# Testing of a Neon Loop Heat Pipe for Large Area Cryocooling

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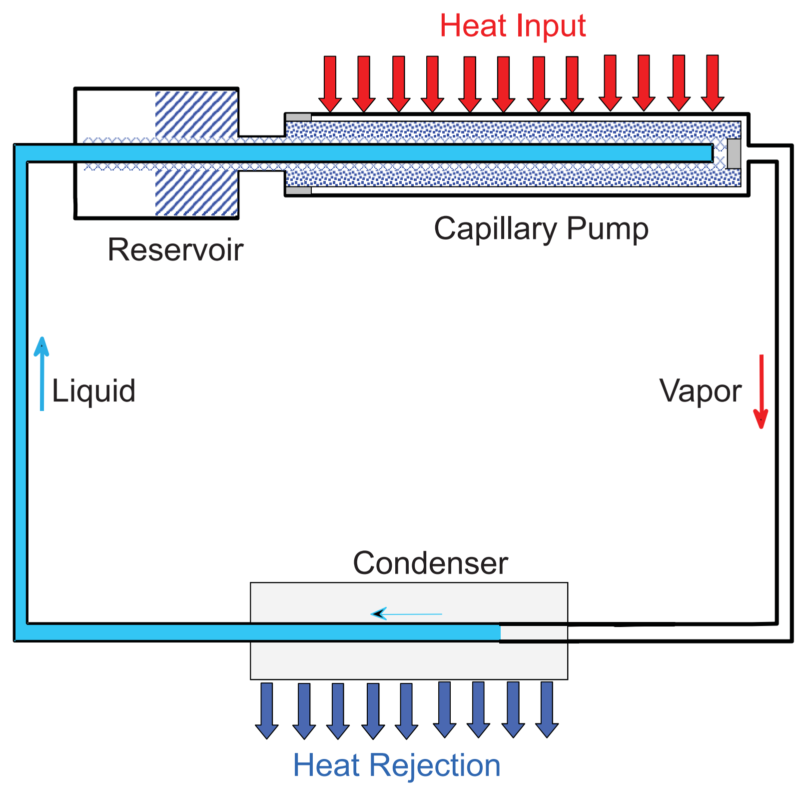
# Outline

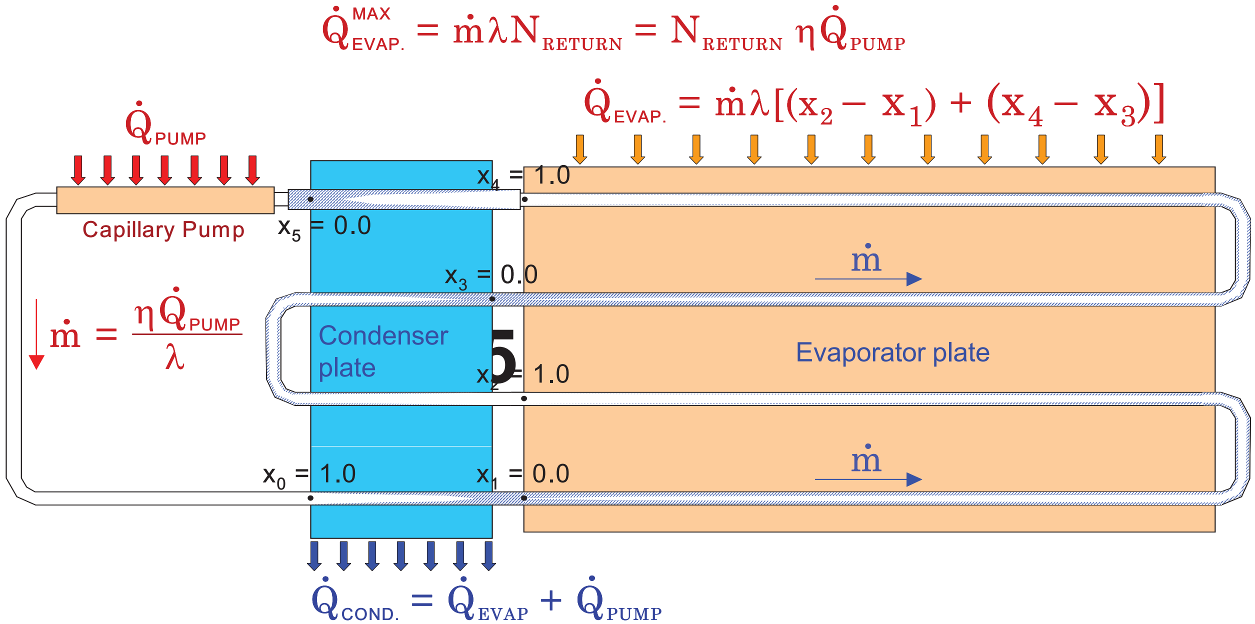
- CLHP Design Concept
- Test Article
- Test Setup
- Test Results
- Lessons Learned
- Conclusions

# Loop Heat Pipe - Background

- Traditional Application
  - Waste heat is acquired over a small area by the LHP capillary pump and transported to a large area (e.g. space radiator) for rejection.
- No External Pumping Power
  - Waste heat provides the driving force.
- No Moving Parts
- Robust Operation
  - Passive
  - Self-regulating
- High Pumping Capability
- High Thermal Conductance
- Smooth-walled and flexible transport lines provide flexibilities for design, integration and testing.



# CLHP for Large Area Cooling Applications

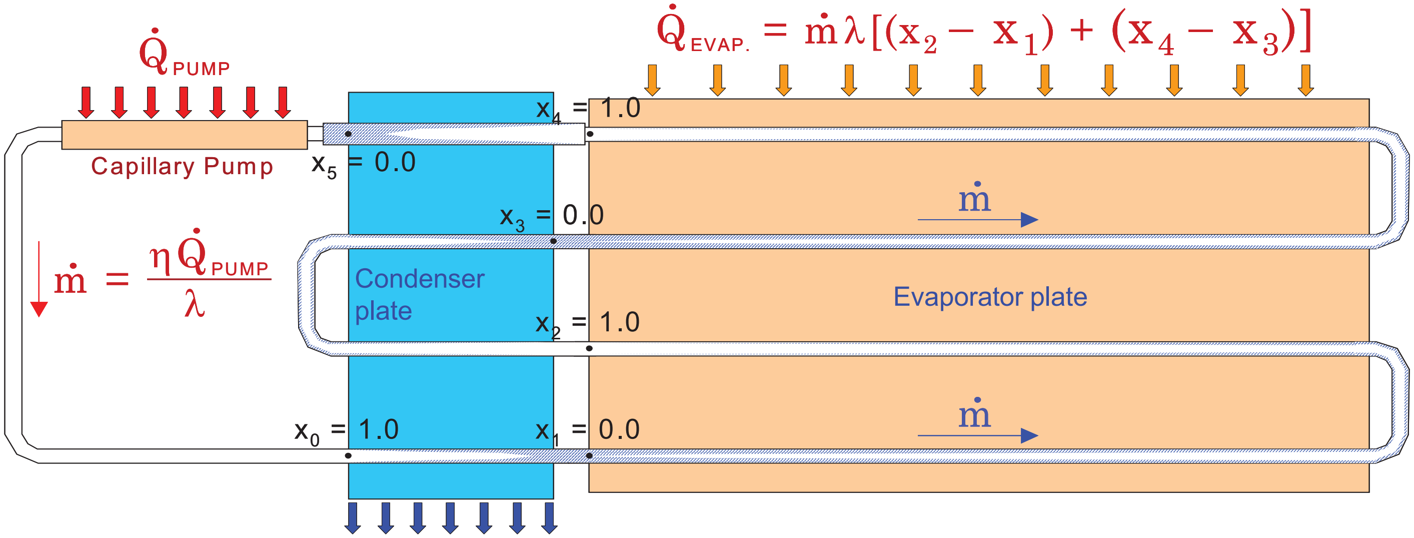



- **Heat is absorbed over a large area (detector array) and rejected into a small area (cryocooler).**
- **An external power is applied to the capillary pump to serve as the driving force for fluid circulation.**
- **The CLHP transport line flows alternately between a condenser plate attached to a cryocooler and an evaporator plate attached to the heat source.**
- **Vapor condenses into liquid as it passes through the condenser plate, and liquid vaporizes as it pass through the heat source.**

# CLHP for Large Area Cooling Applications

$$\dot{Q}^{MAX}_{EVAP.} = \dot{m}\lambda N_{RETURN} = N_{RETURN}\,\eta\dot{Q}_{PUMP}$$

$$\dot{Q}_{EVAP.} = \dot{m}\lambda[(x_2 - x_1) + (x_4 - x_3)]$$




$$\dot{Q}_{COND.} = \dot{Q}_{EVAP} + \dot{Q}_{PUMP}$$

$$Q_{cond} = m\lambda\,[(x_0 - x_1) + (x_2 - x_3) + (x_4 - x_5)]$$

- **The amount of heat that can be acquired is a function of the heat applied to the CLHP capillary pump and the number of passes that the fluid flows through the heat source.**
- **The maximum amount of heat that can be applied to the capillary pump is limited by the heat transport capability of the CLHP.**

# Technical Challenges of CLHP

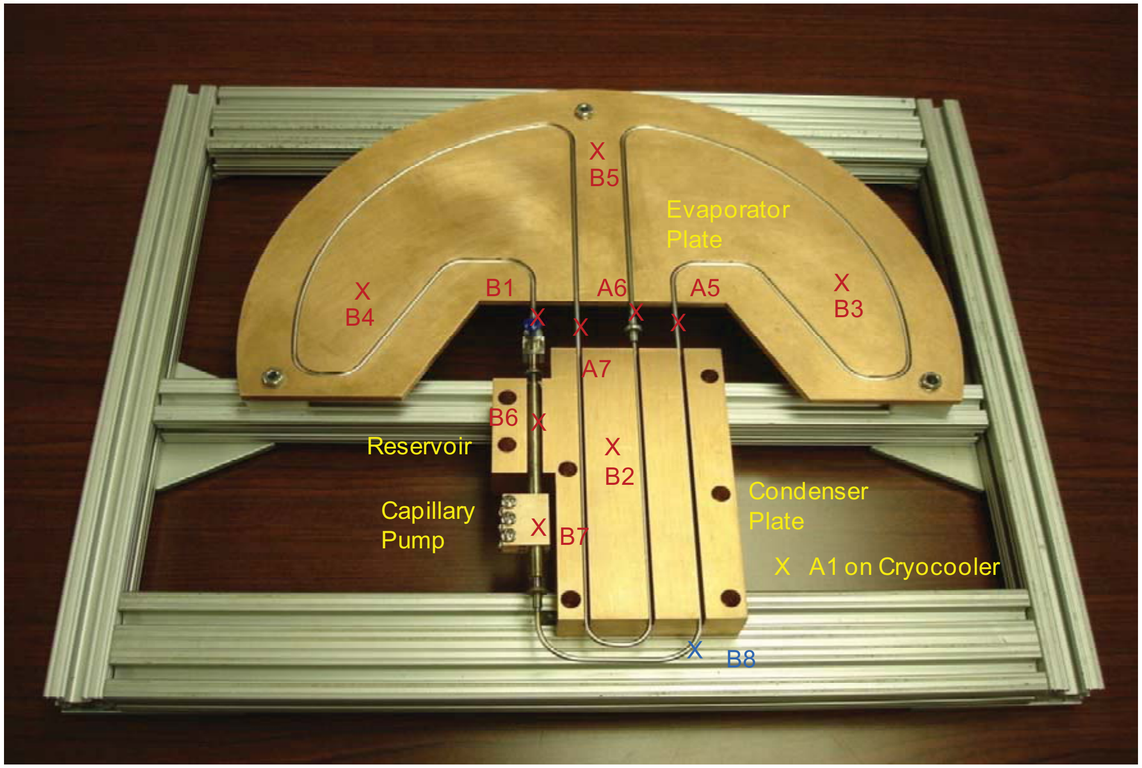
- A mismatch of coefficient of thermal expansion between the capillary pump and the primary wick.
  - Solved by using the same material for capillary pump and primary wick
- Containment of the system pressure at ambient temperature.
  - Solved by using a hot reservoir attached to the CLHP
- Start-up from an initially supercritical state.
  - Solved by using a hot reservoir attached to the CLHP to reduce the system pressure
- Parasitic heat gain at cryogenic temperatures.
  - Minimized by proper insulation

# Testing of Neon Loop Heat Pipe

- **Objective:**
  - Experimentally test a cryogenic loop heat pipe (CLHP) to demonstrate its feasibility as a closed-loop system to cool large areas such as optics, detector arrays, and cryogenic propellant tanks

- **Technical Approach:**
  - Reconfigure a CLHP developed under NASA SBIR program and use a cryocooler as the heat sink (instead of a helium dewar).
  - Test the CLHP in a thermal vacuum chamber.
  - Use neon as working fluid to demonstrate its operation in temperature ranges of 28K to 43K.
  - Characterize the neon CLHP performance under transient and steady state.

# CLHP Test Article



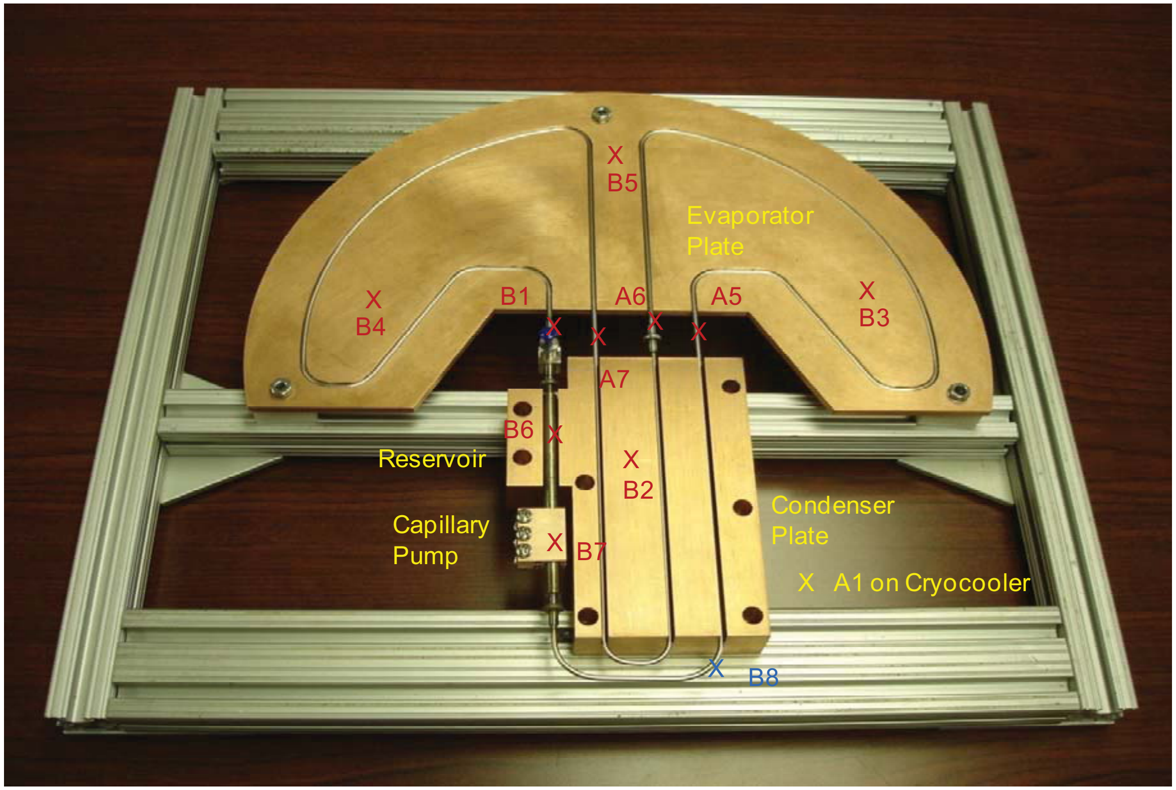

- **Delivered by TTH Research in 2007**
- **Manufactured by Thermacore, Inc.**

- **LHP**
  - **all stainless steel construction**
  - **capillary pump: 1/4"OD x 1.5"L**
  - **wick: 1.2μm x 45% porosity**
  - **reservoir: 1/4"OD x 2.5"L**
  - **transport line: 1/16"OD x 63"L**

- **Evaporator Plate**
  - **copper 10" ϕ 48 in$^2$**
- **Condenser Plate**
  - **copper 3" x 5.5" x 1"**

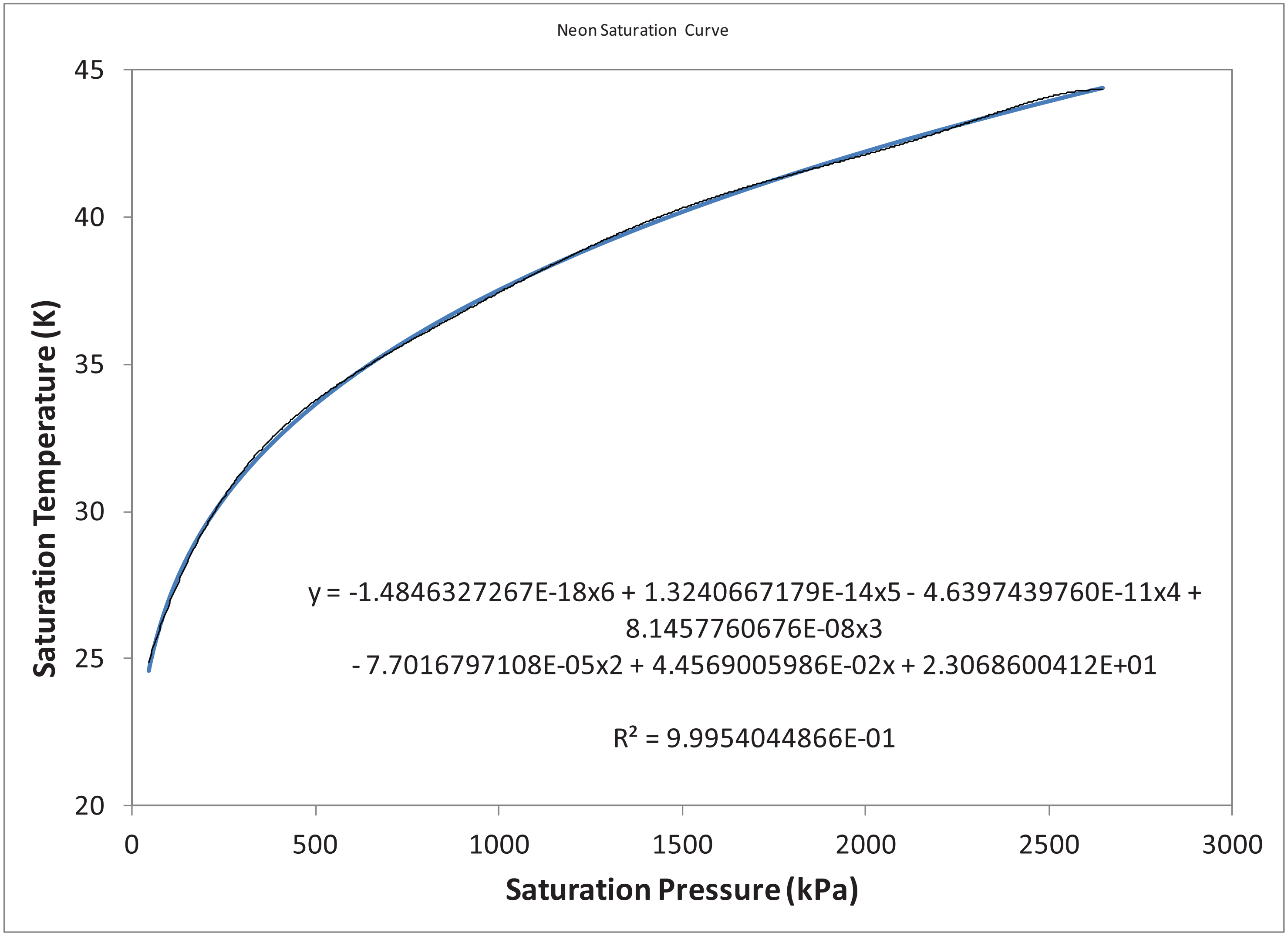
# CLHP Instrumentation

DT-670-SD

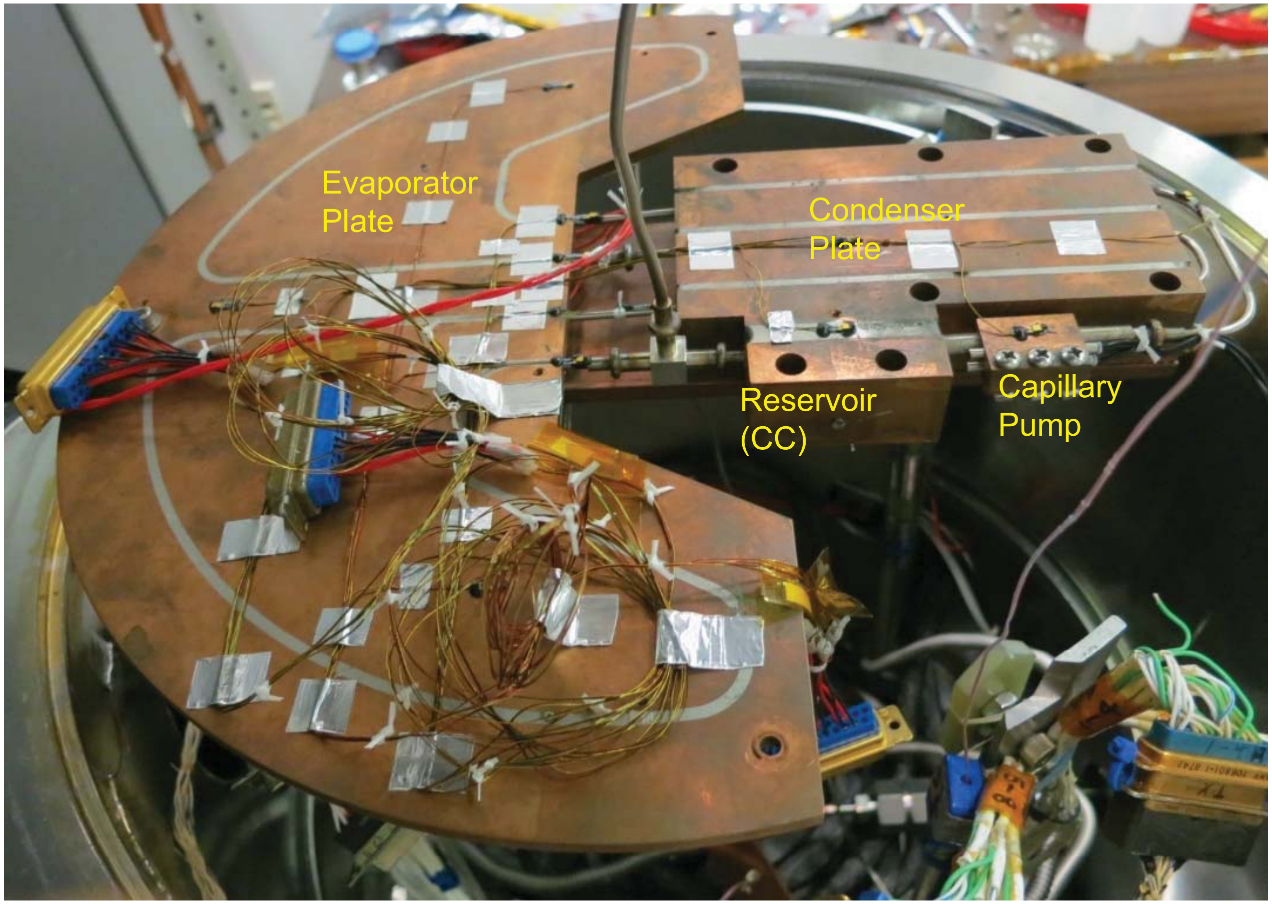



- Temperature sensors: 12 Lakeshore silicon diodes (DT-670-SD)
  - Tolerance: 0.25K (2K to 110K range)
- One absolute pressure transducer
  - 0 - 3.45MPa (0-500psi) with 0.5% resolution
  - System saturation temperature can be derived.

# Saturation Temperature versus Saturation Pressure for Neon

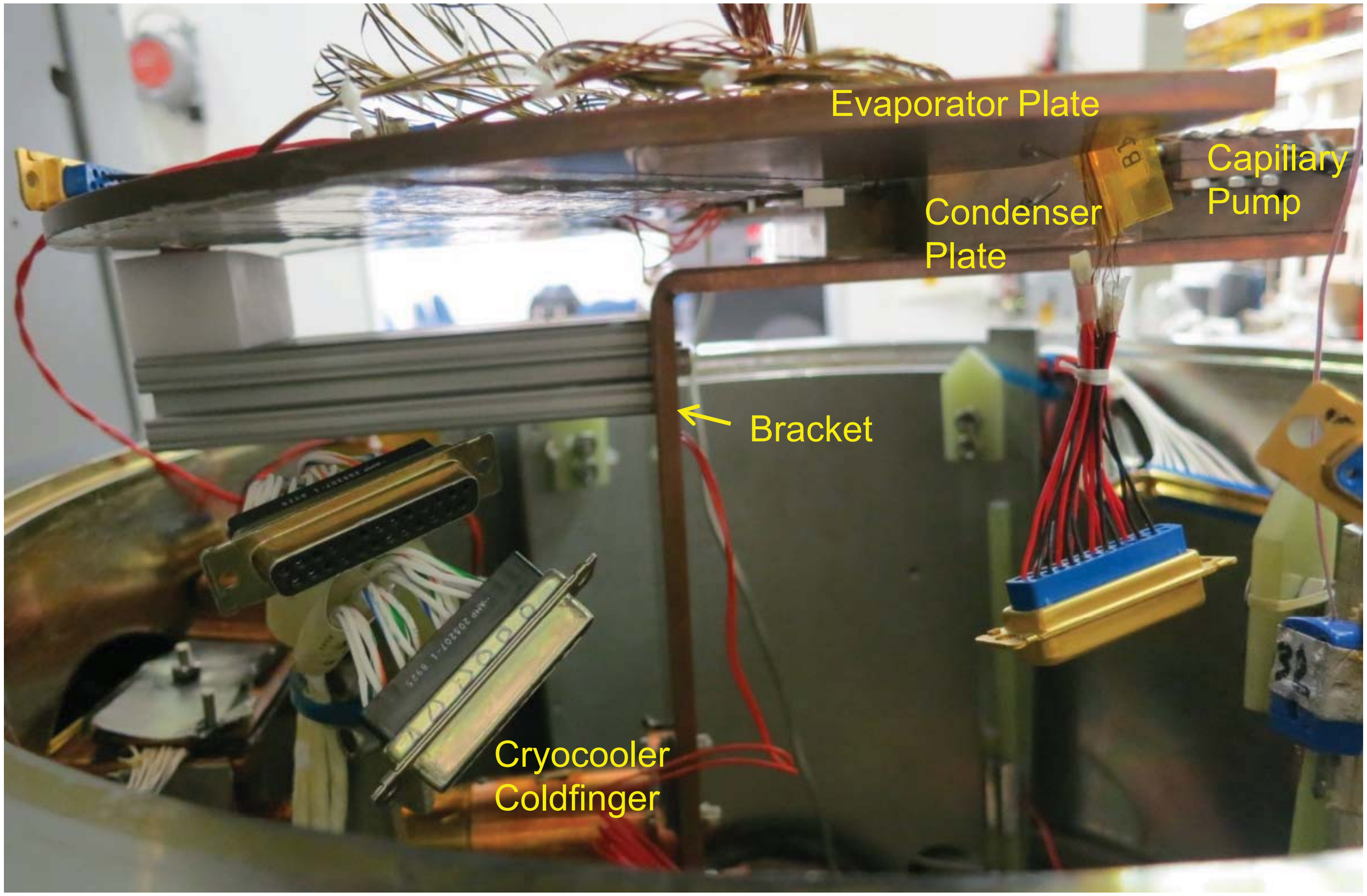


# CLHP Inside Thermal Vacuum Chamber



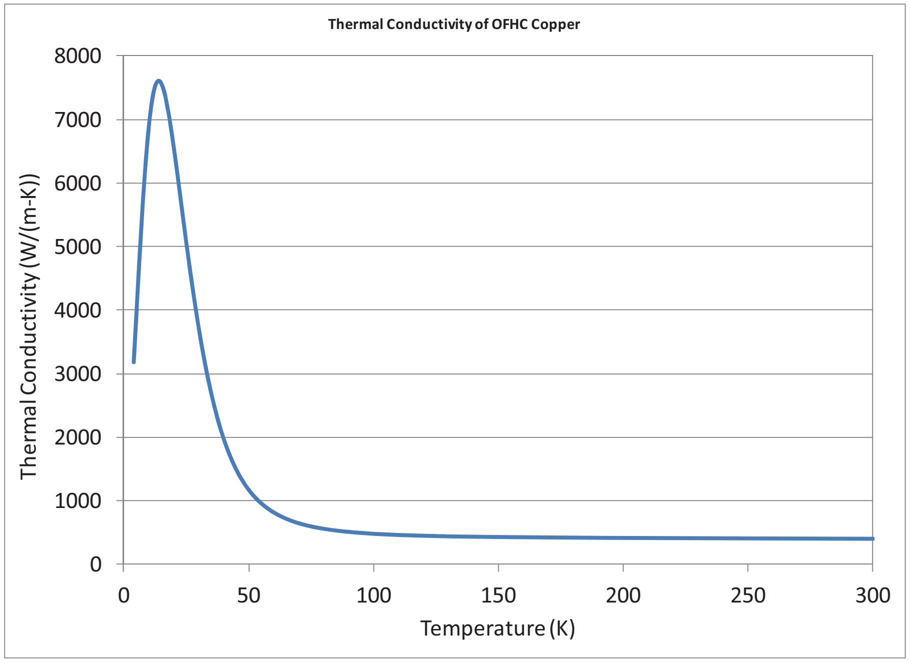

- Three Heater Circuits
  - Capillary pump heater – sustaining flow circulation
  - Condenser bracket heater – maintaining condenser sink temperature between 28K and 35K
  - Evaporator heater – providing heat source power

# Copper Bracket Connecting CLHP and Cryocooler

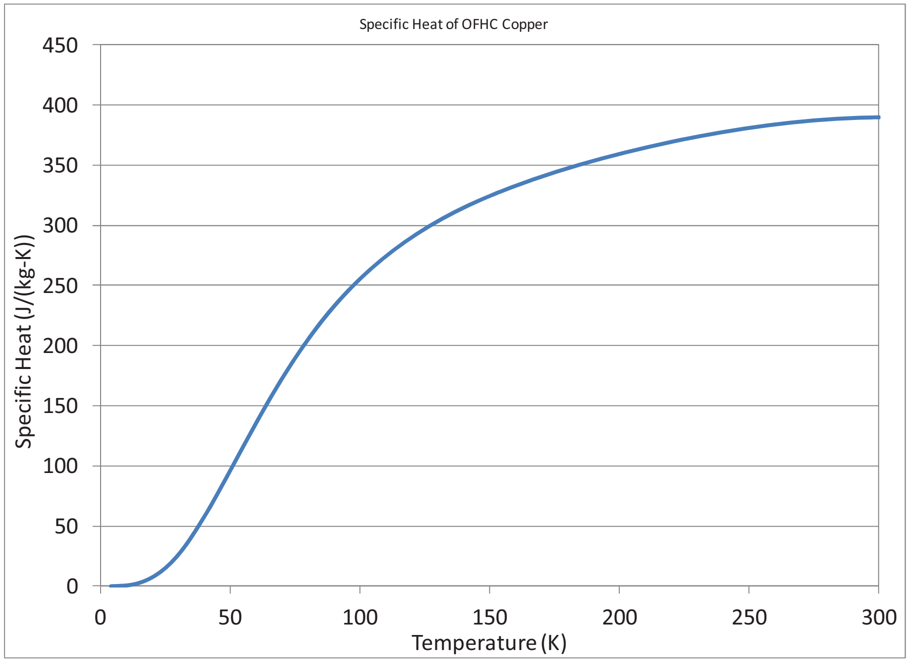



- The CLHP was proof pressure tested to 784 psi.
- The cryocooler has a capacity of 30W at 30K.
- The entire test loop was covered with 12-layer MLI blankets.
- Many TCs for chamber temperature measurements

# Thermal Conductivity and Specific Heat of OFHC Copper



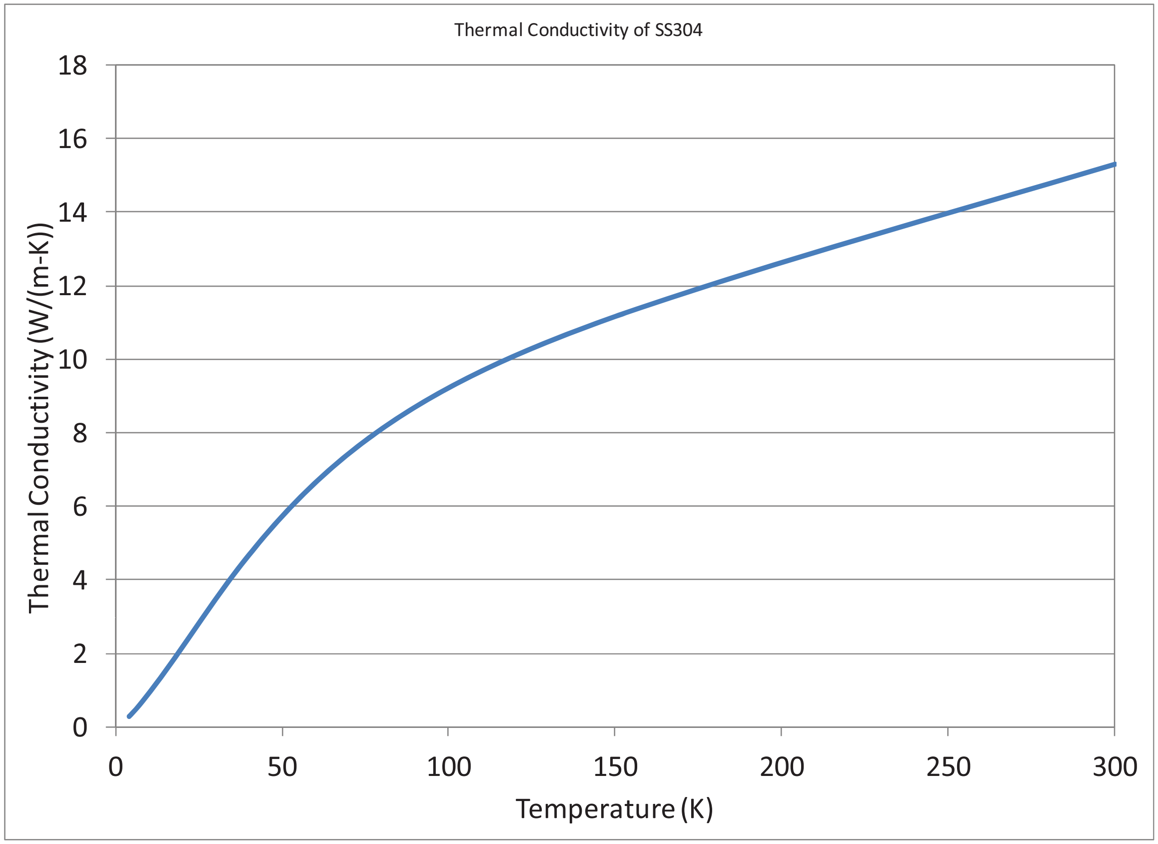

**Thermal Conductivity**




**Specific Heat**

- **The evaporator plate and condenser plate were made of copper, which has extremely high thermal conductivity and extremely low specific heat at low temperatures.**
- **All three temperature sensors on evaporator plate showed uniform temperatures.**

# Thermal Conductivity of SS316



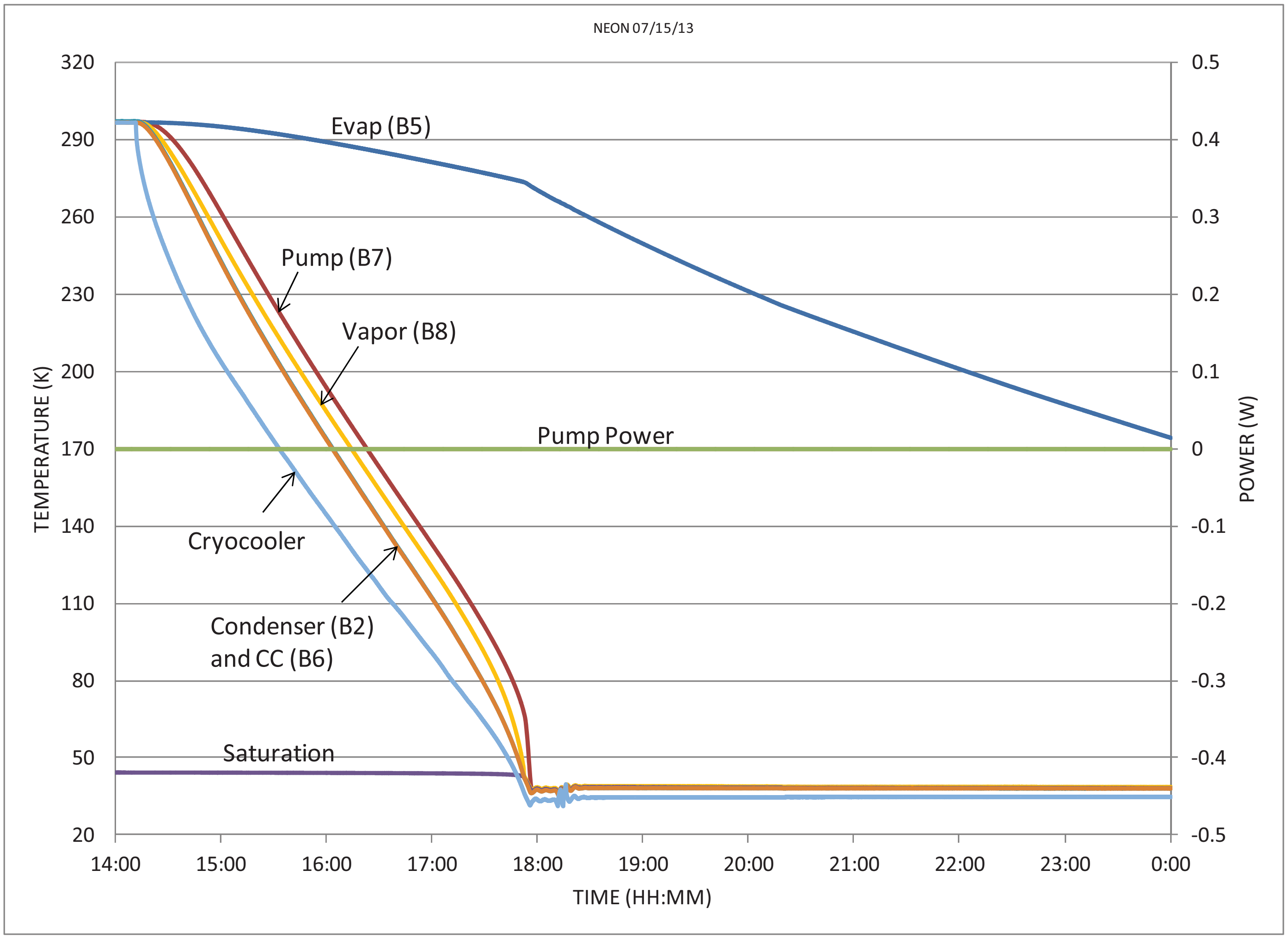

- **The SS used for transport lines, condenser line and evaporator line has very small thermal conductivity at low temperatures, which helped isolate the evaporator and the condenser.**

# Tests Performed

- Evaporator Cool Down from Ambient Temperature
- CLHP startup
- Pump Capillary Limit and Recovery from Dry-out
- Variable Heat Loads to Evaporator
- Evaporator Heat Removal Capability
- Steady State Long Duration Operation
- Effect of Low Fluid Charge on CLHP Performance

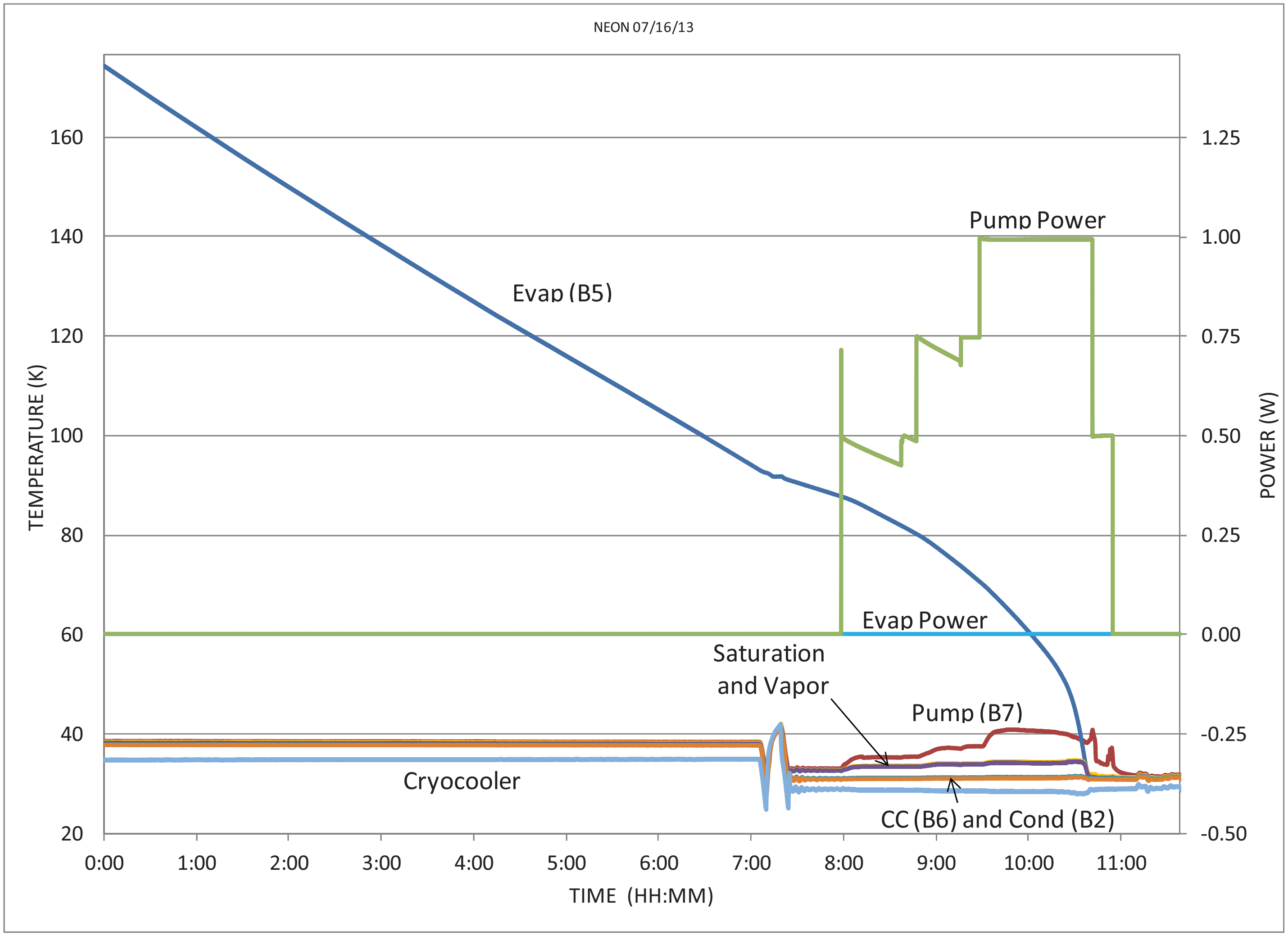
# Initial Cool-down from 298K (1/3)

- **The capillary pump and reservoir were cooled from 298K to 30K in 4 hours.**



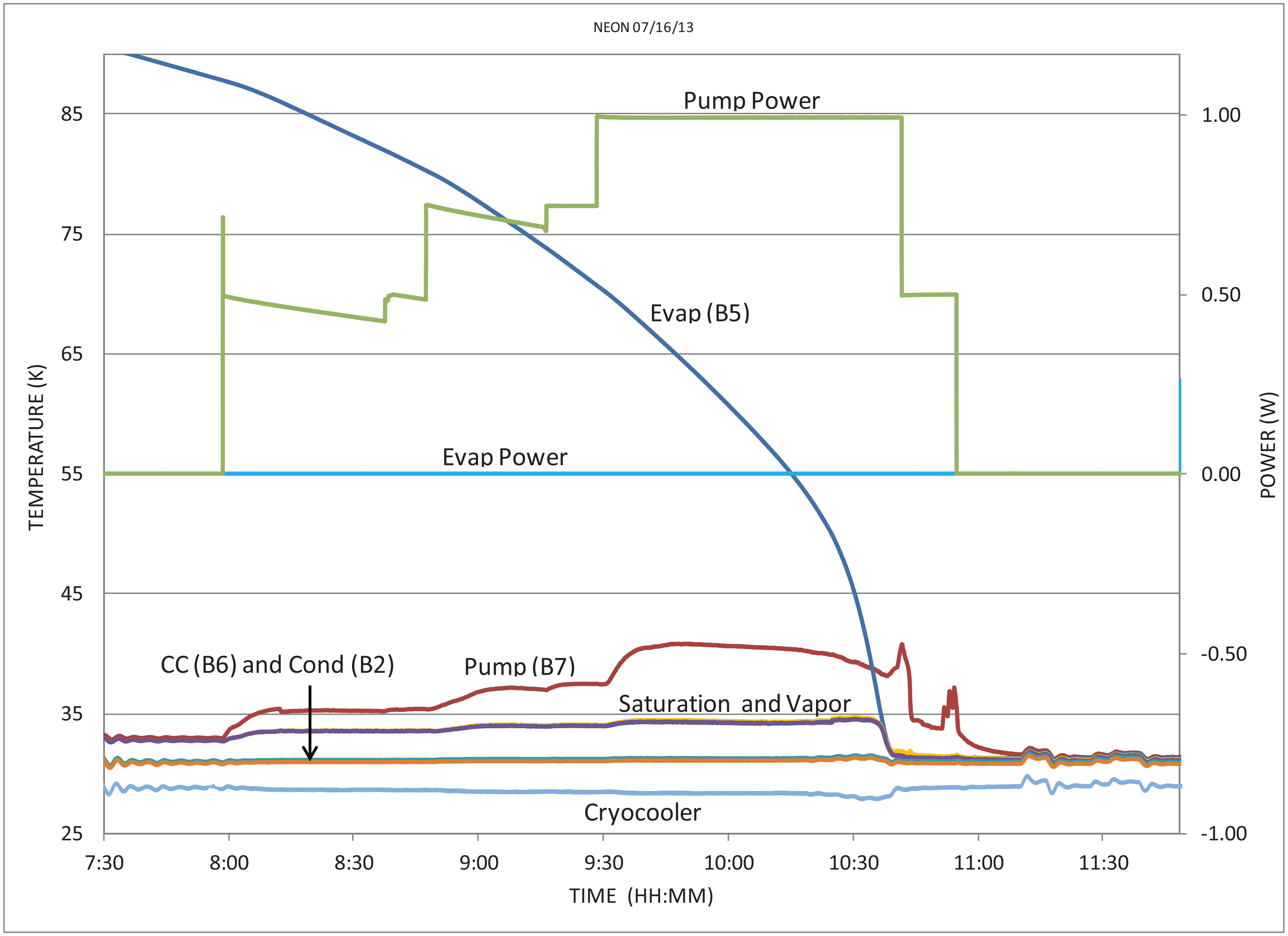
# Initial Cool-down from 298K (2/3)

- **Applying power to capillary pump initiated flow circulation in CLHP, which helped cool the evaporator plate.**



# Initial Cool-down from 298K (3/3)

- **Applying power to capillary pump initiated flow circulation in CLHP, which helped cool the evaporator plate.**

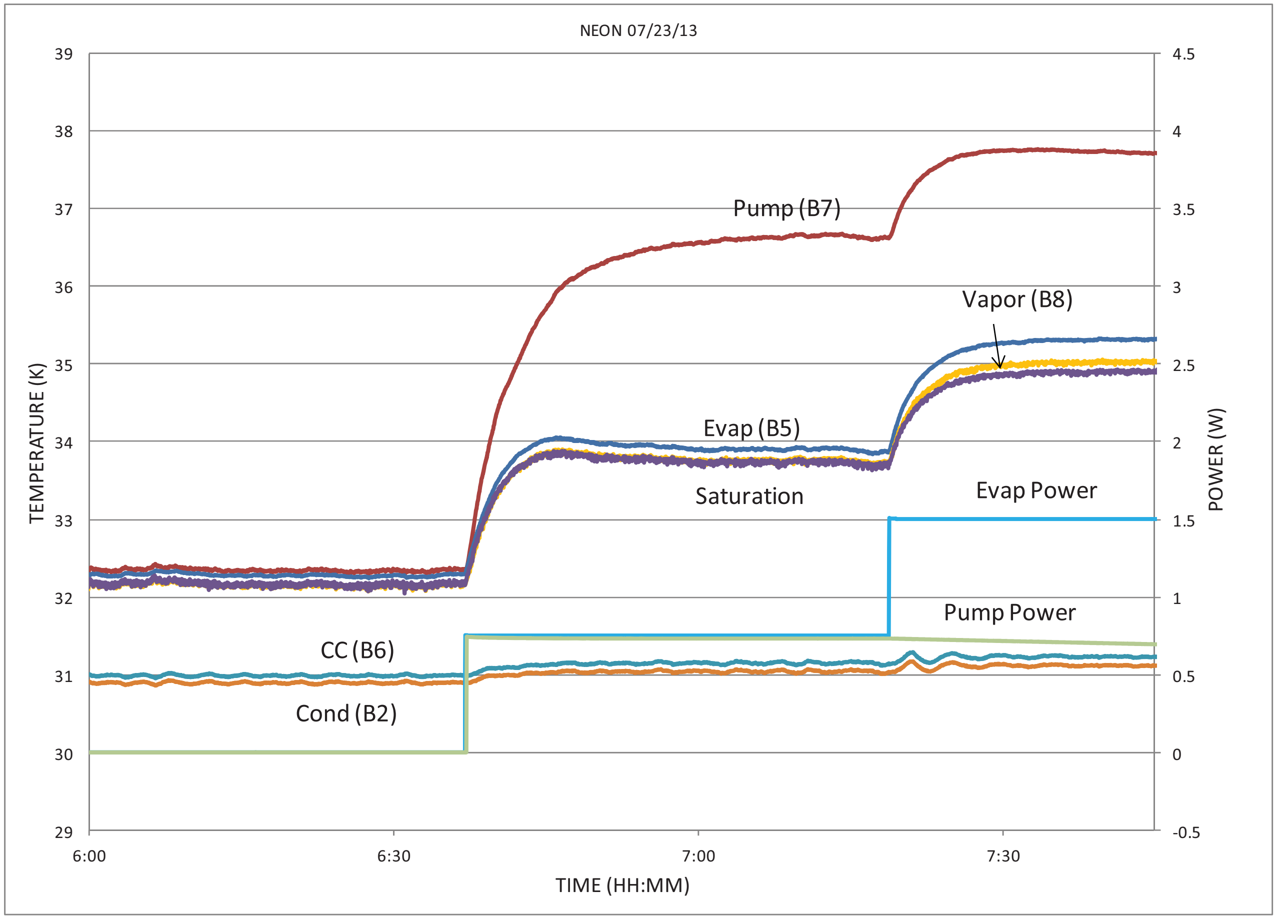


# Startup Tests

- All Startup tests were successful by applying power to the pump and the evaporator.
  - 13 startup tests
  - Pump power/evaporator power combinations
    - » 1.0W/1.0W: 1 time
    - » 0.75W/0.75W: 6 times
    - » 0.5W/0.5W: 5 times
    - » 0.25W/0.25W: 1 time
  - Nearly identical temperature profiles for the same pump power/evaporator power combination
- Startup was not successful by applying power to the pump only and without power to the evaporator
  - Insufficient liquid in CC and pump
  - Evaporator contained mostly liquid
  - Loop started successfully as soon as power was applied to the evaporator

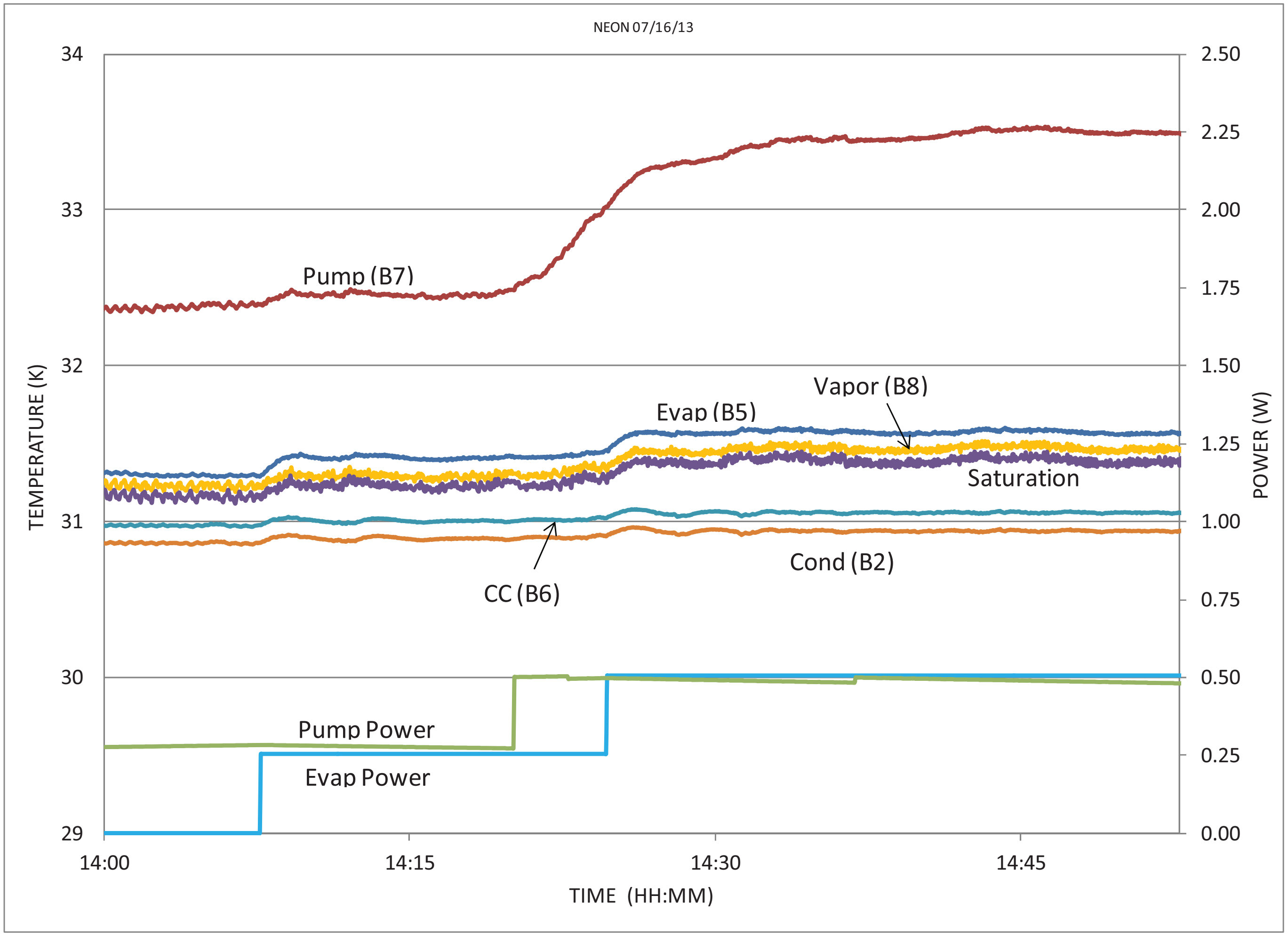
# Start-up (408psi/31K/0.75W/0.75W)

- Loop started successfully by applying 0.75W to pump and 0.75W to evaporator.
- Small temperature fluctuations in condenser were caused by on/off of cryocooler heater which maintained condenser at 31K.
- Saturation temperature was calculated from measured saturation pressure.
- Same test was repeated 5 times, and all were successful and yielded similar results.



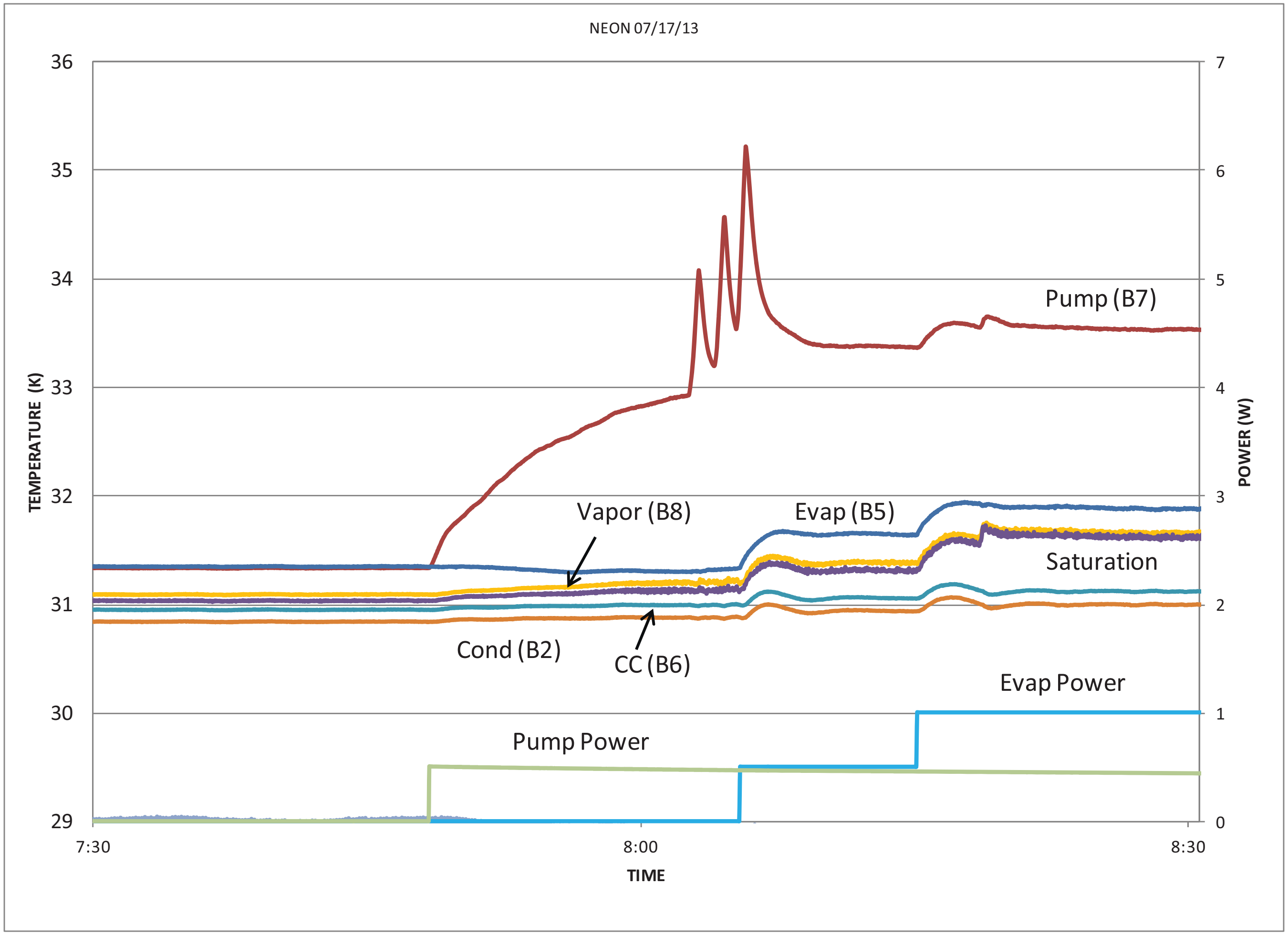
# Start-up (380psi/31K/0.25W/0.25W)

- **Startup was successfully by applying 0.25W to pump and 0.25W to evaporator.**



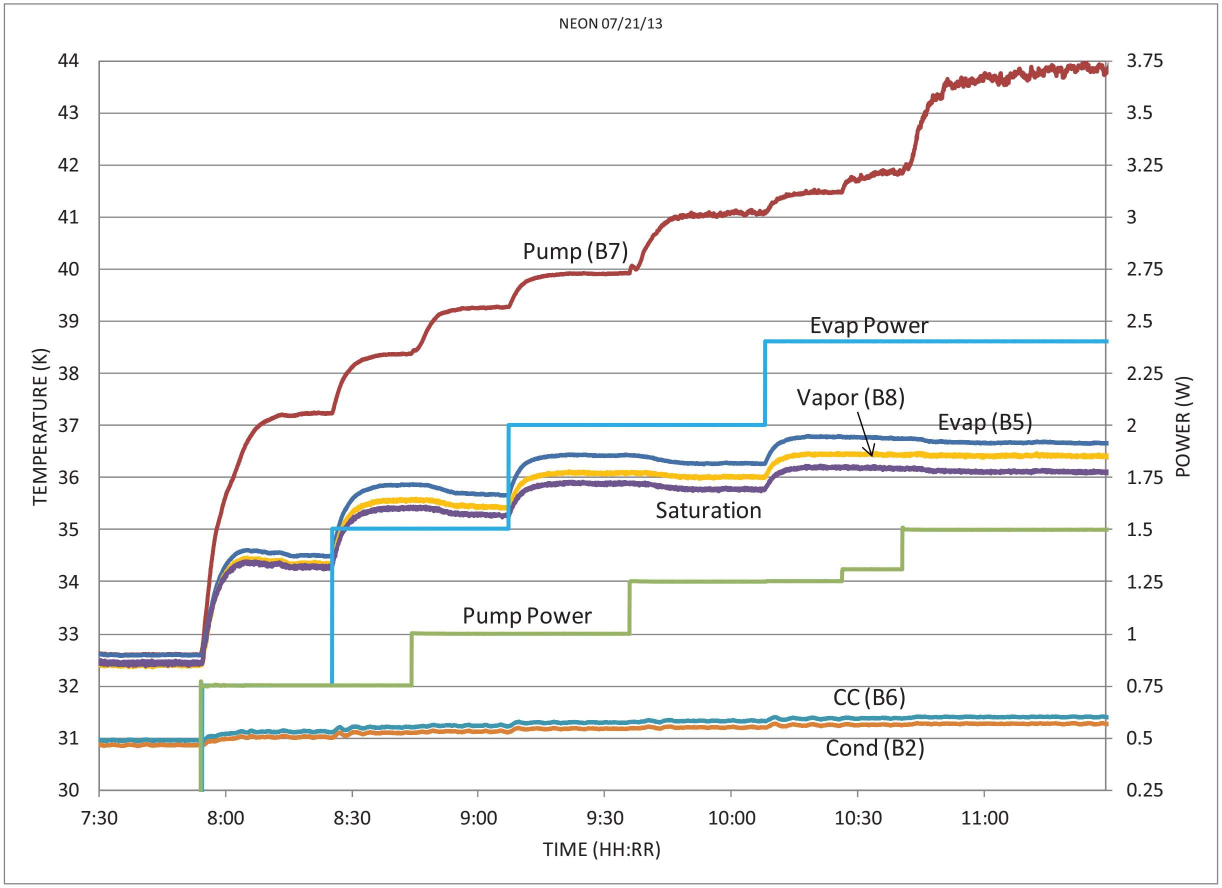
# Start-up (380psi/31K/0.5W/0W)

- Startup was not successfully by applying 0.5W to pump and 0W to evaporator.
- Evaporator contained mostly liquid
- The pump temperature fluctuated due to insufficient liquid in the CC and pump.
- The loop started  successfully as soon as 0.5W was applied to the evaporator.



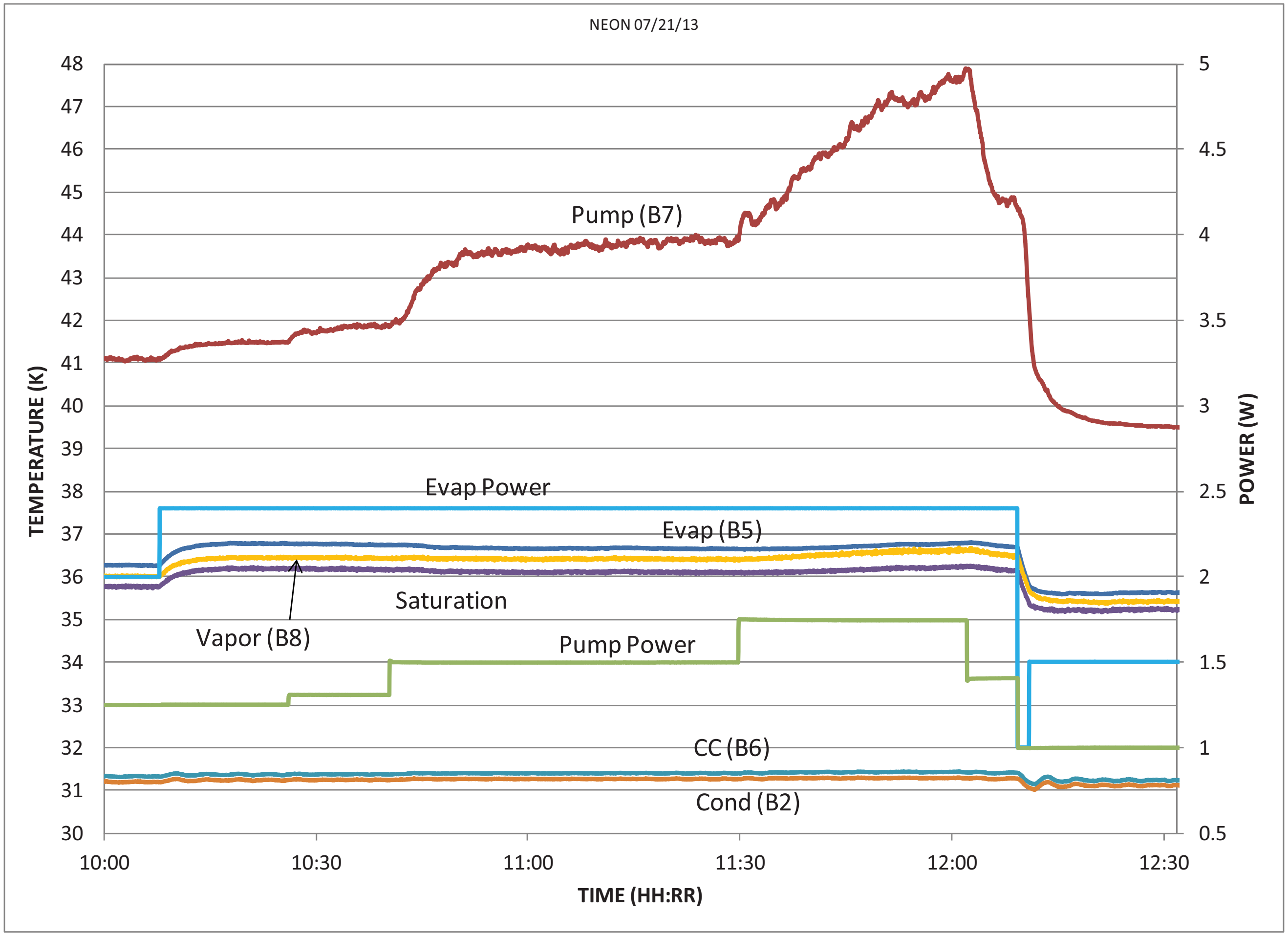
# 1st Power Ramp-up (408psi/31K)

- Same pump power, higher evaporator power: $T_{SAT}$ increased due to less subcooling to CC. The pump, evaporator, and vapor temperatures all increased with $T_{SAT}$.
- Same evaporator power, higher pump power: pump temperature increased. $T_{SAT}$ and evaporator temperature decreased due to increased subcooling to CC.
- Condenser temperature increased as the sum of evaporator power and the pump power increased due to a larger loading to the condenser.



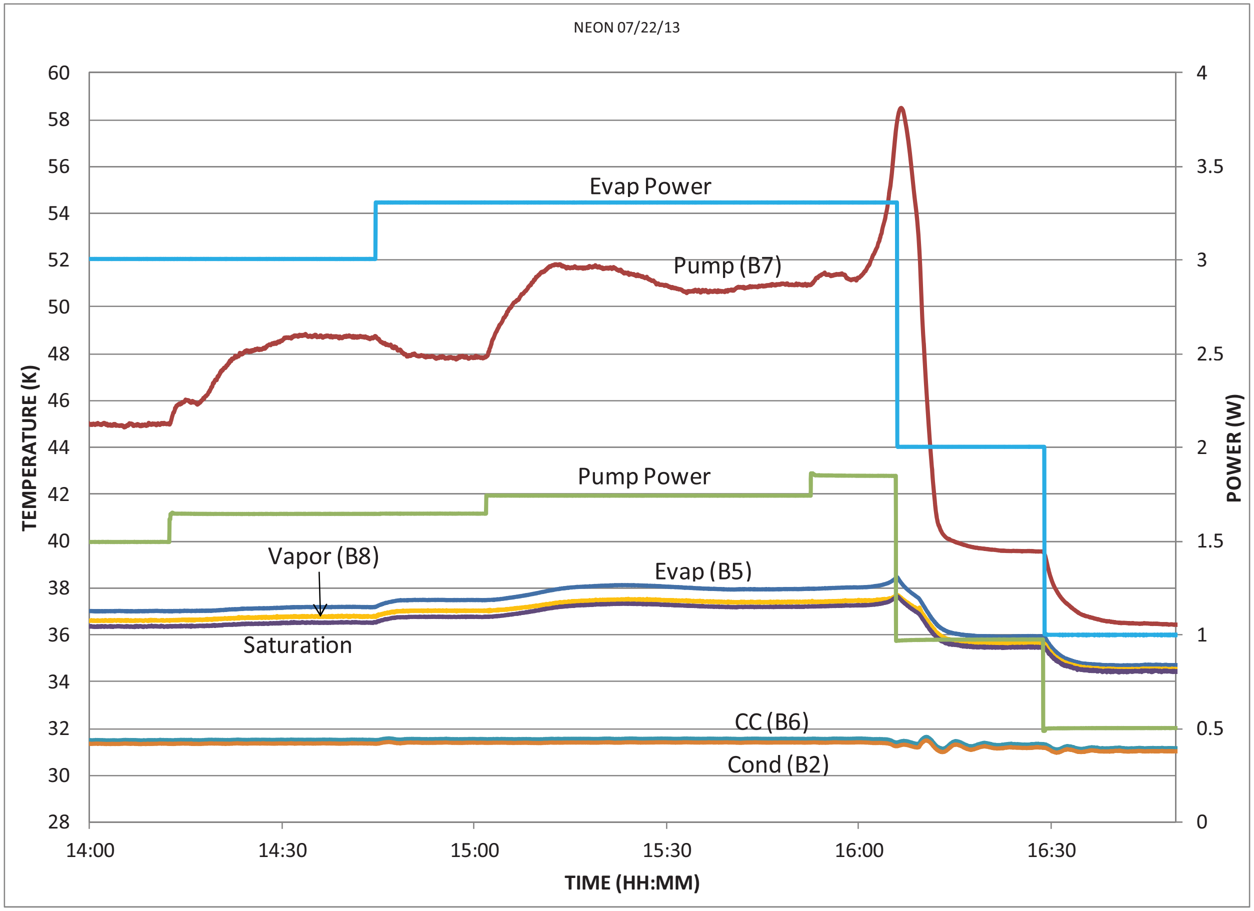
# 1st Pump Capillary Limit (408psi/31K)

- **The pump capillary limit determines the maximum flow rate in the loop, which in turn affects the heat removal capability of the evaporator.**
- **This test showed that the pump capillary limit was between 1.5W and 1.75W**
- **The pump could recover from a dry-out by lowering the pump power.**



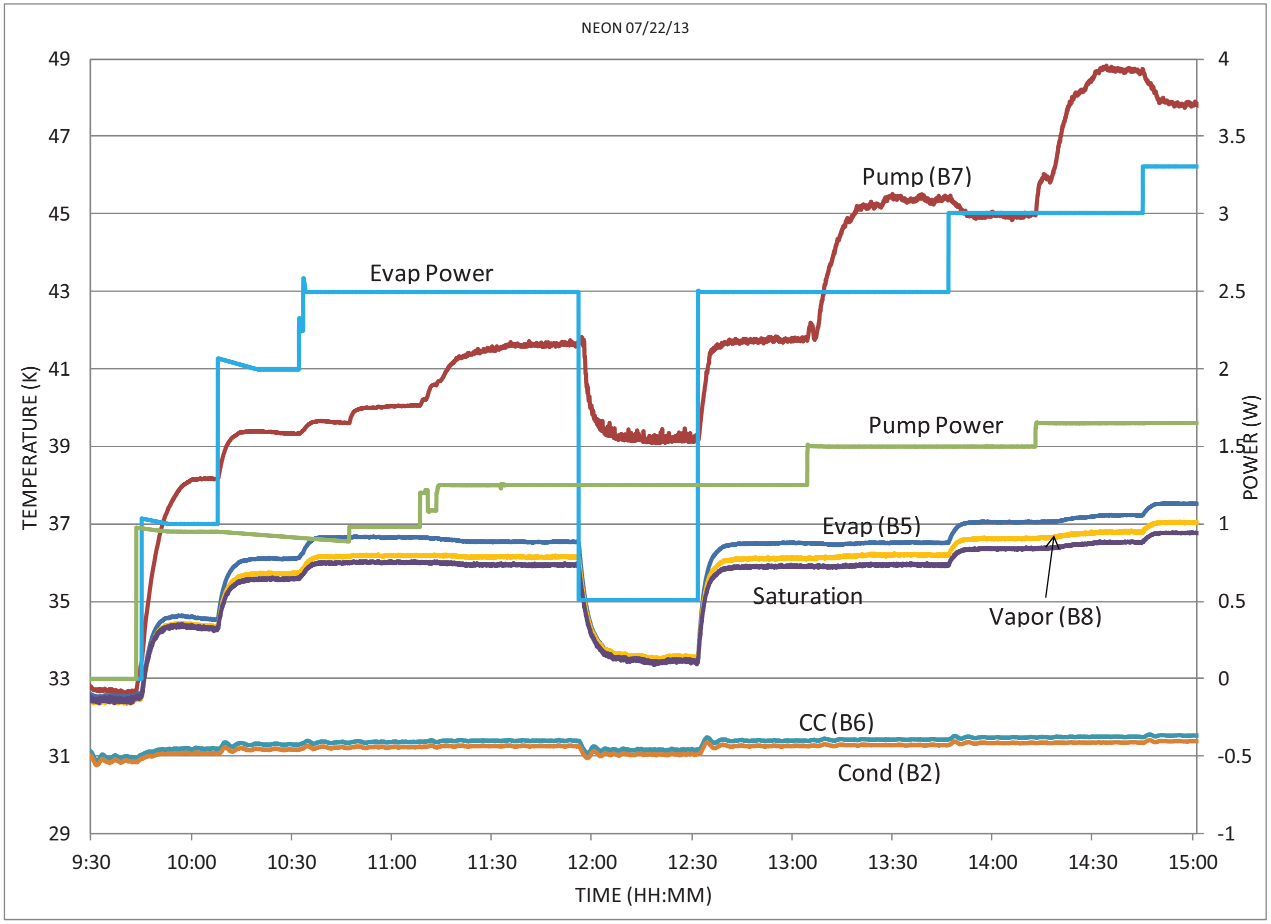
# 3rd Pump Capillary Limit (408psi/31K)

- Several more tests were performed to determine the pump capillary limit.
- The loop worked properly at pump power/evaporator power of 1.65W/3.3W and 1.75W/3.3W.
- The pump dried out at 1.85W/3.3W.
- This test showed that the pump capillary limit was close to 1.75W.



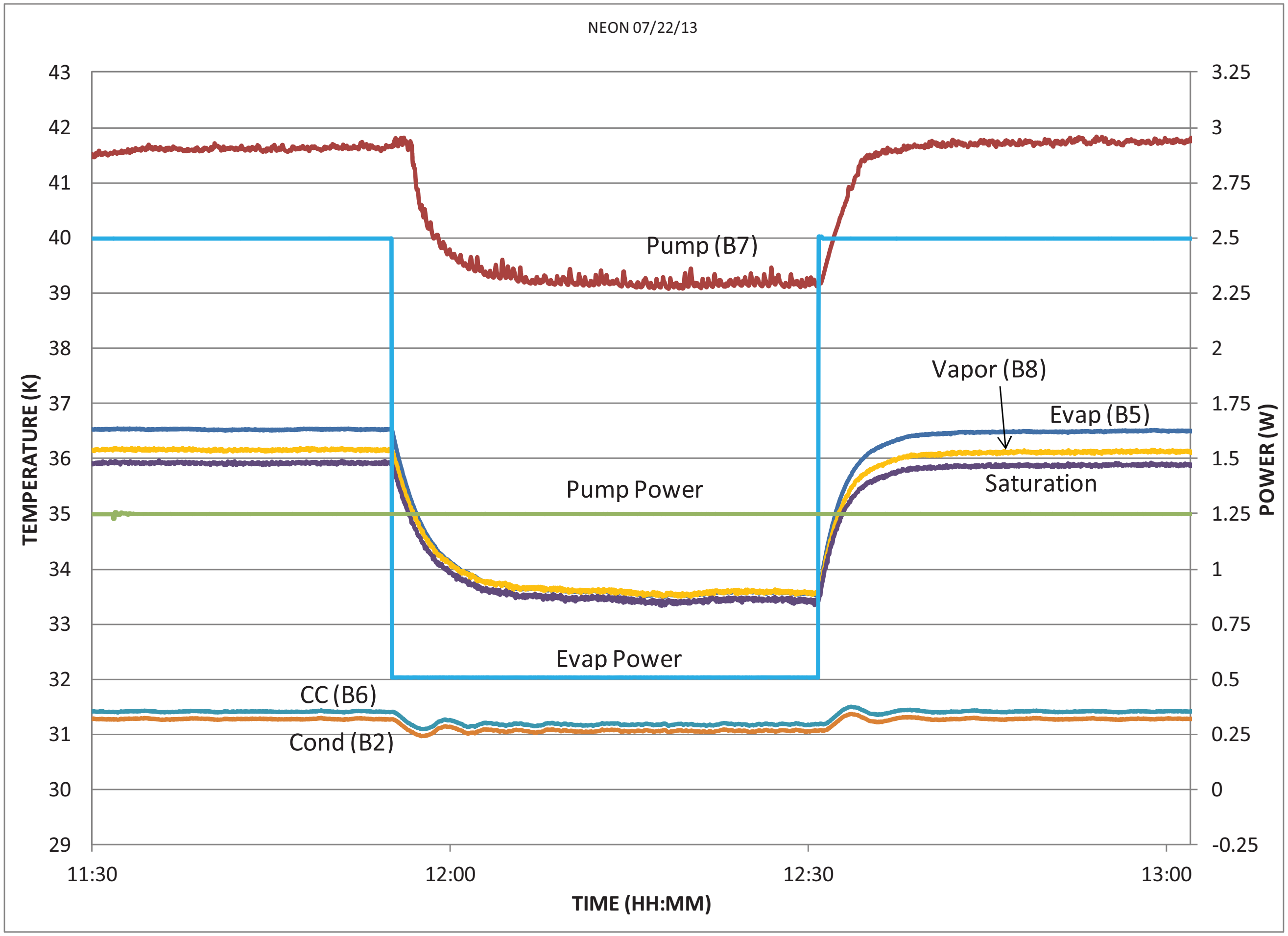
# Evaporator Heat Removal Capability (408psi/31K)

- In theory, the evaporator can remove as much as twice of the power applied to the pump. This was verified by several tests.
- Evaporator  temperature varied with its heat load due to heat transfer requirement.
- Extremely low thermal conductivity of stainless steel resulted in high pump temperature (usually not a concern).



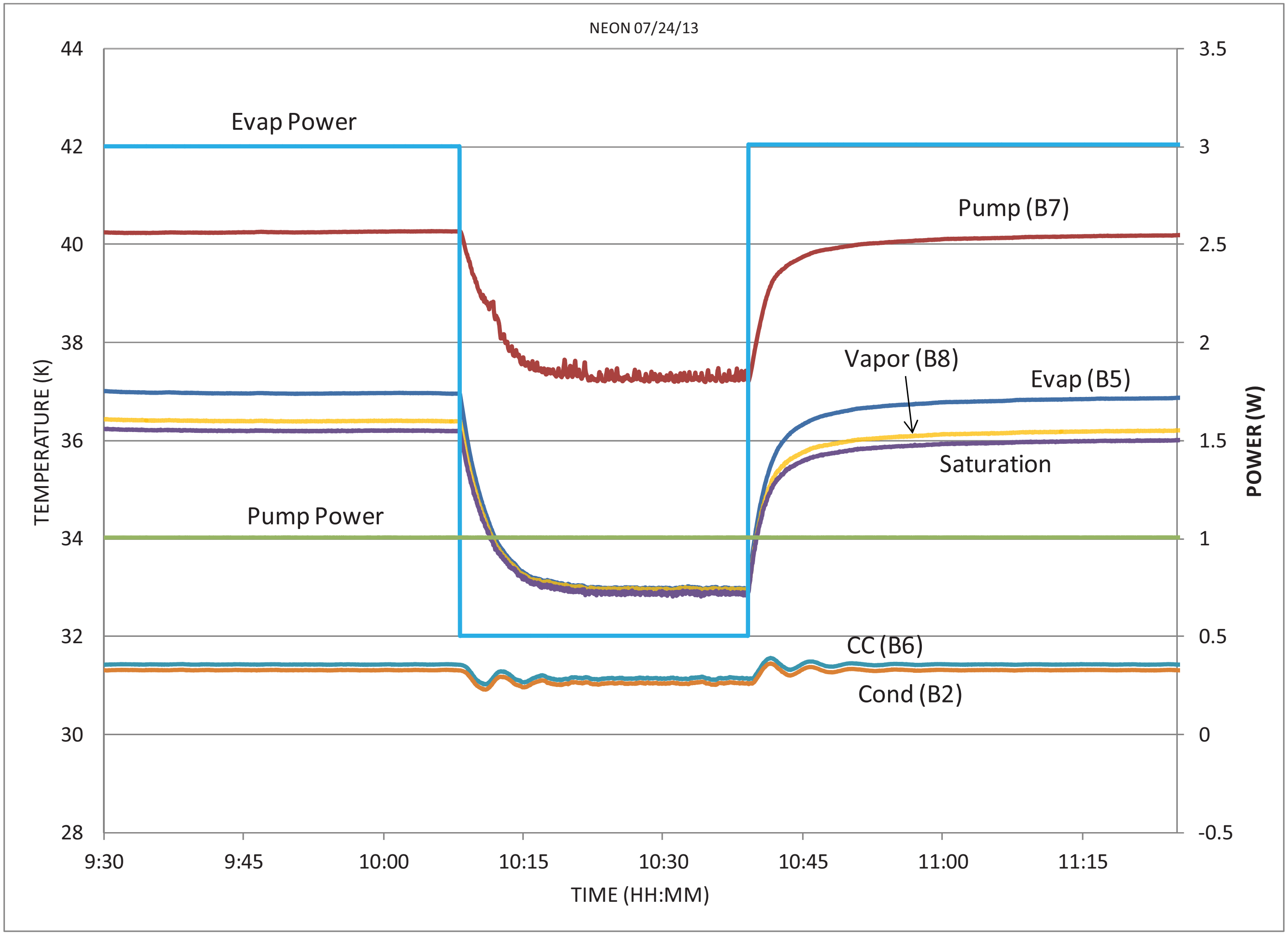
# Power Cycle (408psi/31K) –1.25W Pump Power

- **Power cycle demonstrates the power turn down ratio of the CLHP and the ability of the CLHP to adapt to sudden changes of the heat load. In this case, the turn down ratio of the evaporator power is of most interest.**
- **Evaporator power varied between 0.5W and 2.5W**



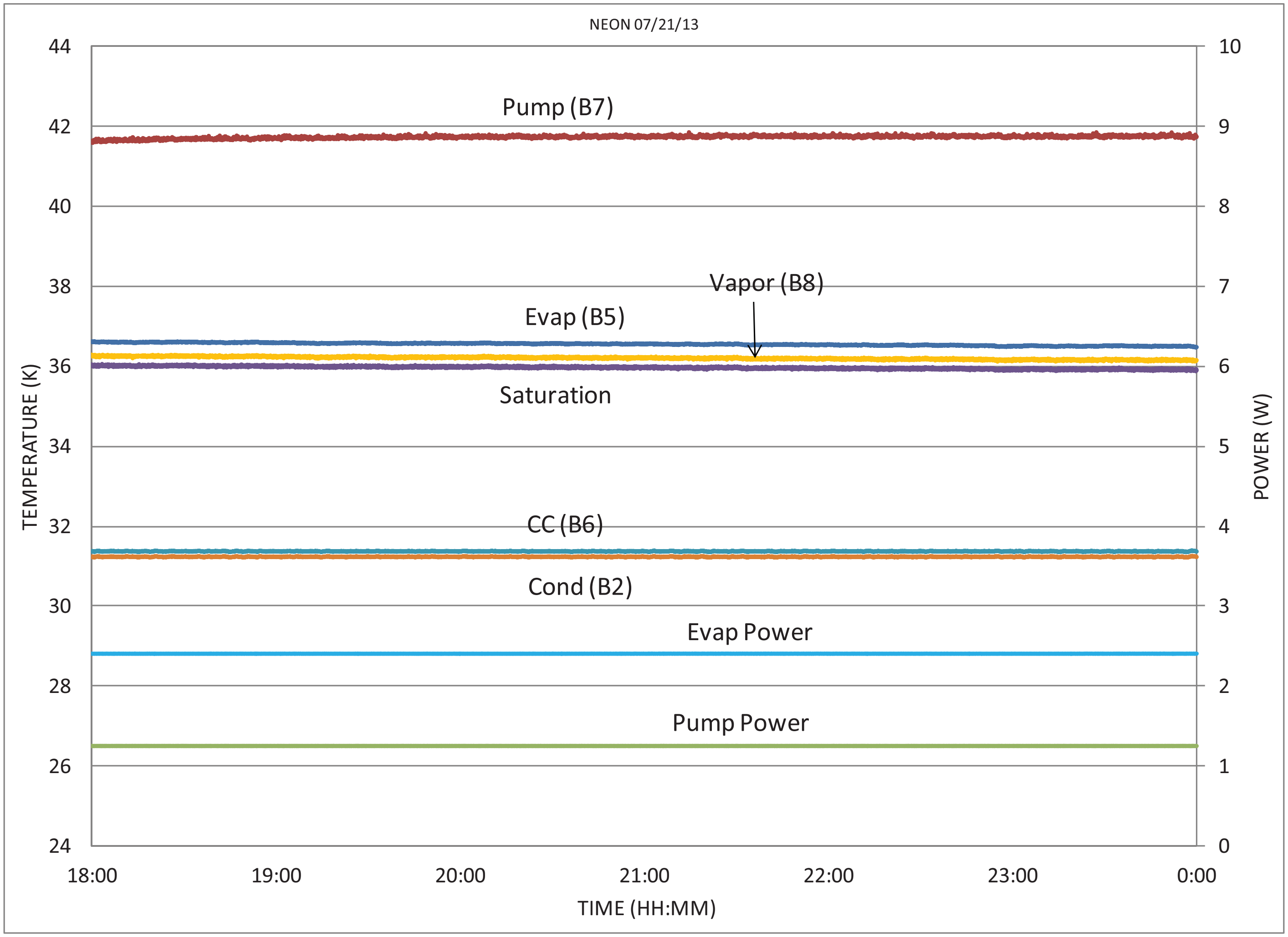
# Power Cycle (408psi/31K) – 1.0W Pump Power

- **Evaporator power varied between 0.5W and 3.0W**
- **Why could the evaporator remove more than two times of pump power?**



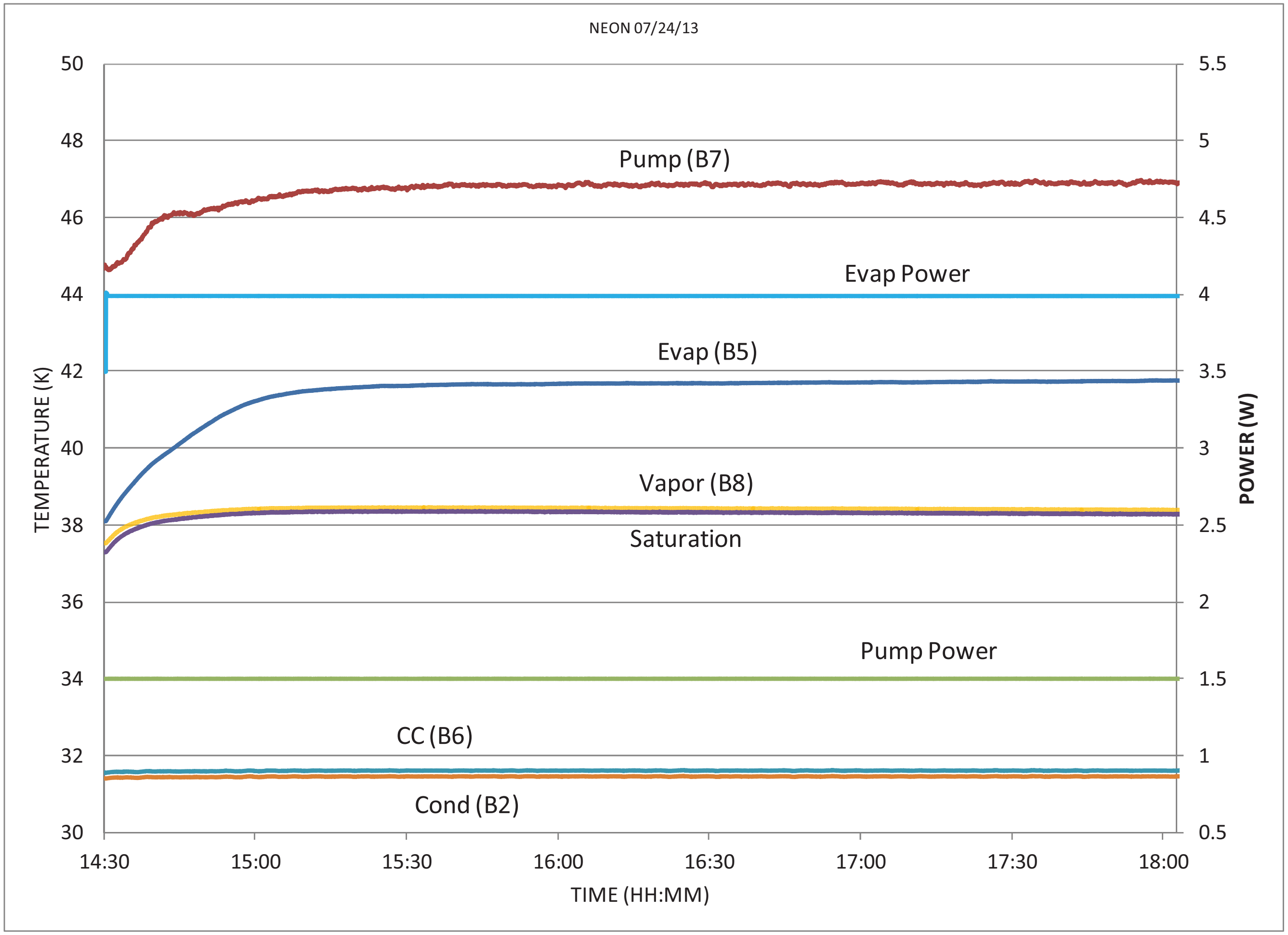
# Steady State Operation (31K/1.25W/2.5W)

- **Steady state operation for more than 6 hours.**
- **Evaporator temperatures (B3/B4/B5) were uniform due to extremely high thermal conductivity of copper at low temperatures.**



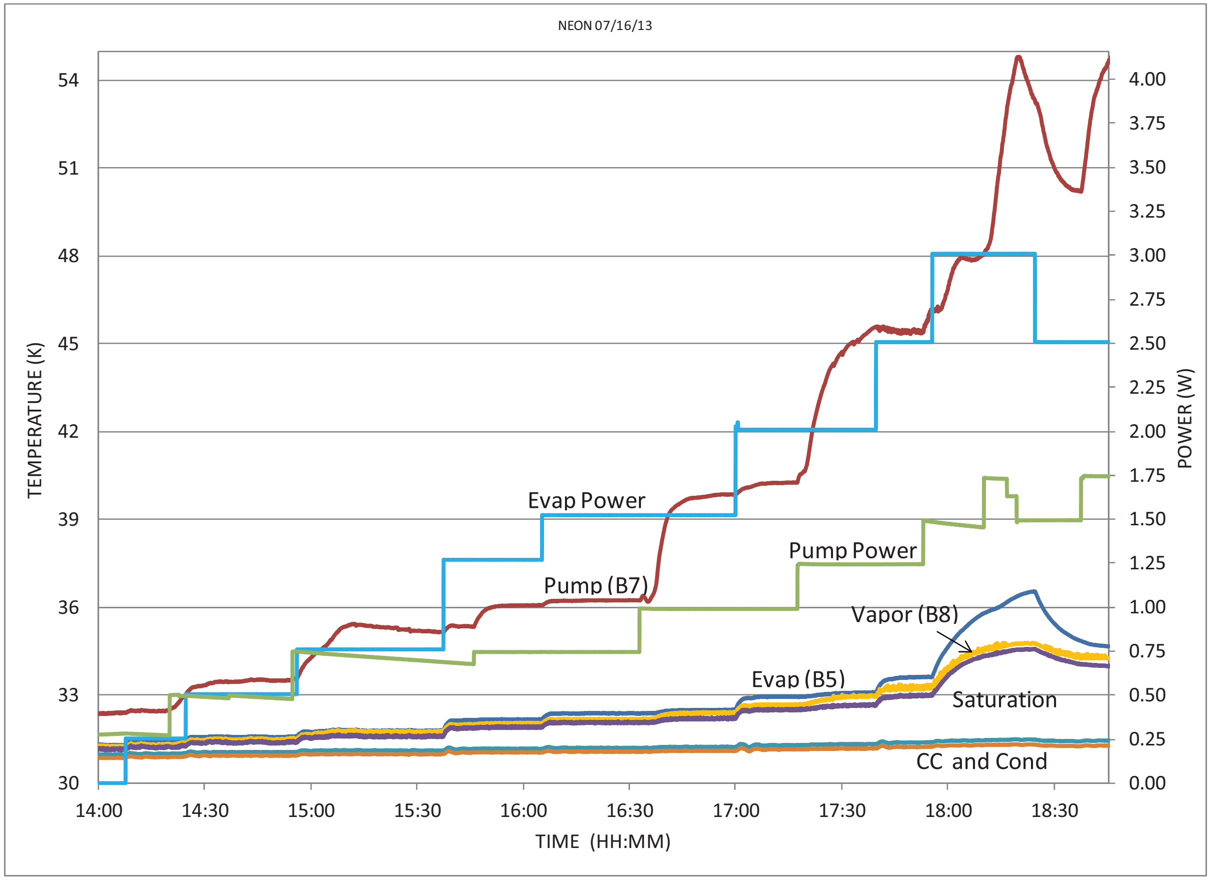
# Steady State Operation (31K/1.5W/4.0W)

- **Steady state operation for more than 3 hours.**
- **Why could the evaporator remove more than two times of pump power?**



# Effect of Low Fluid Charge - Power Ramp-up with 380psi Charge

- $T_{SAT}$ and $T_{EVAP}$ were lower for a given set of cryocooler temperature, $Q_{PUMP}$ and $Q_{EVAP}$.
- The difference between $T_{PUMP}$ and $T_{SAT}$ was higher for a given $Q_{PUMP}$.
- The pump capillary limit was lower due to insufficient liquid in the wick (less than 1.5W with 380 psi charge versus 1.75W with 408 psi charge).



# Summary of Test Results

- The neon CLHP demonstrated robust operation under steady state and transient conditions.
- The CLHP could be cooled from the ambient temperature to subcritical temperatures very effectively.
- The CLHP could start successfully by applying power to the capillary pump and the evaporator without any pre-conditioning.
- The CLHP could adapt to changes in the pump power and/or evaporator power, and reach a new steady state very quickly.
- The evaporator could remove heat loads between 0.25W and 4W.
- When the pump capillary limit was exceeded, the CLHP could resume its normal function by reducing the pump power.
- The CLHP demonstrated steady state operations for 6 hours.

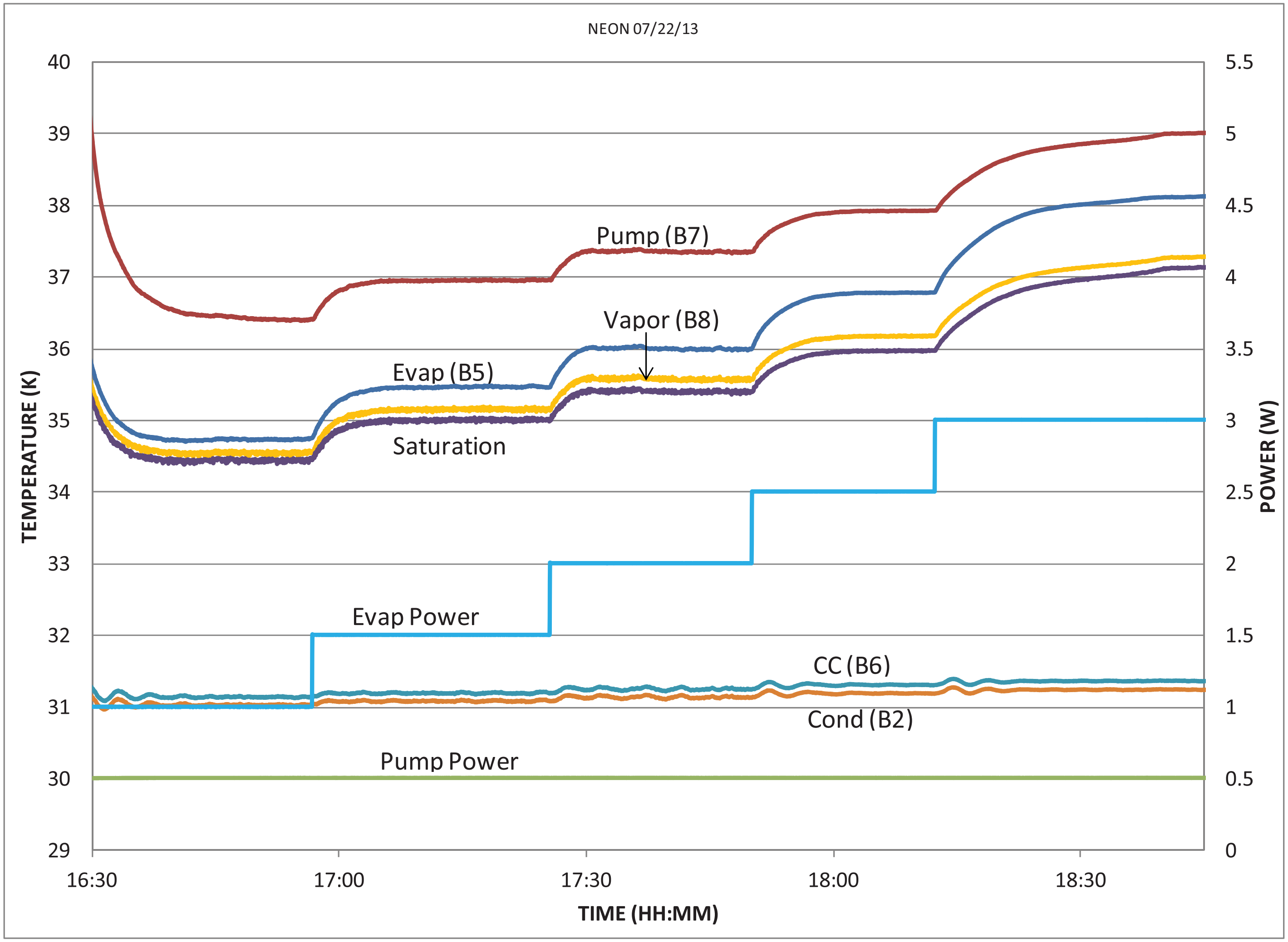
# One Unanswered Question

- In theory, the evaporator cannot remove more than two times of the power applied to the pump.
- Test results showed a much higher $Q_{evap,\ max}$/ $Q_{pump,}$ especially at low pump powers.
- Did subcooled liquid enter the evaporator and/or superheated vapor leave the evaporator?
  - A simple calculation shows that the sum of liquid subcooling and vapor superheating contributes less than 15% to the total heat removal by the evaporator.
- Are there some unknown physical processes?
  - Further investigation in upcoming helium CLHP testing

| Pump Power, $Q_{pump}$ (W) | Maximum Heat Removal by Evaporator, $Q_{evap,\ max}$ (W) | $Q_{evap,\ max}/Q_{pump}$ |
|---|---|---|
| 0.5 | 2.5 | 5.0 |
| 0.75 | 3.0 | 4.0 |
| 1.0 | 3.25 | 3.25 |
| 1.25 | 3.5 | 2.8 |
| 1.5 | 4.0 | 2.67 |

# Steady State Operation 0.5W Pump Power

- Steady state operation for evaporator power from 1W to 3W.
- Why could the evaporator remove more than two times of pump power?



# Lessons Learned – A Humble Experience

- Testing of a CLHP would take much longer time than traditional room temperature LHPs.
- Parasitic heat gains by the CLHP could be detrimental to its operation. Extreme care must be taken to ensure parasitic heat gains are minimized.
- A proper fluid inventory is important for the CLHP operation. Volumes of the CLHP components, hot reservoir, and the connecting line must be measured or calculated as accurately as possible.
- The measurement of the loop pressure is highly recommended in future CLHP tests in order to gain knowledge of the loop saturation temperature.
- The high thermal conductivity of copper hindered the ability to gain understanding of physical processes inside the evaporator plate.

# Summary and Conclusions

- The neon CLHP demonstrated excellent performance and verified the feasibility of using a CLHP for large area cryocooling.
- In addition to cooling the mirrors of large space telescopes and detector arrays, the cryogenic loop heat pipe can also be used in applications such as the zero boil-off cryogen tank, fluid transfer lines, and thermal energy storage devices.
- Many valuable lessons were also learned from this test program, which will help the development and testing of cryogenic loop heat pipes in the future.
- The CLHP will be charged with helium and tested in a thermal vacuum chamber soon to demonstrate it operation over a temperature range of 2.5K to 4.5K.

# Acknowledgements

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