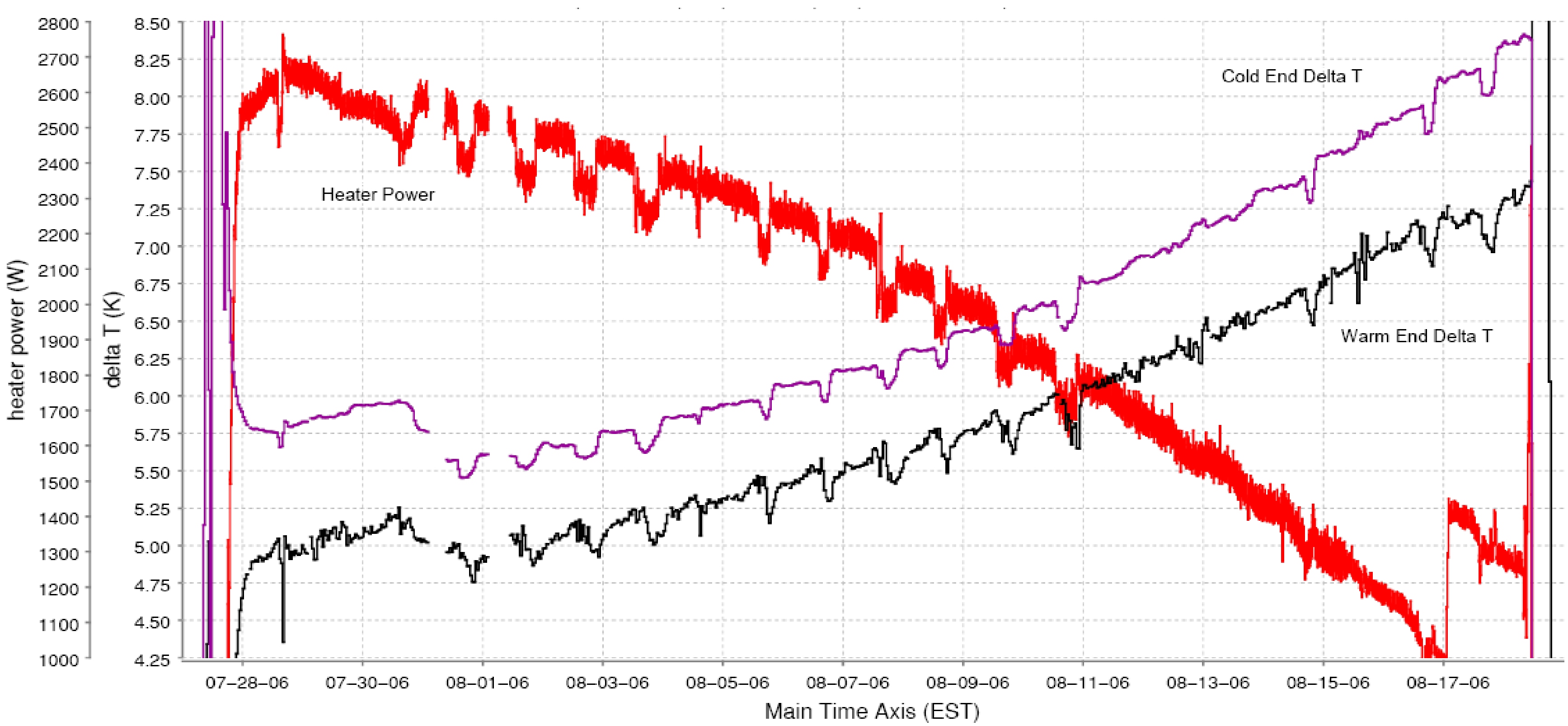
- The function of the Helium Refrigerator is to cool these three parallel-connected hydrogen loops and subsequently maintain a nominal hydrogen supply temperature of 17 K from each heat exchanger against a continuous combined heat load of 7.5 kW.
- As such, the vendor was given responsibility for the design and fabrication of all helium bearing components.
- Temperature control was specified at +/- 0.5 K.
- To meet this requirement, the vendor specified hydrogen-to-helium heat exchangers with a 0.5 K approach.
  - This resulted in a a required 16.5 K helium supply temperature.

Helium Refrigerator Commissioning

- **When the system was originally commissioned in January 2005, it failed its performance test.**
  - **The system was unable to attain its specified 7.5 kW @ 16.5K.**
  - **Not only did it come short of its capacity goal, it could not operate stably at design conditions**
    - **40 psig compressor suction**
  - ***Apparent* stable operation was ultimately achieved at a lower suction pressure of 20 psig**
- **At that time, it appeared that the system would operate sufficiently for a long period of time but at a greatly reduced capacity**
  - **Capacity was still sufficient to support operations in excess of 1MW.**
- **In fear of jeopardizing CD-4, the decision was made to postpone any repair attempts.**

Helium Refrigerator Operation

- **Early in operations, however, it was discovered that the system mysteriously suffered from a steady decline in cooling capacity.**



Contamination?

- **Air Liquide's first suspicion was contamination.**
  - **Water**
  - **Air**
  - **Oil**
- **A number of tests and analyses were performed and it was concluded that the system was clean and dry.**
- **During the testing phase, operation at design conditions would result in a rapid decay.**
- **Lowering the suction pressure, however, appeared to allow the system to recover.**
  - **This was inconsistent with the assumption that the heat exchanger was fouling due to contamination.**

Flow-Induced Mal-distribution?

- Two openings were made along the length of the cold box to allow for access to the heat exchanger.
  - RTD's were attached across the height of the heat exchanger at these two locations.
  - RTD readings were logged during subsequent production runs.
- These readings clearly showed that the top of the heat exchanger was warmer than the bottom.
- It was also clear that the heat exchanger was becoming progressively shorter as a function of time.
  - 90K only 1 foot from the cold end operating at ~30K!
- These results coupled with analysis performed by Air Liquide, lead to the conclusion that the heat exchanger was suffering from a propagating mal-distribution perhaps caused by small pressure drop in the core.
  - The pressure drop is significantly reduced by the fact that the flow in the channels is actually laminar as opposed to turbulent.

Helium Refrigerator Modifications

- After presenting their analysis to SNS Management, it was agreed that the heat exchanger should be removed and perforated plates be installed into each of the headers.
- This work was performed during the ‘06 Christmas outage.
  - The heat exchanger was extracted, shipped to CHART for repair, re-installed, and the system operational before the end of the outage.
- Initial indications were promising as the system appeared to operate stably at design conditions for a period of 4 days.
  - Before the modification, operation at design conditions resulted in a noticeable decay in performance within 45 minutes.
- Continued operation of the system, however, during the following cycle revealed the fact that the system continued to suffer from a slow degradation in capacity.

Contamination, again?

- **After the header modifications only resulted in a decrease in the rate of performance degradation, Air Liquide once again turned to contamination as an explanation and initiated a new battery of tests:**
  - **Compressor oil samples were analyzed.**
  - **HX was isolated at the conclusion of a production run, and pumped down through a LN2 cold trap.**
    - **Negligible quantity of water found.**
  - **Consolidated Science performed detailed on-site analysis of the helium both in the process stream as well as the buffer tank.**
    - **17 ppm of Nitrogen found in the buffer tank helium.**
- **At the conclusion of these tests, Air Liquide suggested that the helium be purified by operating the refrigerator for several brief periods between which the adsorber was regenerated.**
  - **At the conclusion of the purification process, the buffer tank nitrogen concentration was down to ~2 ppm.**
  - **During subsequent operation of the refrigerator, the rate of decay was unaffected.**

Tower Water Instability?

- Quickly running out of theories, our attention turned to the noticeably noisy warm end temperature differentials.
- The after cooler on the compressor skid was cooled using the site's tower water facility.
  - The temperature control for this system is rather poor resulting in large temperature swings that correspond to when the cooling water fans cycle.
- This instability in tower water transmitted its fluctuations directly into the helium stream entering the high pressure header on the warm end of the heat exchanger.
- Operational experience during the winter months indicated a system preference to cool weather which coincidentally corresponded to periods of more stable tower water temperature.
- The tower water cooling circuit was disconnected from the after cooler and was replaced by a more stable chilled water cooling circuit.
- While noticeably smoothing the warm end temperature differentials, the rate of decay was seemingly unaffected but did yield some additional cooling capacity.

Impacts on Future Operation

- **Our current mode of operation was unacceptable.**
  - **~20 day run cycles were resulting in frequent cycling of components and equipment.**
- **If the beam ramp up schedule is met, SNS will be operating at 1.4 MW by October 2009.**
- **At 1.4 MW, the refrigeration system will be able to accommodate cold neutron production for ~6 days continuously before it will be required to be warmed.**
  - **Each warm up / cool down cycle requires 3 days.**
- **There is no way SNS can meet its beam availability goal of >90% with a refrigeration system that can only provide at best 66% availability.**
  - **Not to mention that with the excessive number of thermal cycles, something WILL break eventually.**

External Advisory Committee

- With no clear path forward, an external advisory committee was formed.
- The committee recommended that we "develop a short term fix that would provide more stable capacity for the short term, and an appropriate fix for the long term."
- To that end, we procured two replacement HX's that would have been installed this summer to addresses the long term.
  - The design of this replacement pair of HX's are based on the operating experience of a similar but stably operating Air Liquide facility.
- While waiting for our new HX's, we faced the prospect of progressively shorter refrigerator run cycles resulting from the expected ramp up in beam power.
- Our attention then turned to developing a short term fix.

Self-propagating Mal-Distribution Causes

- We had investigated a number of potential causes for a self-propagating mal-distribution.
- The two causes that remained were:
  - Manufacturing defects in the HX that results in a significant non-uniformity of channel cross section areas,
  - Temperature gradient across the stack height as the result of HX's horizontal orientation.
- Recent experience at the WTRF in Korea, however, indicated an almost identical slow degradation of the refrigeration system's performance over time.
  - This implied a low probability that the cause was a manufacturing defect, as the two HX's were manufactured by different companies.
- This left us with gravity-driven mal-distribution.
  - The ILL refrigeration system consists of one HX block with NO LN2 pre-cooling and has been operating in a stable manner since the 70's.
    - The HX, however, is oriented vertically.

Short-term Fix Proposal

- Last Christmas we demonstrated the ability to extract the HX, ship it to CHART for repair, re-install the HX, and leak test in a period of one month.
- The proposal involved once again extracting the HX but to install it into a new vertically oriented auxiliary vacuum enclosure to be located at the cold end of the existing cold box.
- The HX would be extracted by the same team that performed this work previously.
- The HX would then be shipped to AET for installation into the new box while work would proceed on site preparing the new piping connections.
- The new auxiliary vacuum enclosure would need only accommodate 4 single walled piping connections.
  - Warm piping would by-pass the existing cold box externally
  - Cold piping connections would be made via a 24” access port

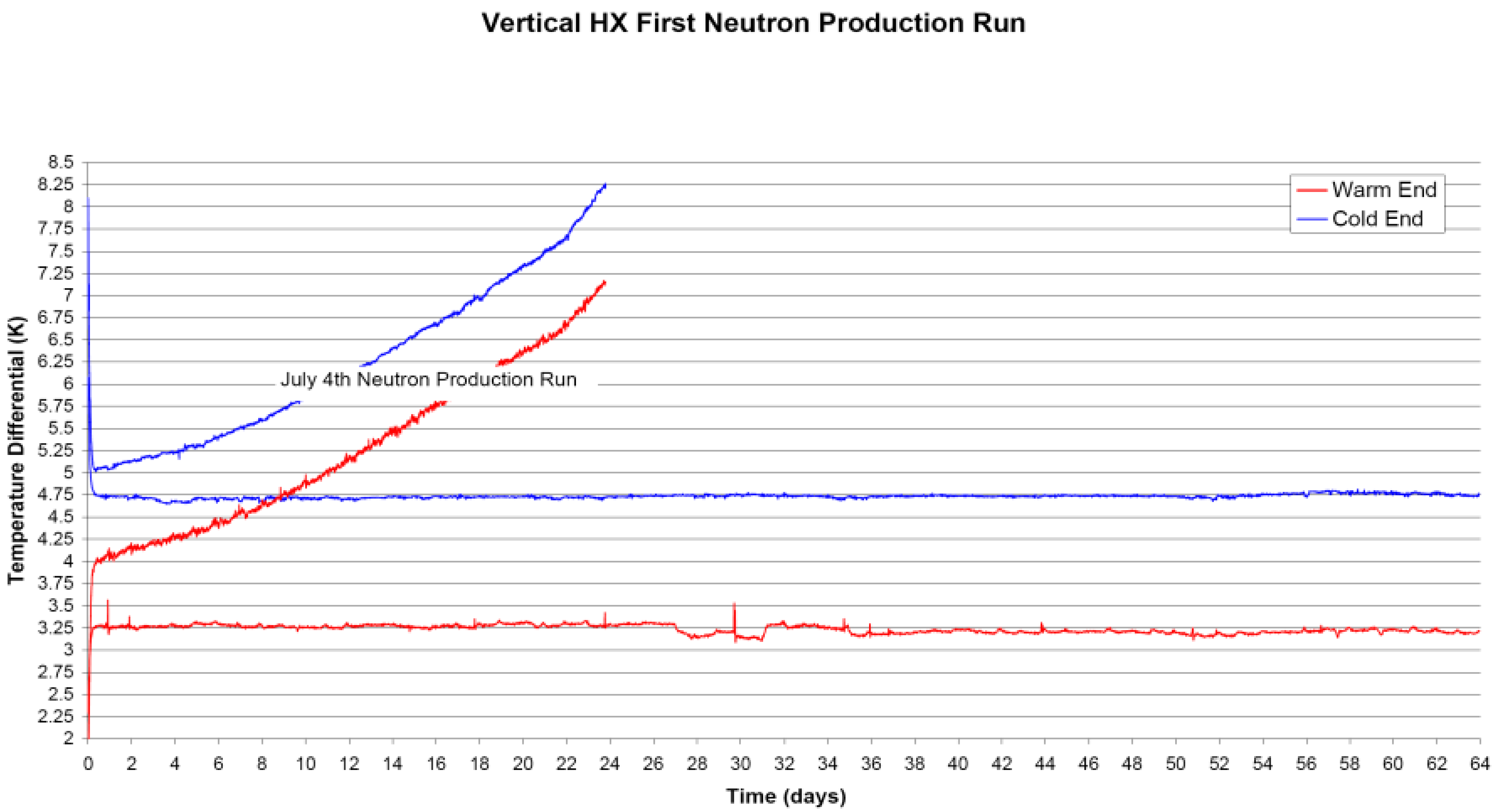
HX Re-orientation Schedule of Events

- The extraction process started on October 4.
- HX shipped to AET on October 7.
  - Oil found in process piping at AET on October 10.
    - Sent to Consolidated Science for Analysis.
    - Control sample of our compressor oil sent for comparison
  - Analysis repeated by Consolidated confirms presence of compressor oil in cold box piping.
- Witch's hat inspected on October 22.
  - Presence of charcoal and oil indicate failure of the Oil Removal System.
    - Oil Removal System Rebuild started on October 24.
- Methanol flushing of process piping began on October 26.
- The new cold box arrived on October 31.
- Refrigerator was re-started on November 5.


EXIT


Ace

Operational Experience to Date



Summary

- **Accumulator-based pressure control system has been successful at passively controlling the loop pressure of a circulating supercritical hydrogen loop.**
  - **Projections indicate that the system will be able to accommodate full beam power at 1.4 MW.**
- **Despite suffering from a capacity degradation, the helium refrigeration system has been successful at controlling the hydrogen circuits to within +/- 0.5 K.**
- **Re-orientation of the HX from horizontal to vertical has proven successful.**
  - **Operation of the refrigerator at design conditions is projected to yield ~8 kW of cooling.**