Thermal-Vacuum Testing of a Hybrid Additive Manufactured Pressure Vessel for Broad Area Cooling

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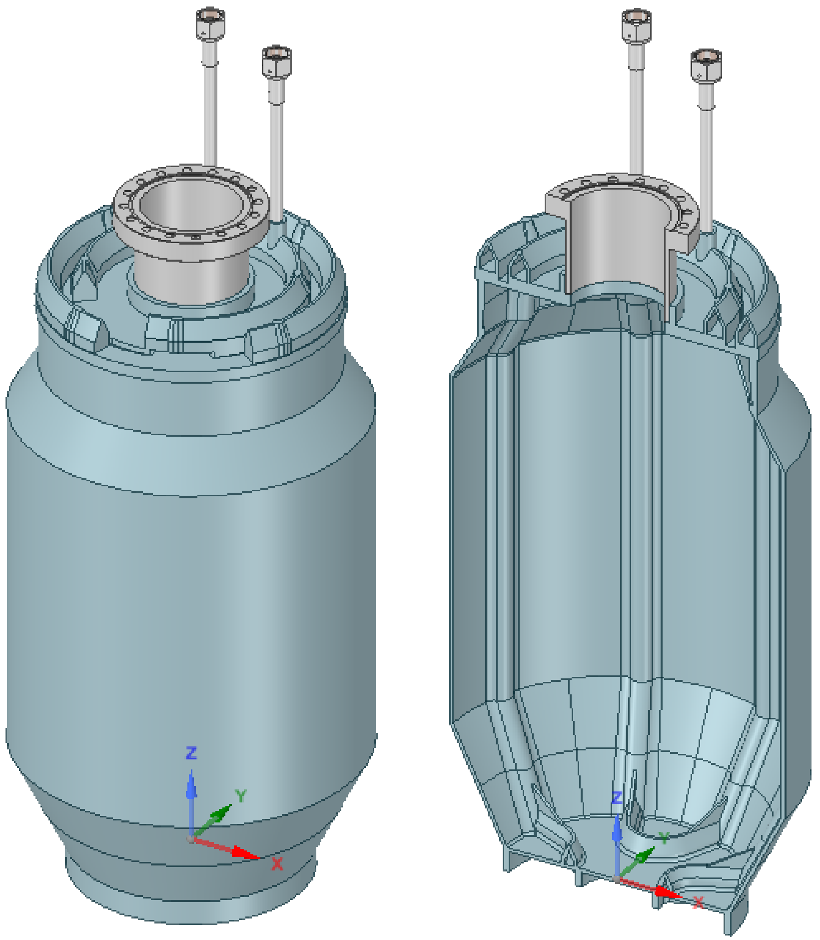
Thermal & Fluids Analysis Workshop
TFAWS 2024
August 26-30, 2024
NASA Glenn Research Center
Cleveland, OH

Introduction

- NASA SBIR for a cryogenic-rated pressure vessel with Broad Area Cooling (BAC) channels built into tank walls
- Hybrid additive manufactured tank combines 3D printing and traditional machining practices
- Hybrid Additively-manufactured Tank-integrated Channels for Broad Area Cooling (HATCHBAC)
  - Aluminum 2319
  - Internal Volume ≈ 13 gal
  - Tube Diameter ≈ 0.4 in
  - Manufactured by partners at Big Metal Additive (BMA)
- Tank is designed to hold nitrogen internally while flowing helium through BAC channels
- **Goal of test campaign is to prove nitrogen liquefaction occurs in tank at predicted 0.2 g/s**
- Analysis and sizing efforts have been completed previously[1]

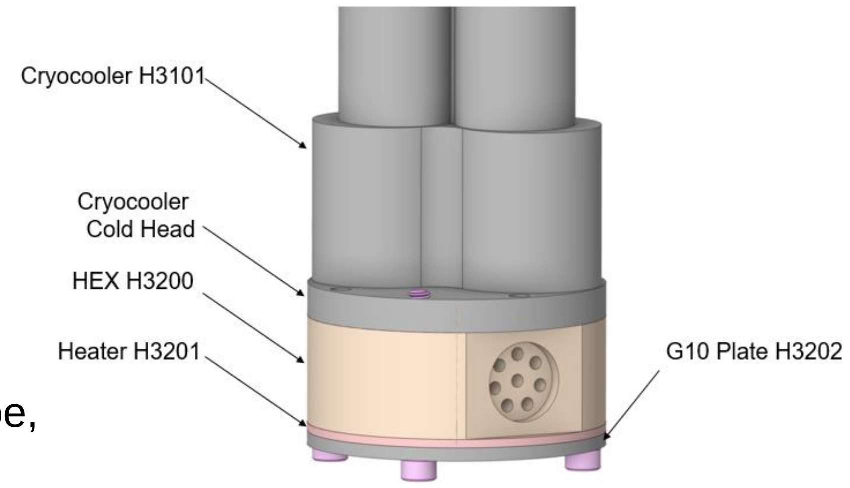


SpaceClaim model of HATCHBAC tank showing BAC channels

[1] **A. Carney, A. Walker, T. Skaff (2023, January 19). *Broad Area Cooling with Hybrid Additive Manufactured Pressure Vessel Analysis* AIAA 2023-2361.**

Test Design

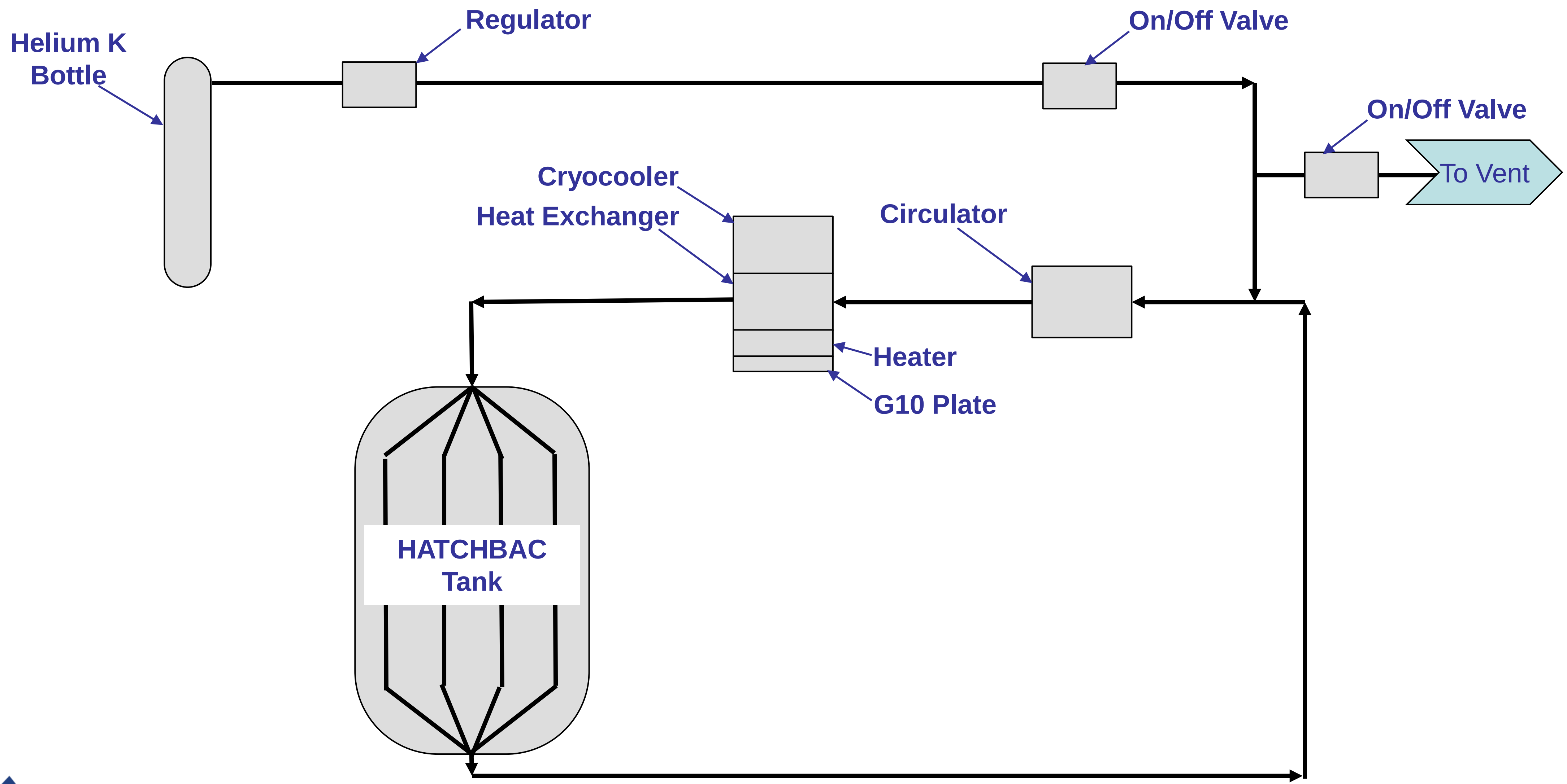
- Helium Circulation Loop
  - Cold helium flows through HATCHBAC tank channels where it is warmed by nitrogen in tank, is pushed through a circulator, and then goes through a heat exchanger attached to a cryocooler to chill the helium back down to the appropriate temperature
- Heat Exchanger
  - Heat exchanger is a copper cylinder with small channels
  - Sandwiched between a cryocooler and a heater to maintain temperature gradient and heat transfer
- Nitrogen Gas System
  - Gas inlet goes through the center of an annular flange, through a dip tube, and into the tank
  - Nitrogen gas is pushed through the inlet at the rate of liquefaction to maintain tank pressure during testing
  - Gas vent goes through the outside portion of the annular flange
- Tank Wall
  - MLI is wrapped around tank wall and piping to prevent additional heat leak into system
  - Liquefaction occurs on channel wall surface within tank



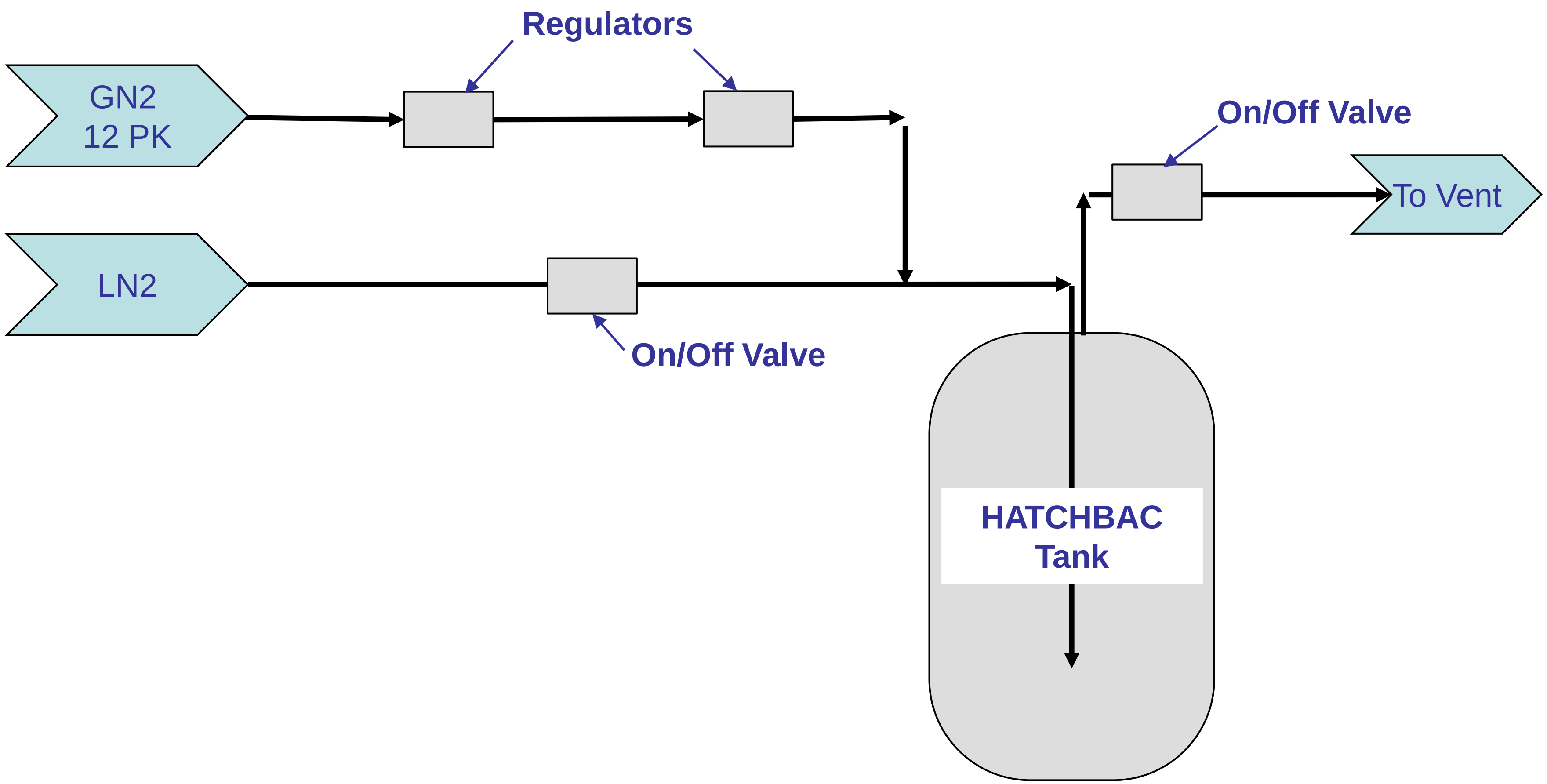
Test Procedure

1. Tank is pre-chilled with liquid nitrogen and vented
2. Helium enters cooling loop and is chilled via cryocooler-heat exchanger system
3. Tank nitrogen vent is closed, and liquefaction test begins
4. Test ends when tank is filled to sufficient liquid level

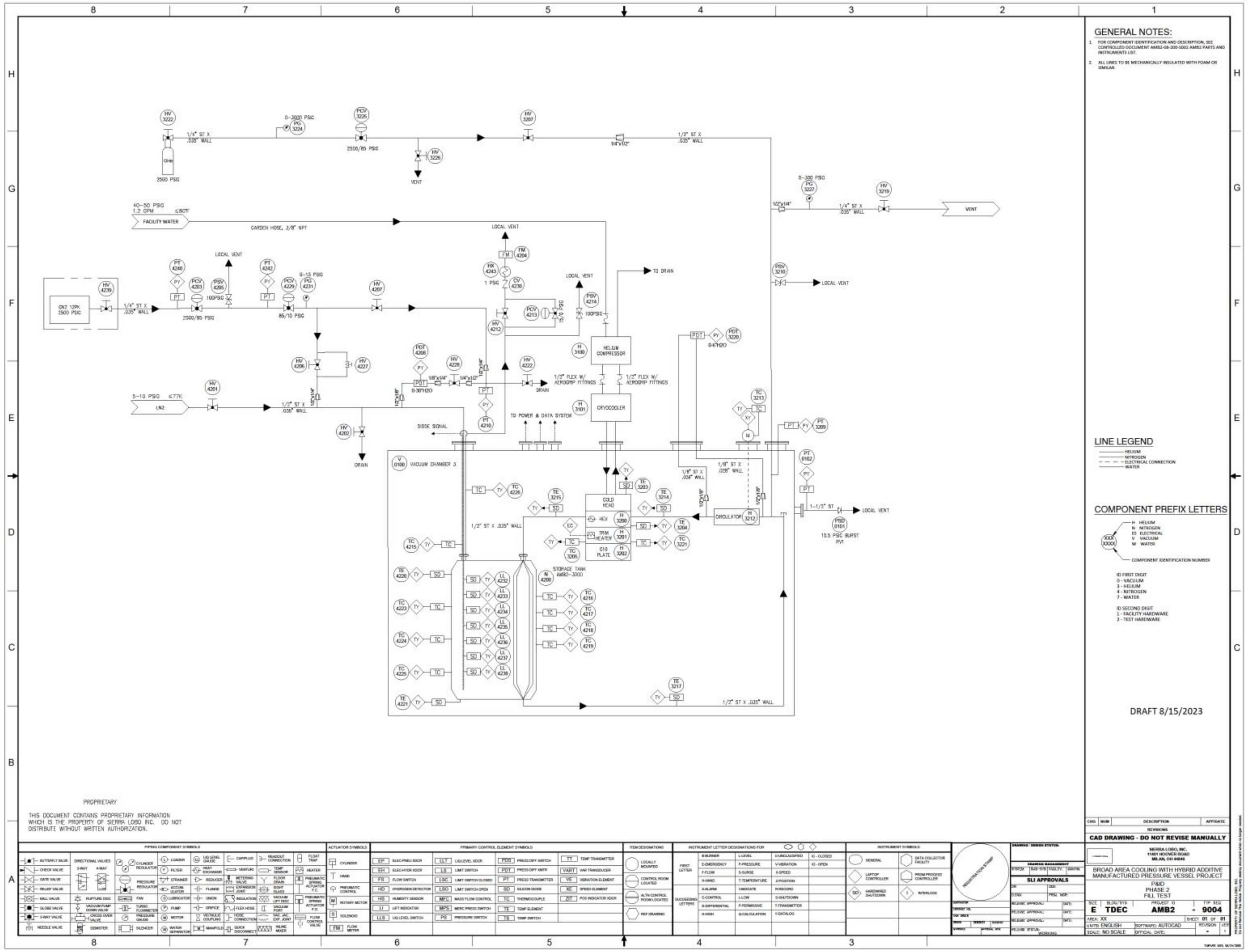
Thermal Test Simplified Helium Diagram



Thermal Test Simplified Nitrogen Diagram



Thermal Test P&ID



Test Campaign Overview

- Structural Testing
  - Cold Shock Test
  - Proof Pressure Test
  - Helium Mass Spectrometry Leak Test
- Independent Verification and Validation (IV&V) Tests
  - Cryocooler
  - Orifice and Heat Exchanger
  - Circulator
- Thermal-Vacuum Testing
- Thermal-Fluid Model Anchoring

Test setup featuring control panel, compressor, and vacuum chamber

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Structural Testing

- Cold Shock conducted by filling tank half-full of liquid nitrogen and rotating along longitudinal axis
- Proof Pressure Test
  - Pressurized in 10% increments of maximum pressure
    - Tubes: Room temperature nitrogen with maximum 94 psig
    - Tank: Room temperature water with maximum 128 psig
  - Conditions held at each increment for 5 minutes before moving to next pressure
  - Maximum pressure held for 15 minutes
- Helium Mass Spectrometry Leak Test completed for both tubing and tank
  - Two leaks found in tubing between 10^{-6} and 10^{-7} $Pa \cdot m^3 \cdot s^{-1}$
  - Leaks welded shut, and tank was once again successfully cold shocked and proof pressure tested

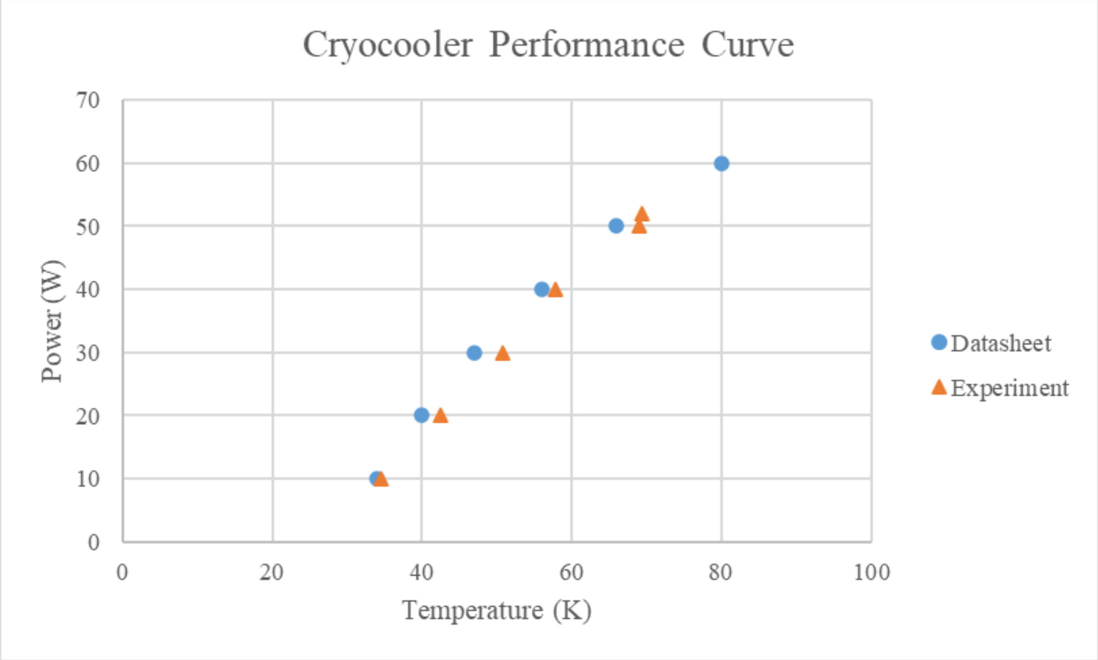
Broad area cooling tank cold shock was performed outside of Sierra Lobo's shop

IV&V Tests

- 3 critical components of the thermal test were validated to confirm functionality:
  - IV&V 1 – Cryocooler
    - The cryocooler was used to chill helium in the system after it warmed through BAC channels
    - Verification ensured the cryocooler performed according to the performance curve
  - IV&V 2 – Heat exchanger and orifice
    - The heat exchanger transferred heat between the helium and the coldhead of the cryocooler
    - Characterization included validating the temperature drop over the heat exchanger and anchoring the thermal model used to predict heat exchanger performance
    - An orifice was used to assist in IV&V 3 to validate the flow rates seen through the circulator
  - IV&V 3 – Circulator
    - The circulator drove the mass flow rate of the helium throughout the circulation loop which enabled the heat transfer throughout the system
    - Validation efforts included determining the mass flow rate as a function of impeller speed and pressure gain

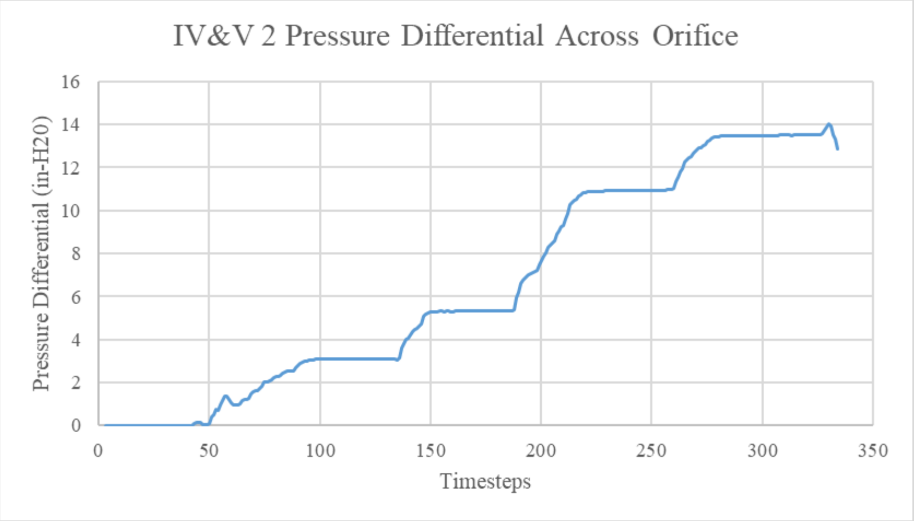
IV&V 1 – Cryocooler

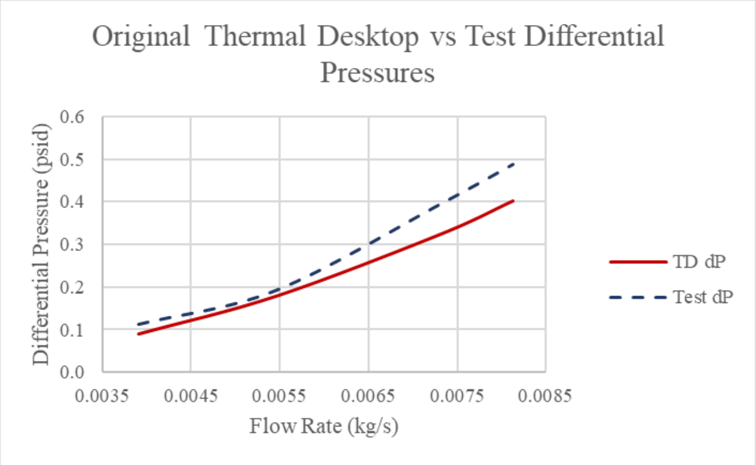
- Results of the first IV&V test show that PT-60 cryocooler performance reported on the datasheet agrees well with the measured heat load as a function of cryocooler head temperature.
- Error between experimental and given data averaged 4.5% when excluding the last data point (power draw at 60 W)
  - Can be ignored due to incomplete testing and failure to reach steady state

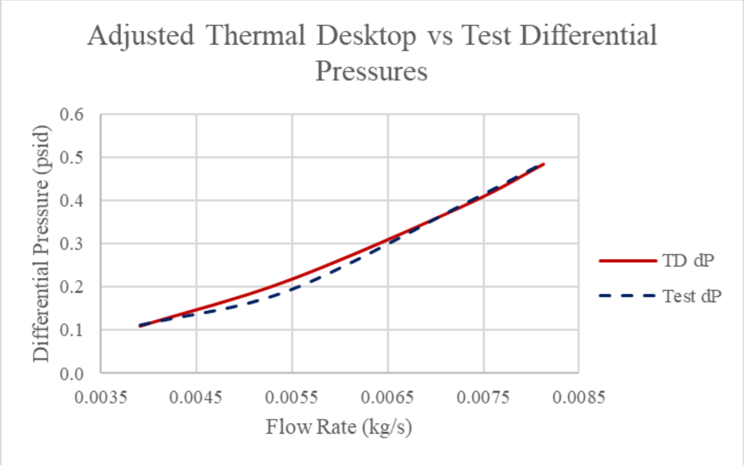


IV&V 2 – Orifice

- Orifice test performed with room temperature 100 psia nitrogen
- Pressure differential measurements across the orifice machined for the second IV&V test provided a calibration curve which was used for the third IV&V test.
- Initial orifice differential pressure predictions as a function of flow rate made using the Thermal Desktop model did not match the data well.
  - Orifice machined in house using approximate drill bit size
- A corrected Thermal Desktop model provided orifice differential pressure predictions as a function of flow rate much closer to those measured during the second IV&V test.

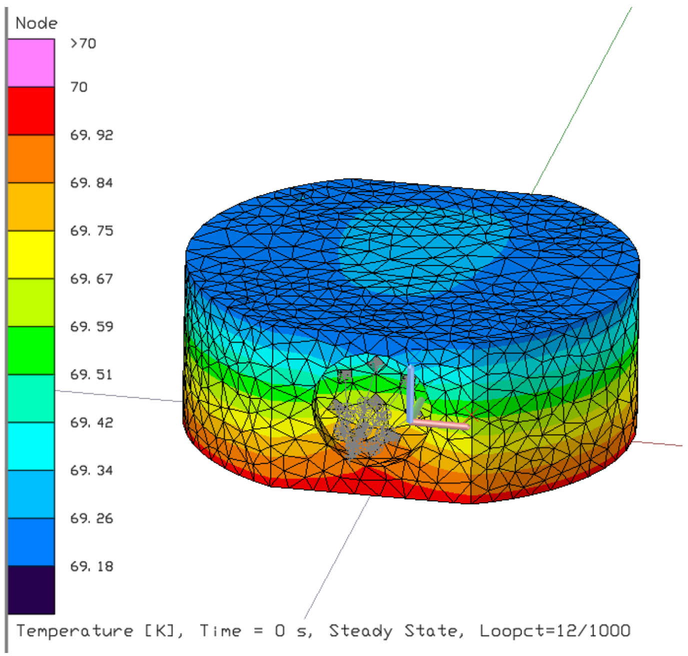




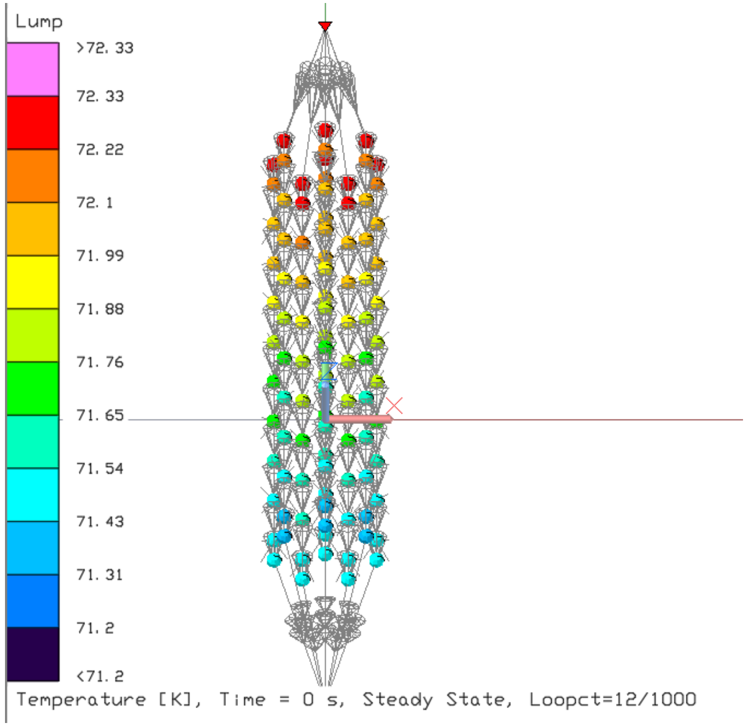


IV&V 2 – Heat Exchanger

- Heat exchanger surface and fluid temperature validated using Thermal Desktop given input conditions seen in testing
- Heater set to maintain 70 K on bottom half of heat exchanger



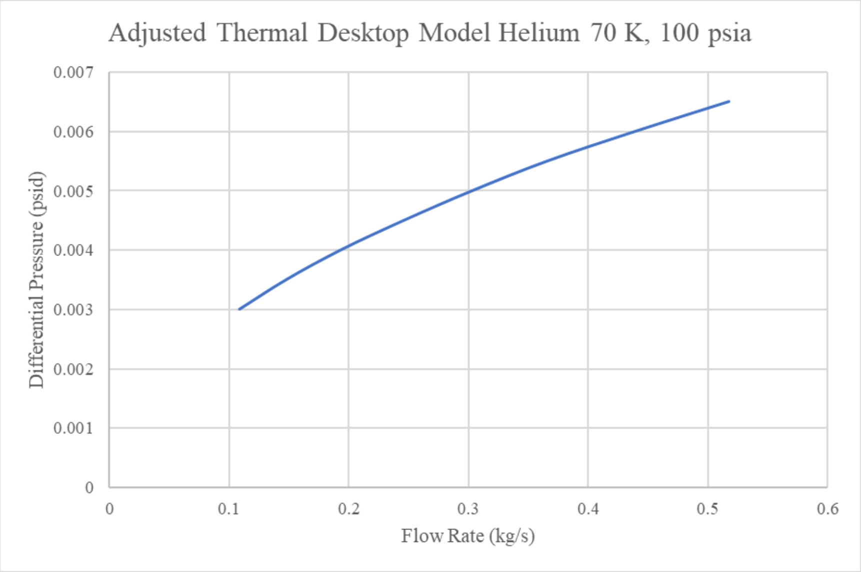
Surface Temperature

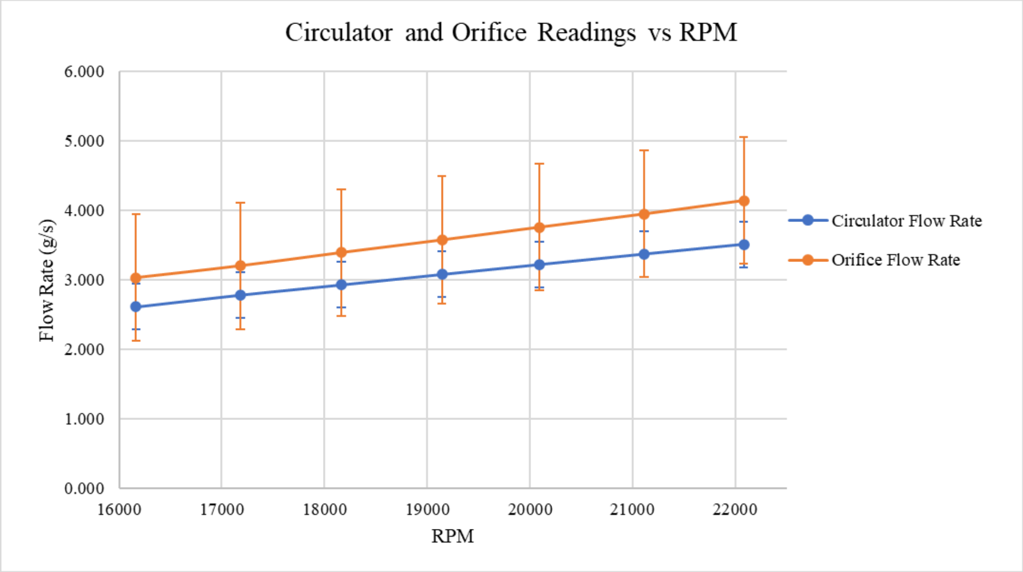


Fluid Temperature

IV&V 3 – Circulator

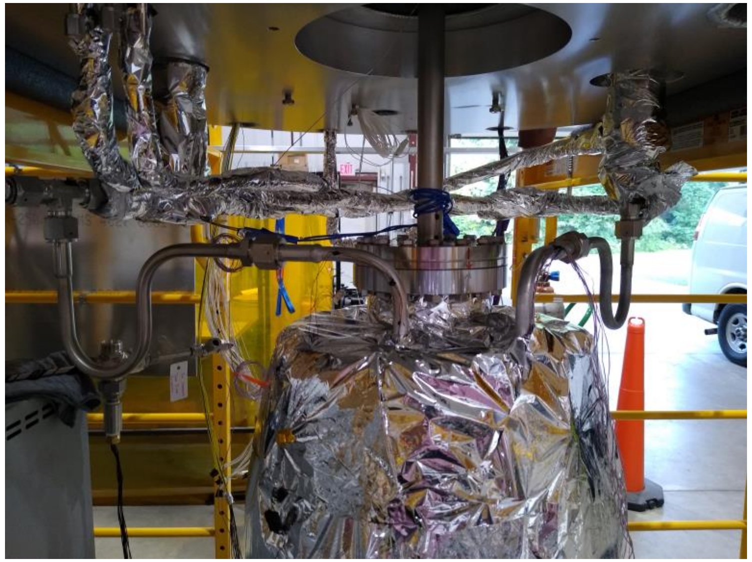
- Validated thermal desktop model previously generated to model orifice pressure drop in IV&V 2 was updated for use in helium at 70 K and 100 psia to yield a relation between pressure drop over the orifice and estimated cooling loop flow rate.
- Comparison of the flow rate measured using the custom-made orifice calibrated in IV&V 2 against the flow rate measured using the circulator flow rate prediction equations shows agreement within the estimated bounds of uncertainty.
  - Flow rate prediction equations given by circulator vendor and solved using pressure drop across circulator





Thermal Testing Overview

- Goal was to verify analyzed liquefaction rate for the BAC system
- SLI achieved a liquefaction rate of ~0.096 g/s about 50% of model-predicted values
- Helium conditions to be kept at 85 psig, 70 K
- Nitrogen conditions to be kept at 10 psig, saturated



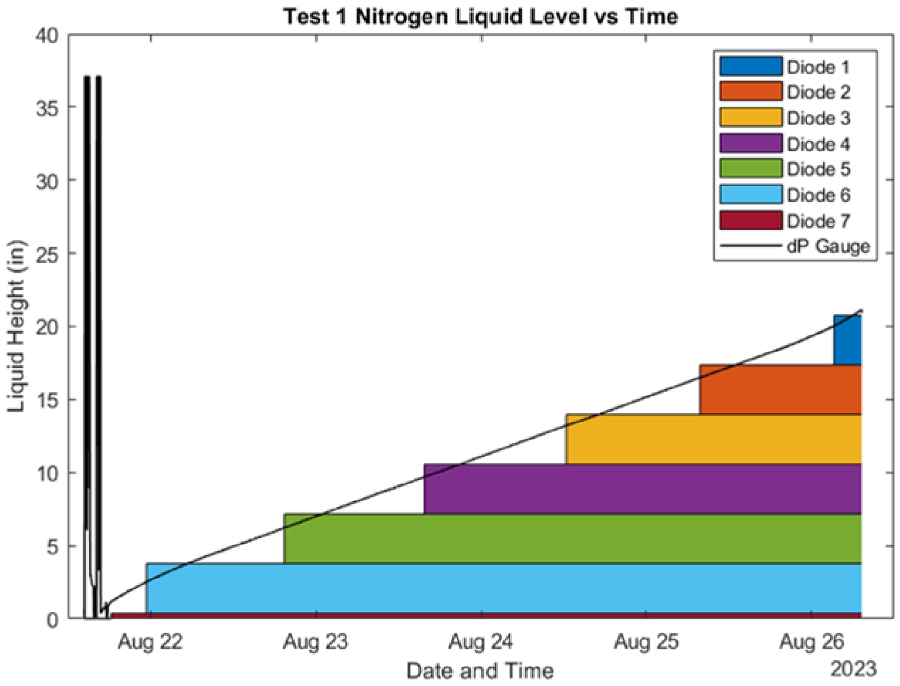
HATCHBAC tank and pipes wrapped in MLI and mounted to vacuum chamber lid

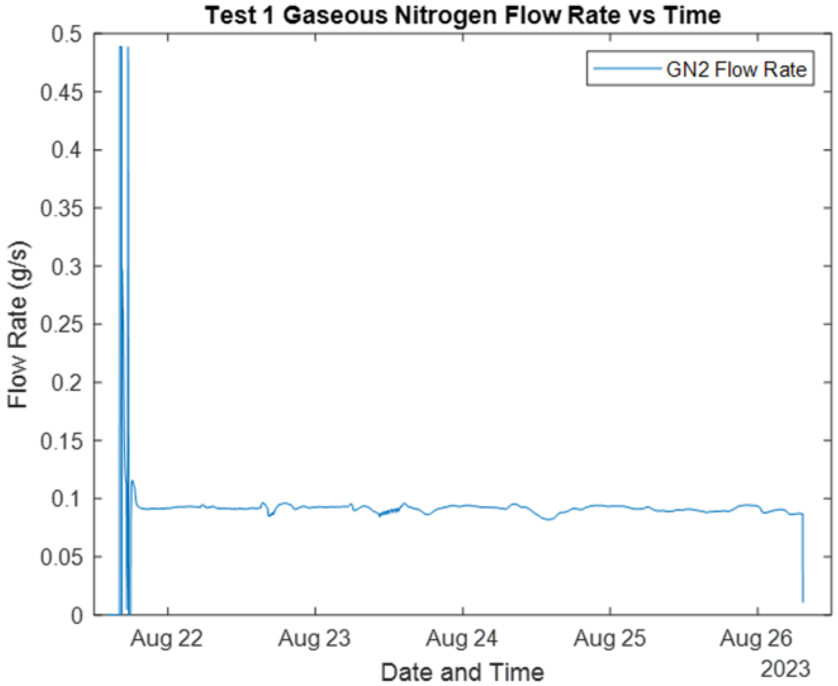
Liquefaction Rate

- During thermal testing, liquefaction rate can be determined via three methods implemented
  1. Liquid level diodes
  2. Differential pressure gauge
  3. Gaseous nitrogen inlet flow rate
- Liquid level diodes
  - 7 diodes were placed along the dip tube entering the HATCHBAC tank
  - Diodes calibrated to indicate when liquid has reached the level of the diode
- Differential pressure gauge
  - Gauge placed with one side upstream of nitrogen inlet to tank and other side upstream of vent
- Gaseous nitrogen inlet flow rate
  - Indicates required nitrogen mass needed to maintain pressure, should match liquefaction rate

Liquefaction Rate Results

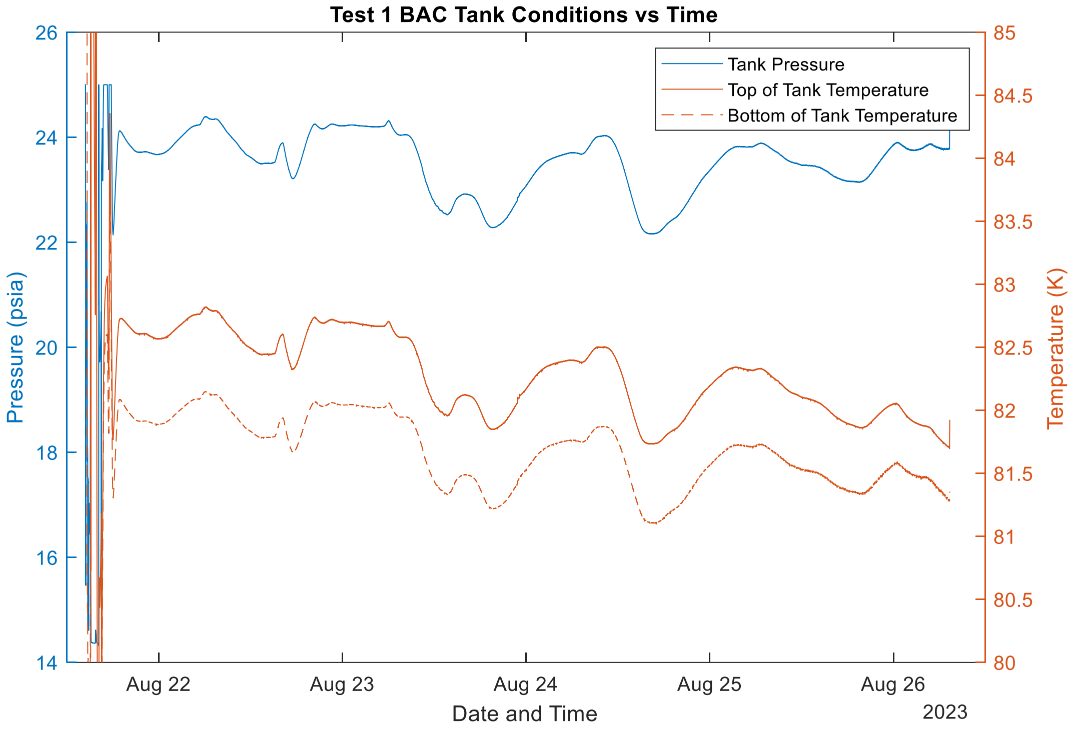
- Nitrogen liquid level is directly measured with the diodes and differential pressure gauge
  - Liquid level increases at 4.2 inches per day
  - Liquefaction rate ≈ 628 in^3/day ≈ 10.29 liters/day ≈ 8.3 kg/day ≈ 0.096 g/s
- Gaseous nitrogen inlet flow rate can directly be converted to an equivalent liquefaction rate





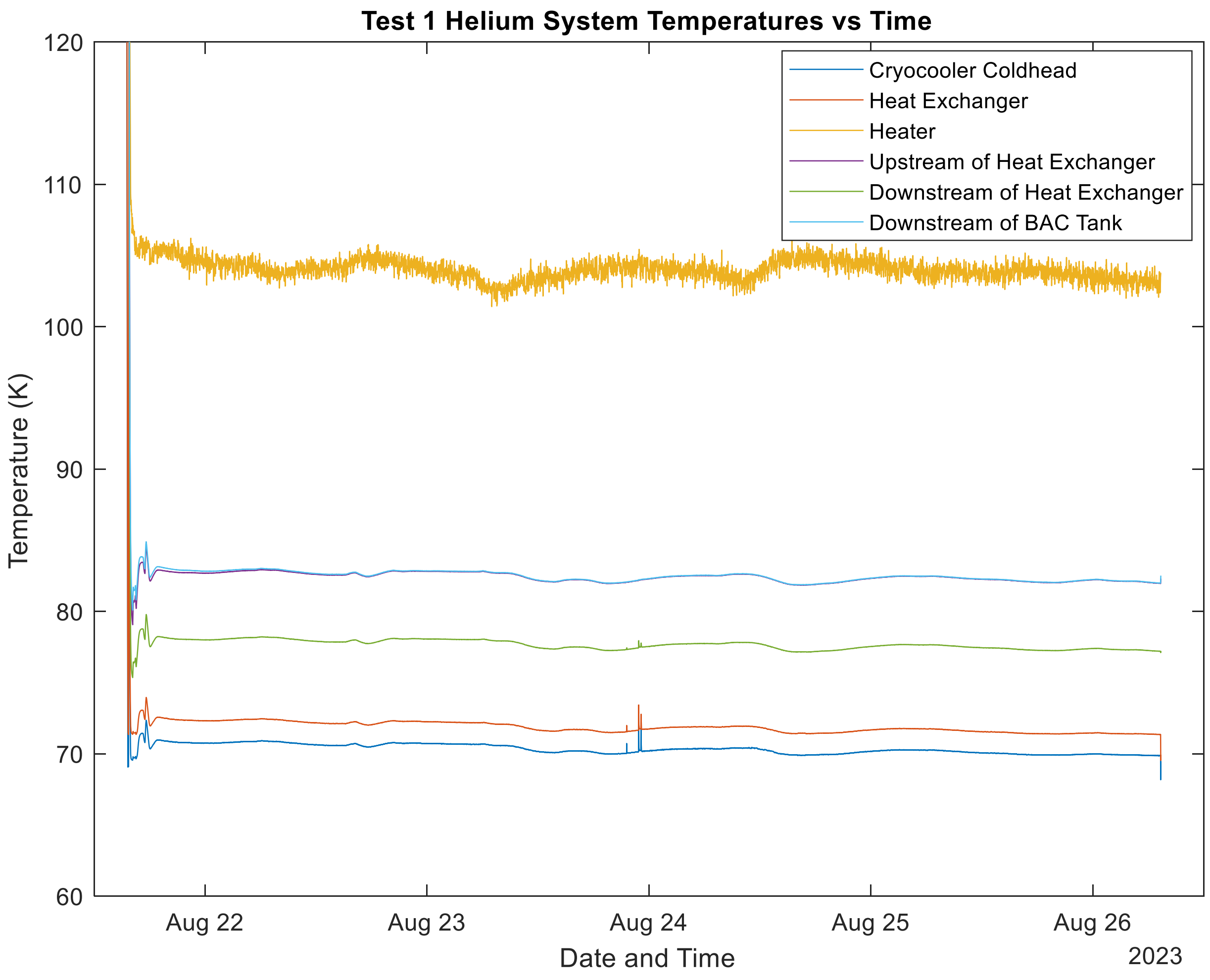
Tank Conditions Through Testing

- Tank temperature and pressure monitored through a pressure transducer and two temperature diodes underneath MLI
- Observation of testing indicated no significant condition changes, but higher-than expected tank wall temperatures (~ 82 K)



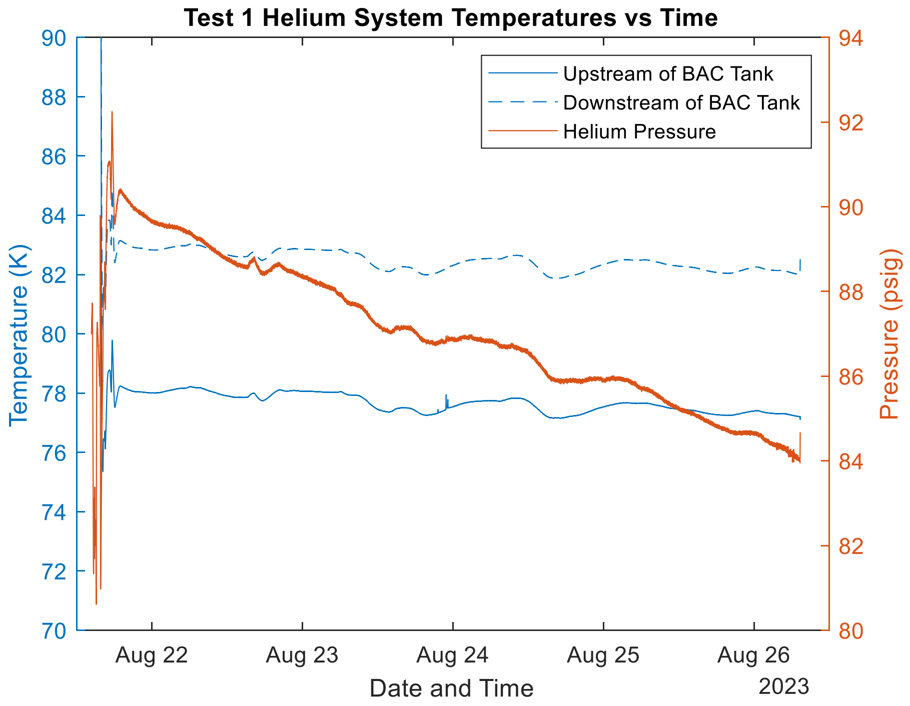
Helium Test Temperatures

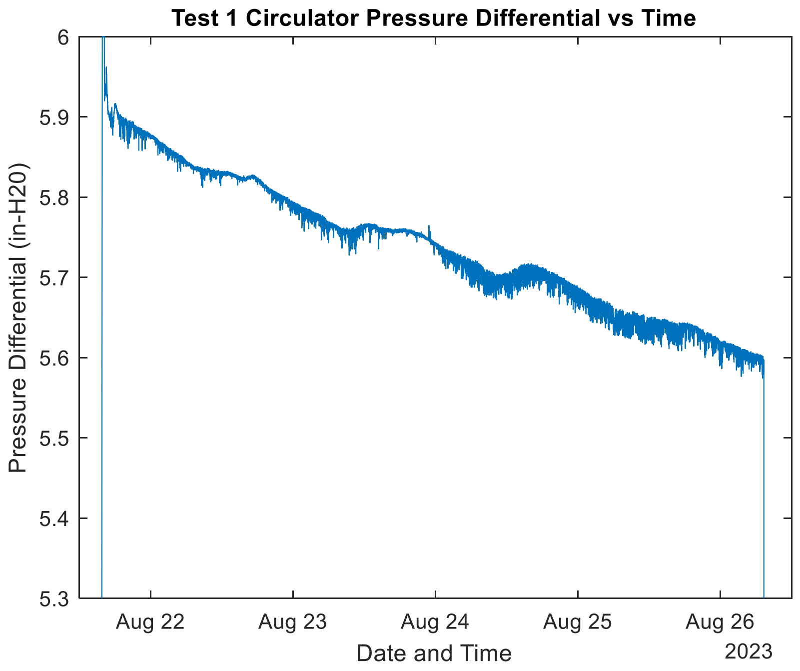
- Temperatures in helium system determined by array of temperature diodes and thermocouples
- Indicated helium system was running warmer than expected with helium temperatures not dropping to desired 70 K
- Helium temperatures remained at about 78 K



BAC Helium Lift

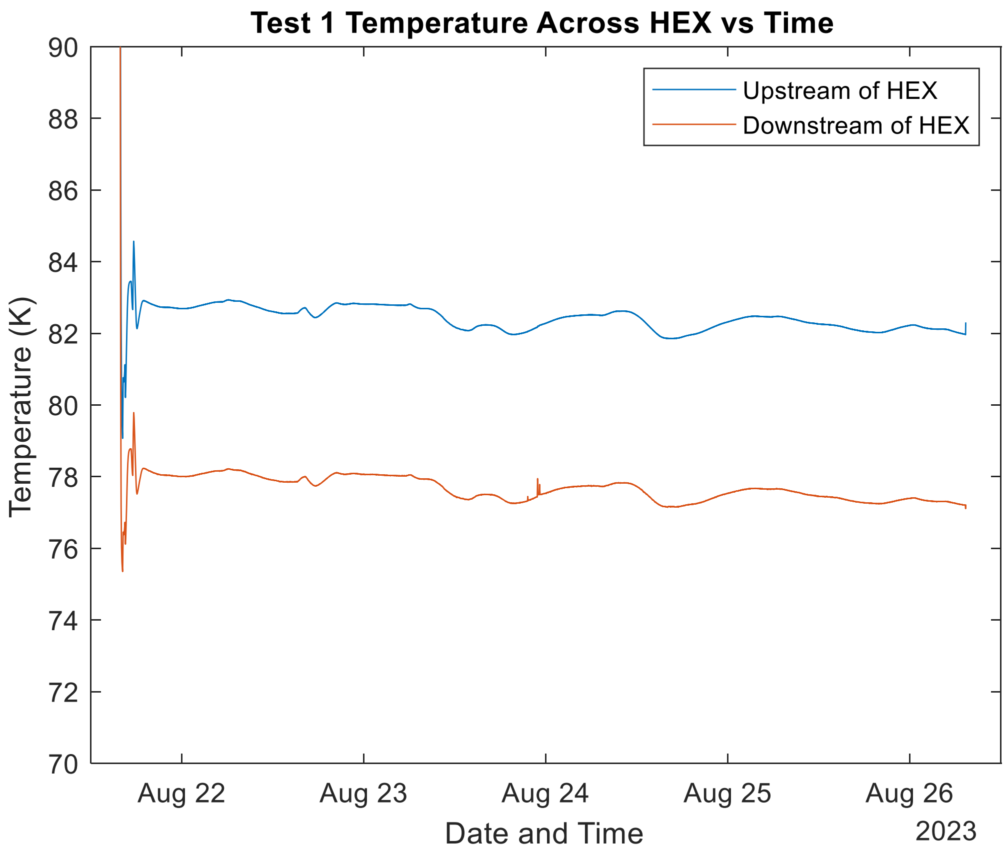
- Helium lift across BAC tank found to be ~47.5 W using temperature diodes, a pressure transducer, and a differential gauge placed across the helium circulator
  - Pressure differential across circulator gives flow rate of helium through system





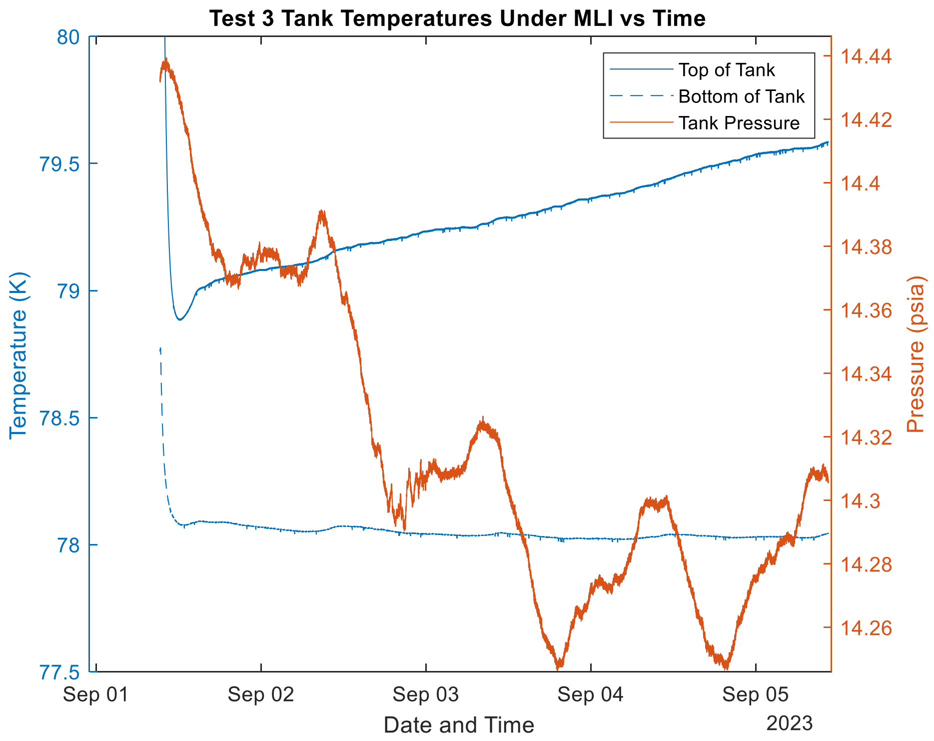
Cryocooler Lift

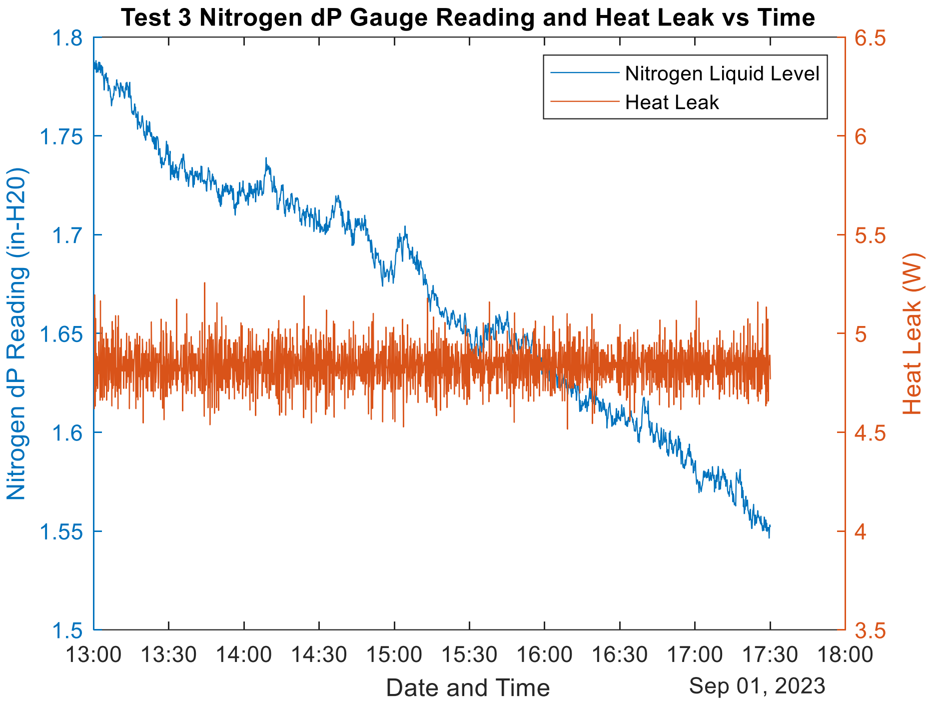
- Cryocooler lift determined to be ~46.7 W calculated from set of temperature diodes both upstream and downstream of BAC channels, as well as pressure and flow rate found from the pressure transducer and differential pressure gauge



Additional Boil-Off Testing

- Boil-Off Testing was conducted to solve for additional heat leak into the system
- ~4.8 W Heat Leak into liquid in tank was found through MLI, matching predicted values





Anchoring Thermal-Fluid Models

- Predictions of models used to design HATCHBAC system inconsistent with heat leak measured during testing
  - Temperatures through system were much higher than anticipated
- Models are detailed in former published work but include:
  - Heat exchanger heat transfer
  - BAC heat transfer
  - Circulator heat transfer
  - Liquefaction rate
  - Radiation into tank
  - Conduction along dip tube
  - Diode heat leak
  - Flange heat transfer
    - Holds high uncertainty due to unknown contact resistance

Heat Transfer Analysis Validation

- **Test 1**: Liquefaction test run under standard conditions (~10 psig)
- **Test 6**: Liquefaction test run with high-pressure nitrogen within tank (~30 psig)
- **Test 8**: Liquefaction test with top-fill (~6 psig)

	Test 1 (W)	Test 6 (W)	Test 8 (W)
Heat Exchanger (±13.140 W)	46.525	80.023	78.996
BAC Tank (±13.140 W)	47.068	79.205	75.844
Nitrogen Cooling and Condensation	38.427	43.781	36.201
Total Heat Leak	20.925	22.985	34.986
Circulator	-0.543	0.818	3.152
Radiation	1.236	0.764	2.371
Dip Tube	0.920	0.875	0.862
Diodes	0.250	0.250	0.250
Flange	19.062	20.278	28.351
Theoretical System Heat Leak	8.641	35.424	39.643
Unaccounted for Heat Leak	12.827	-13.257	-7.809

Conclusions

- HATCHBAC system was able to perform liquefaction at rate of 0.096 g/s
- Significant unaccounted for heat leak and large uncertainty contributed to lower-than-expected liquefaction rate
- Further testing with added instrumentation would assist in capturing source of heat leak
- Increased heat leak reducing measure could be taken to improve efficacy of HATCHBAC tank for future applications
- Higher capacity cryocoolers would be beneficial for increased performance and scale for future HATCHBAC tanks

References

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