Transient Liquefaction on the Lunar or Martian Surface Operational Demonstration

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INTRODUCTION

- NASA has been studying Lunar and Martian surface propellant production for approximately 30 years.
- Greater than 55% of any Lunar or Martian return vehicle is oxygen by mass.
  - Production on the surface decreases lander mass which decreases launch vehicle mass.
- Oxygen production on Mars was demonstrated by Mars Oxygen ISRU Experiment (MOXIE) as a part of the Perseverance rover at rates between 1.5 and 11.2 mg/s.
  - Done on stationairy portion of the rover using carbon dioxide gas from the atmosphere.
  - Lunar production done either through mining water ice or reforming oxides within regolith.
- Last step of propellant production is the liquefaction process.
  - Initially done within lander tanks, simply refueling them.
- NASA created Cryogenic Fluid In-situ Liquefaction for Landers (CryoFILL) project to demonstrate liquefaction processes.

CRYOFILL BACKGROUND

CryoFILL will demonstrate *cryogenic capabilities* on the *Lunar* and *Martian surfaces* for landers, In-Situ Resource Utilization (ISRU), and the integration of the two at a *relevant scale*, in a *relevant environment* with hardware that can be used in ISRU End to End tests.

- Human Lander System (HLS) Sustainable Lunar Architecture
- In-Situ Resource Utilization (ISRU)

Objectives

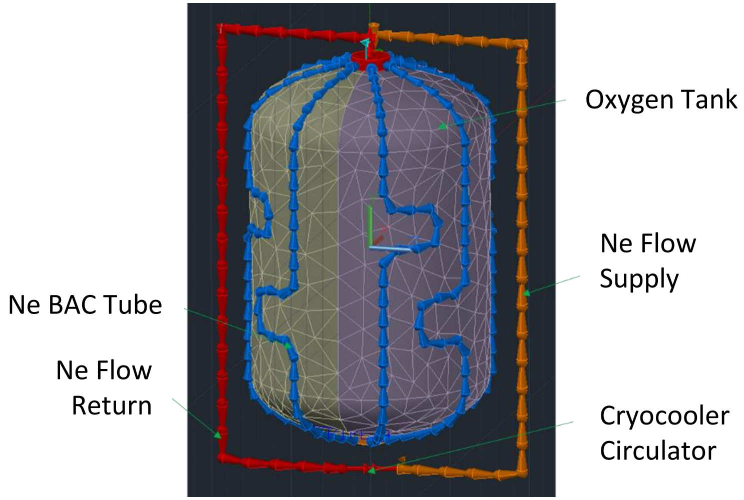
- Design, build, and test a prototypical lander tank with a liquefaction system capable of incorporating prototype flight components as they are developed.
- Demonstrate liquefaction processes in a relevant environment.
- Provide data for validation of two-phase cryogenic fluid models in development.

Current Status

- Oxygen liquefaction demonstration complete on Prototype tank
  - Half scale liquefaction rate (1.1 kg/hr +) demonstrated on half scale (by surface area) tank
  - Incorporated Fiber Optic Sensing System (FOSS) for better understanding of ullage stratification
  - Final report to be published as NASA Technical Publication, draft completed
- Modelling of test data in progress
- Block 2 testing (with flight-like 90 K cryocooler) slipped to FY24 due to funding constraints

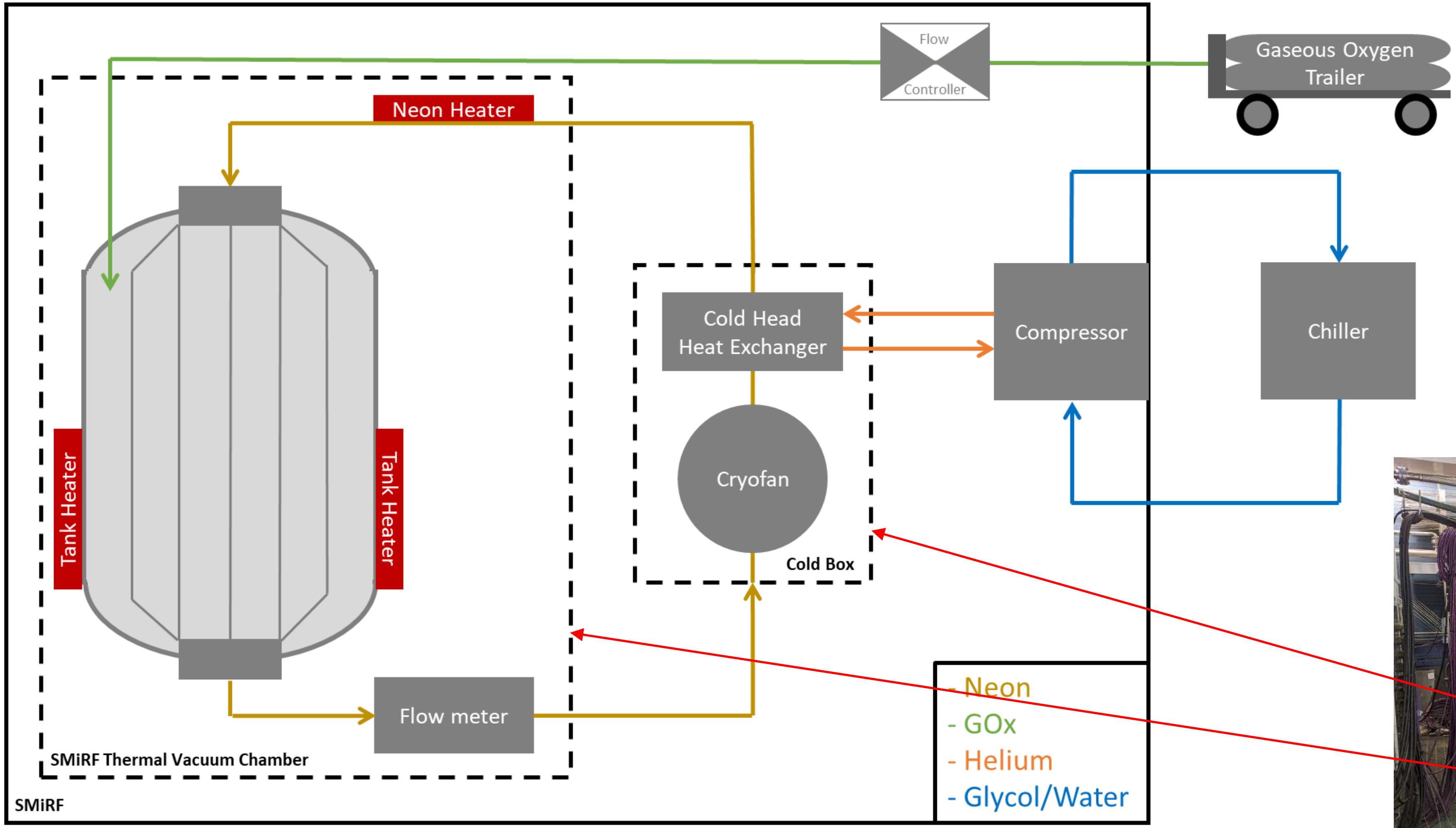
NASA GRC SMiRF Facility with Prototype Test Article in Vacuum Chamber. Industrial cryocooler coldbox in the foreground.

Prototype Tank Thermal Desktop Model



CryoFILL Tank Uninsulated on a Support Stand

TEST SCHEMATIC



Test setup using industrial integrated cryocooler system

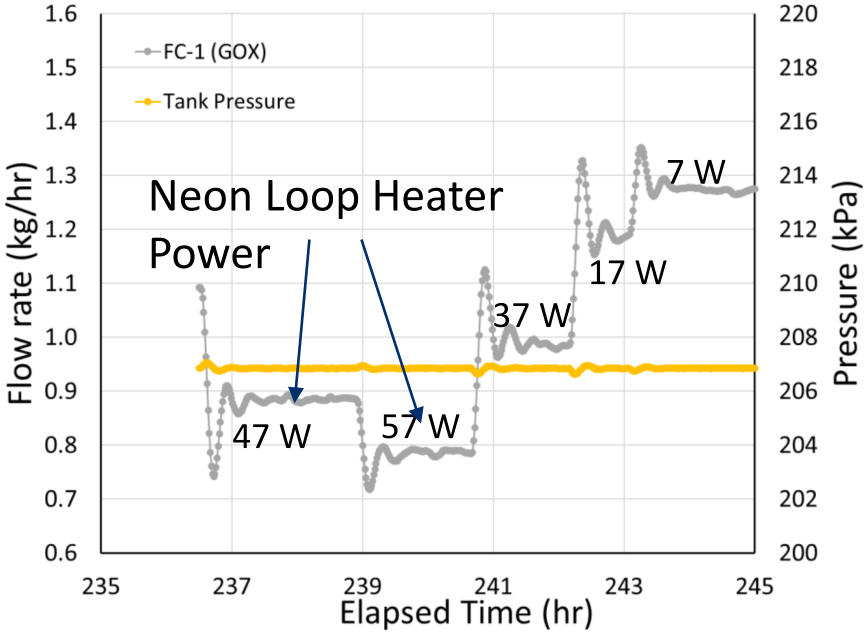
- Plan to incorporate flight-like cryocooler system in future.
- For transient operations, varied neon heater power, oxygen flow rate, and thermal vacuum environment.

PROTOTYPE BLOCK 1 TEST OVERVIEW

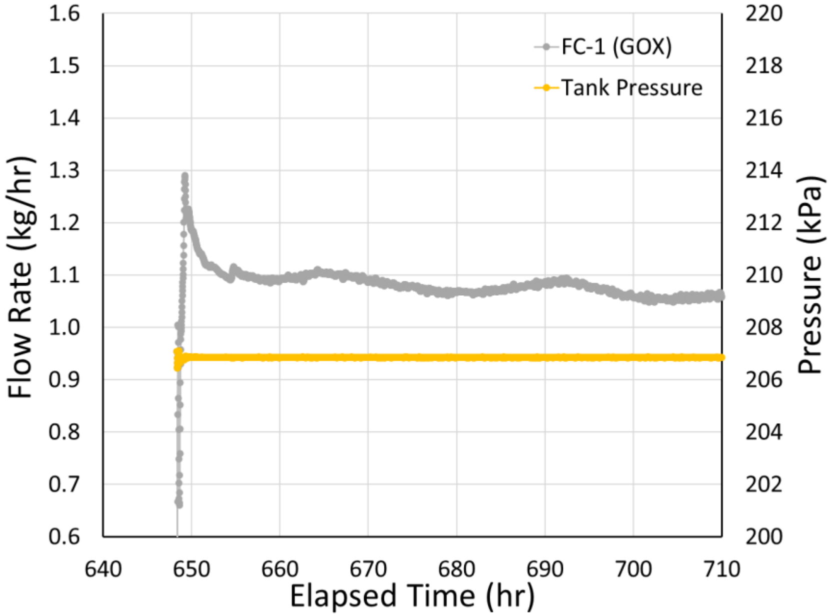
- Nitrogen checkout testing completed
- Three Phases of oxygen testing:
    1. Evaluation of Nominal Performance Determination
    2. Constant Liquefaction Operations
    3. Transient Liquefaction Operations

Phase Objectives:

1. Confirming understanding of effects of the knobs controlling the system operations.
2. Verifying steady-state system performance.
3. Exploring transient operations that may be needed within a complex system.



Phase 1 Sample Results



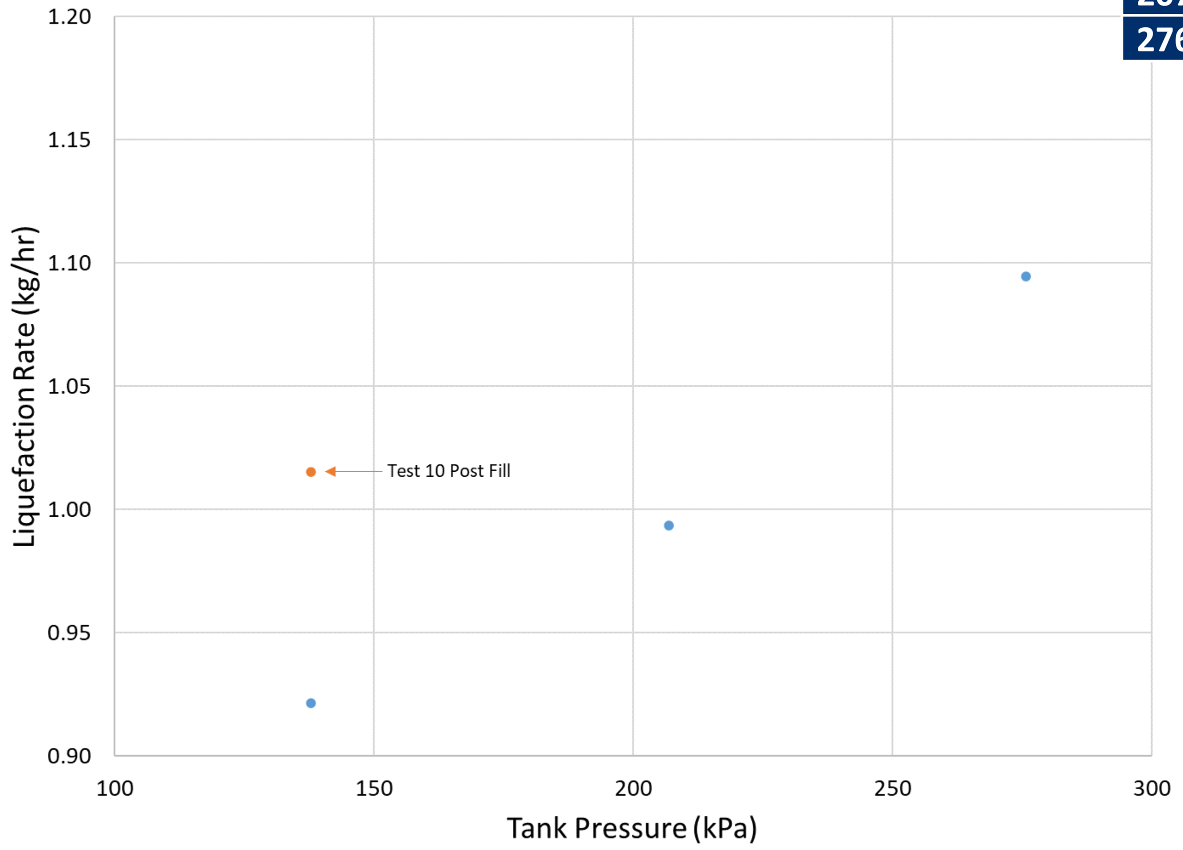
Phase 2 Sample Results

Characterizing system response to cryocooler power levels

Constant liquefaction with pressure set to 30 psia

EFFECT OF TANK PRESSURE

Test Pressure (kPa)	Demonstrated Liquefaction Rate (kg/hr)	Demonstrated Relative liquefaction rate (%)	Enthalpy change for inlet temperature at 300 K (J/g)	Analytical Liquefaction Rate (constant cryocooler) (%)
138	0.93	93%	412	98%
207	0.99	100%	404	100%
276	1.09	110%	397	102%



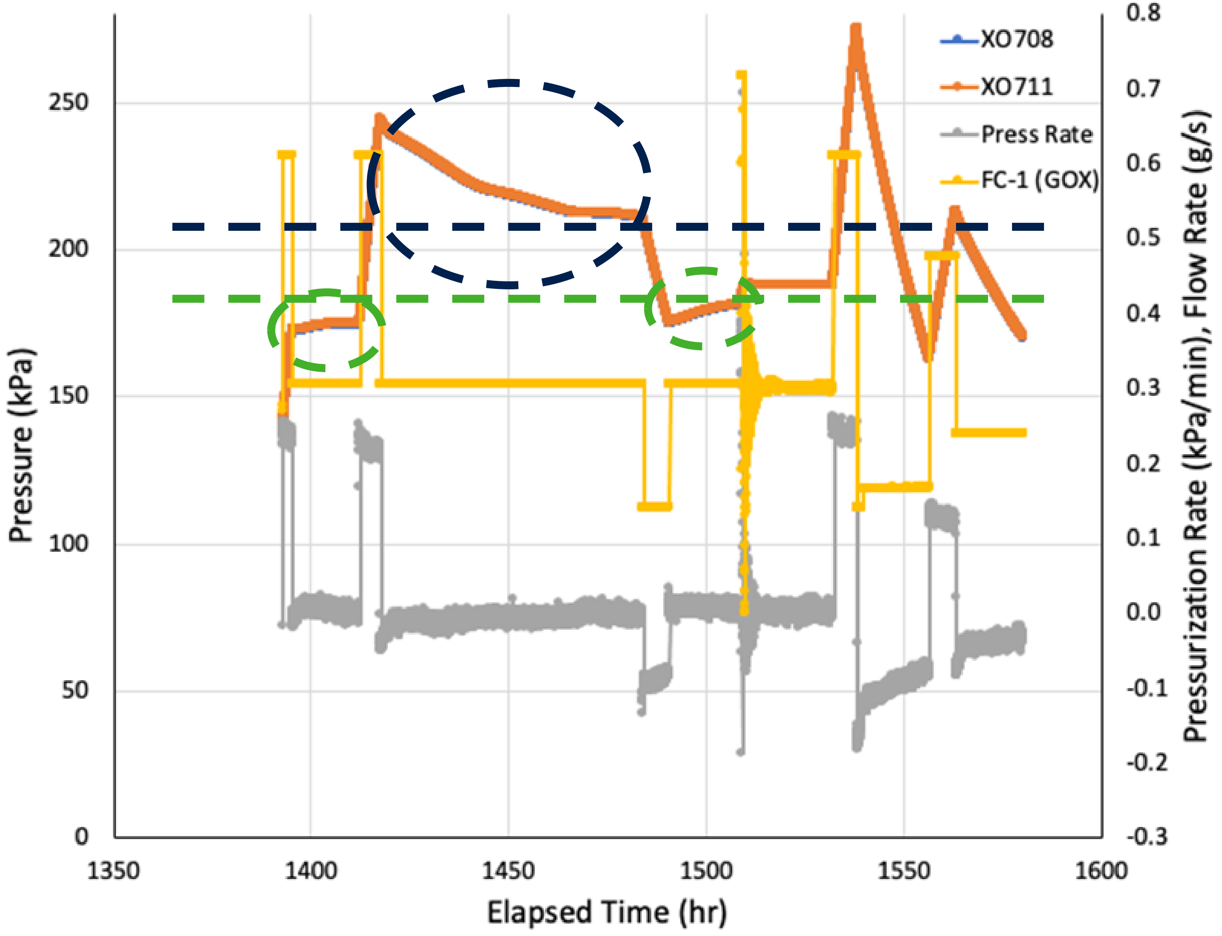
Effect of tank pressure goes beyond thermodynamics or change of enthalpy (4% expected change in liquefaction rate).

Change in cryocooler efficiency due to liquid temperature change more important (17% change in demonstrated liquefaction rate).

- Saturation temperature changes from 93 K at 138 kPa to 101 K at 276 kPa.

Recharged neon loop in the middle of 138 kPa test, change from 417 kPa to 501 kPa. Change in liquefaction rate (11%) nearly entirely due to change in neon density (15%).

EFFECT OF FLOW RATE



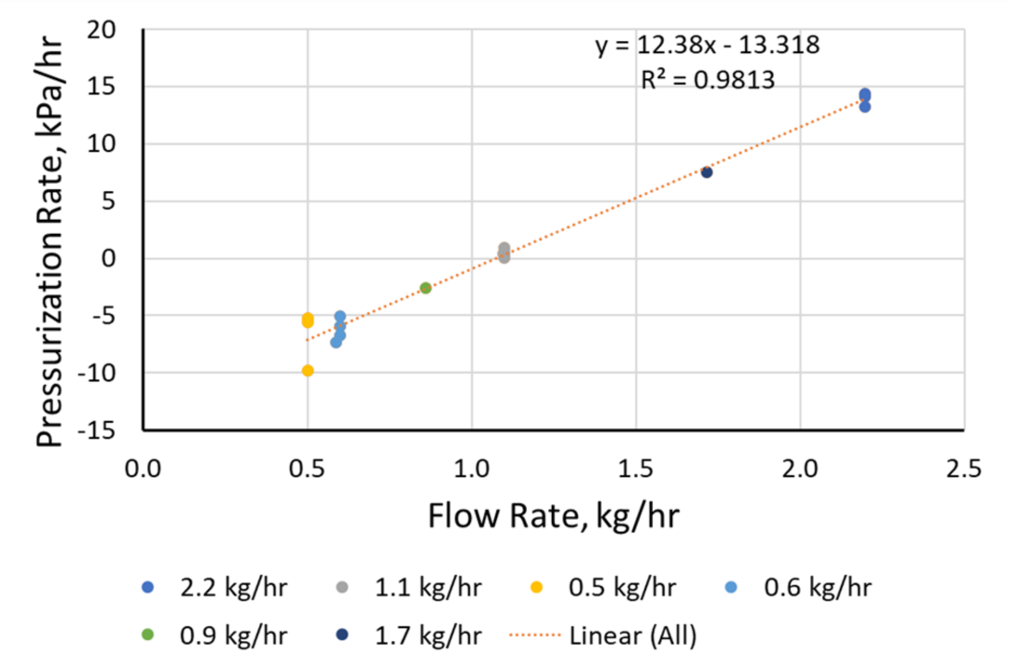
Ran tests adjusting the flow rate as a function of time to see tank pressurization rates.

- Depressurization rates show much more change over time than pressurization rates.

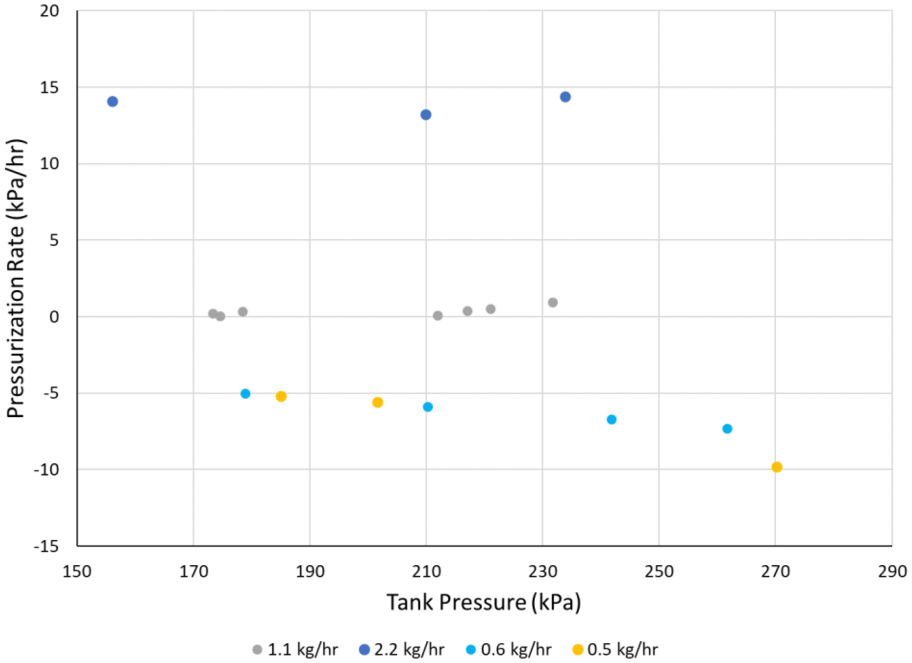
When flow rate was set to 0.3 g/s (1.1 kg/hr), pressure appeared to asymptotically approach a pressure, but the pressure was different when pressure approached from above than from below.

- Probably due to slight alterations in neon flow loop and small difference in equilibrium states.
- May have further collapsed if let run long enough.

PRESSURIZATION RATE ANALYSIS

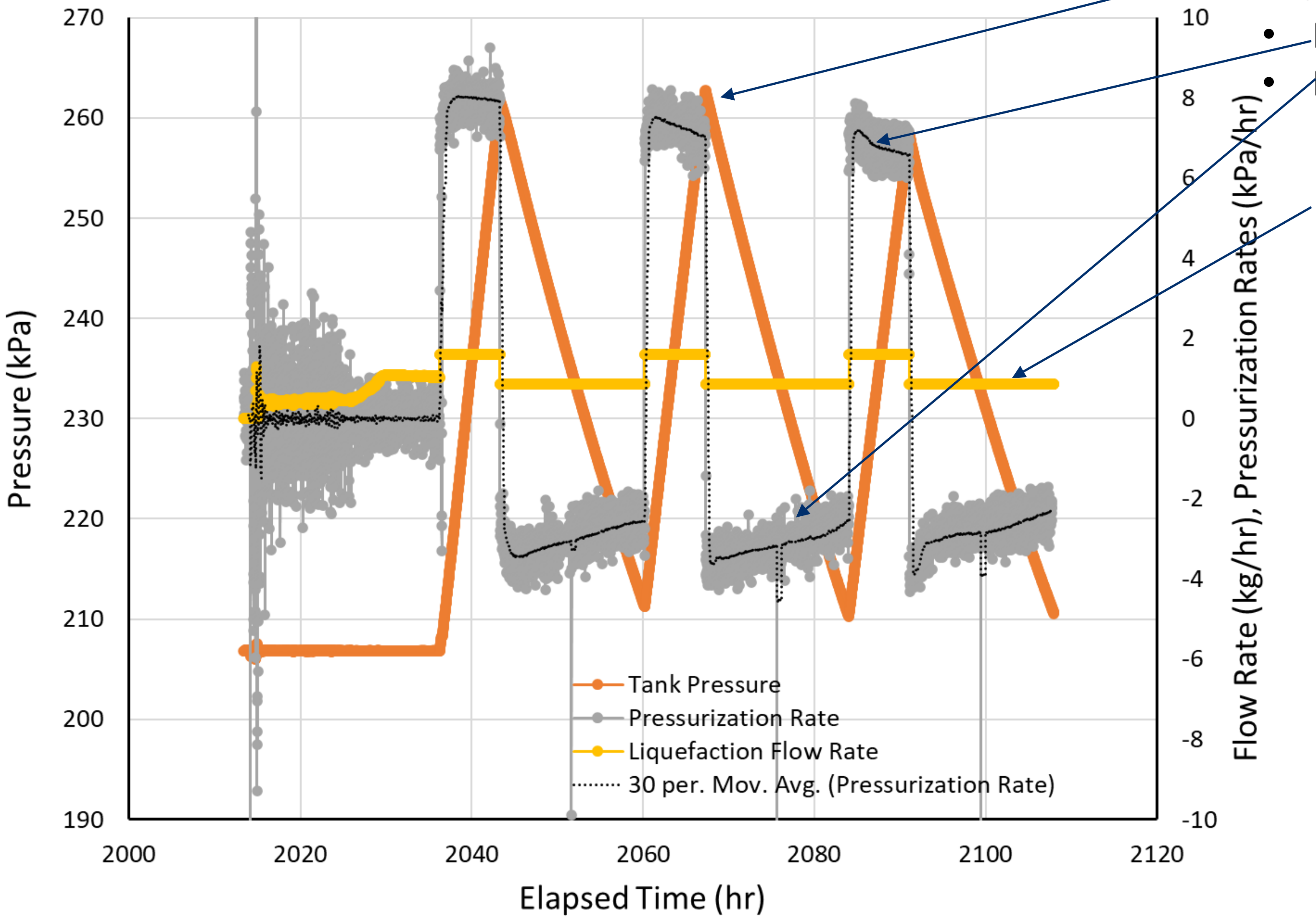


- Pressurization rate a linear function of mass flow rate.
    - Used for setting transient test operations rates.
- Some spread near 2.2 kg/hr, 1.1 kg/hr, and 0.5 kg/hr



- No tank pressure dependency in 2.2 kg/hr test data, appears to be just noise in data
- Perhaps some small levels of sensitivity in 1.1 kg/hr test data.
- Strong dependance on tank pressure for 0.5 – 0.6 kg/hr test data.

FLOW RATE TRANSIENTS (PHASE 3)



Pressure Response (changes by 60 kPa)

- Pressurization rate: 7.2 kPa/hr
- Depressurization rate: - 3.0 kPa/hr

Driving oxygen flow

Used steady-state results from Nominal Performance testing to predict pressurization rates within 10%

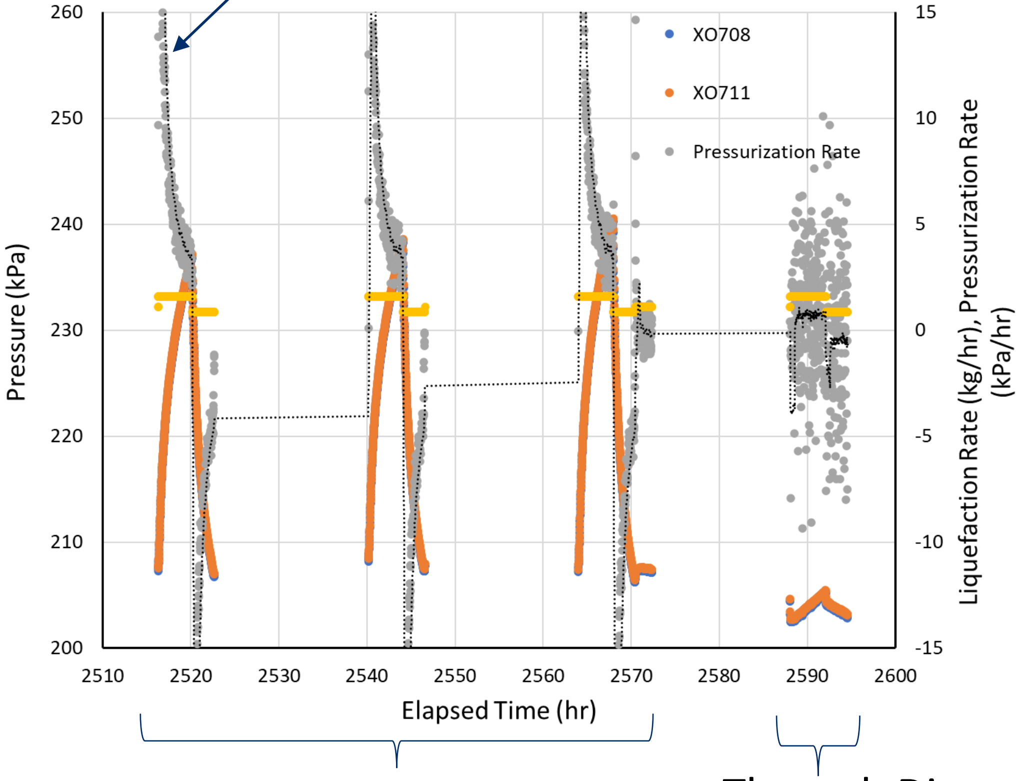
Cycle oxygen flow rate between 1.6 kg/hr and 0.9 kg/hr to simulate oxygen production and pressure swings with constant cryocooler settings.

Repeatable over 3 cycles.

Fill level between 0 and 10 percent

HIGH FILL MASS FLOW TRANSIENTS (PHASE 3)

Pressurization rates much less constant than other tests



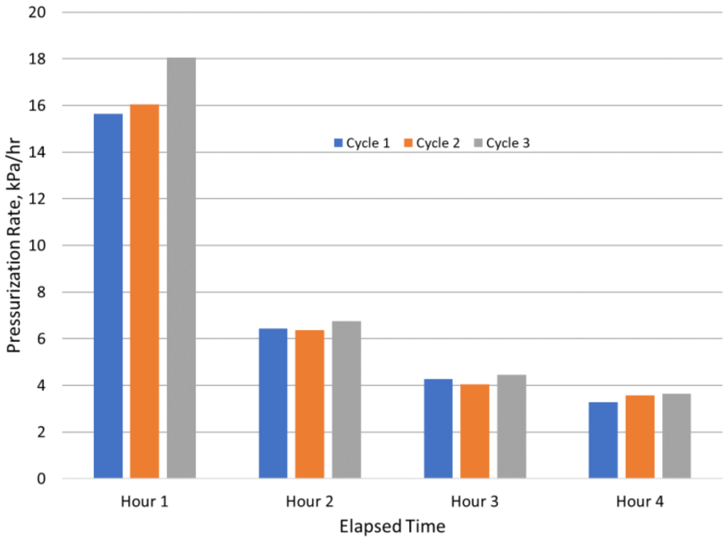
Into ullage

Through Dip tube

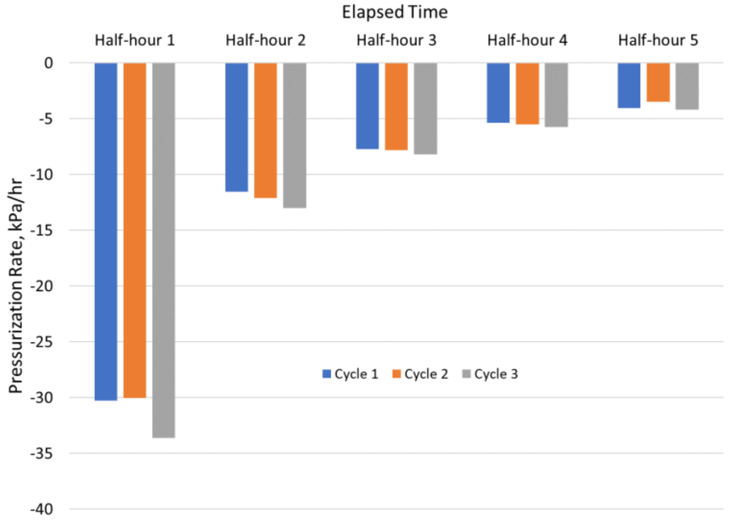
Average Pressurization rates:

- 7.86 kPa/hr
  (7.2 at low fill)
- \- 12.5 kPa/hr
  (-3.0 at low fill)
- Repeatable within 6%

Dip Tube discussed by Grotenrath.

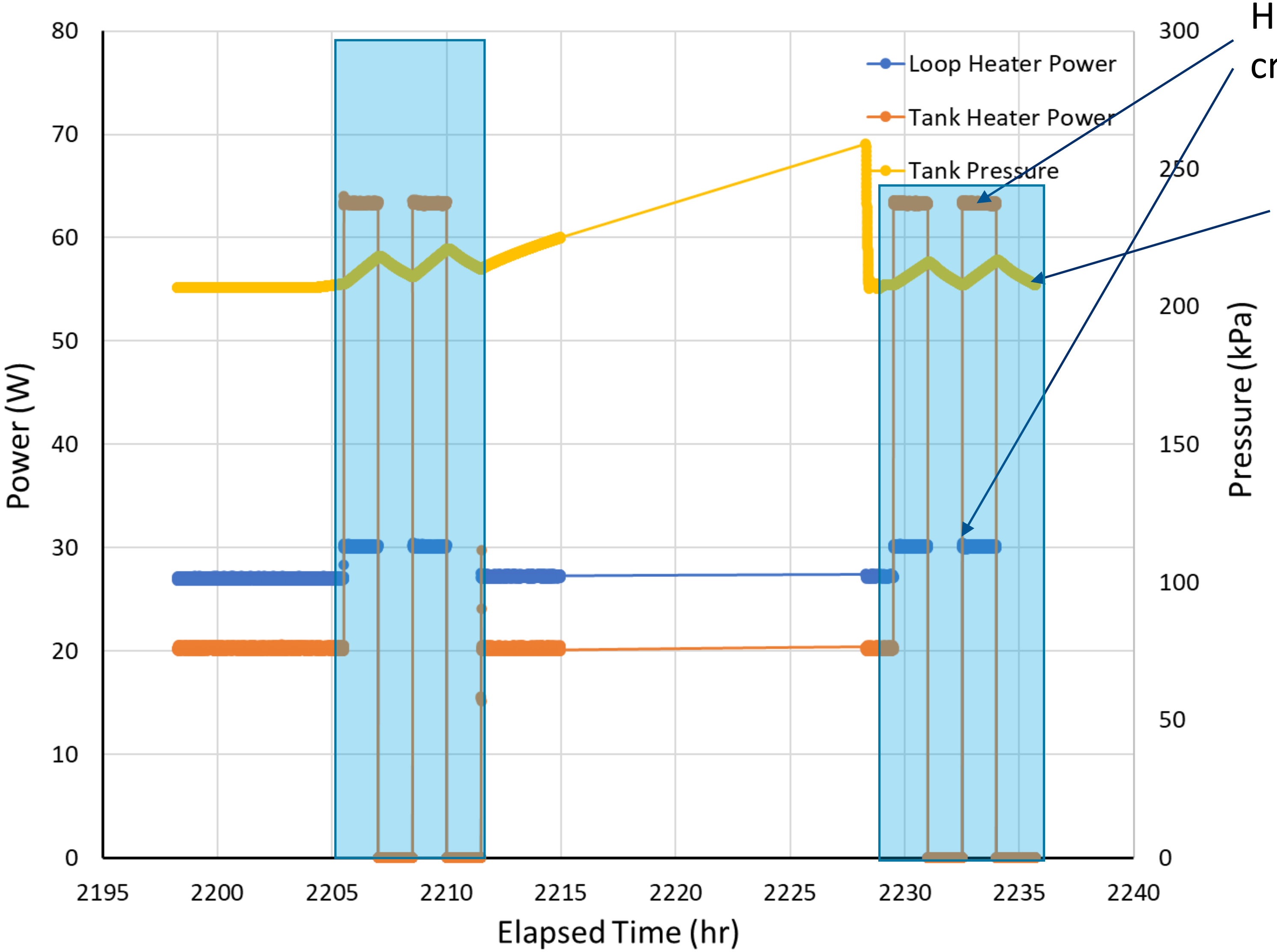


Pressurization rates (top) and depressurization rates (bottom) over defined periods within test data shown on left.



Fill level greater than 90 percent

CRYOCOOLER POWER TRANSIENTS (PHASE 3)



Heater variations to simulate cryocooler power changes

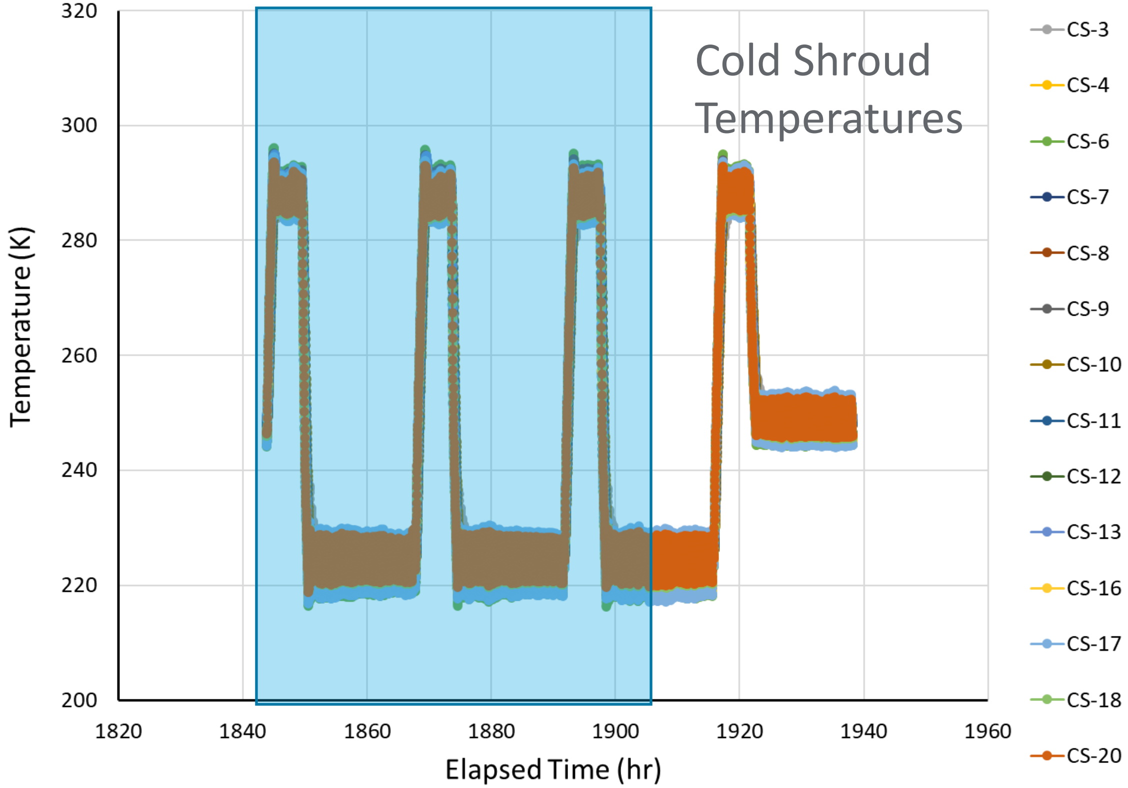
Pressure Response

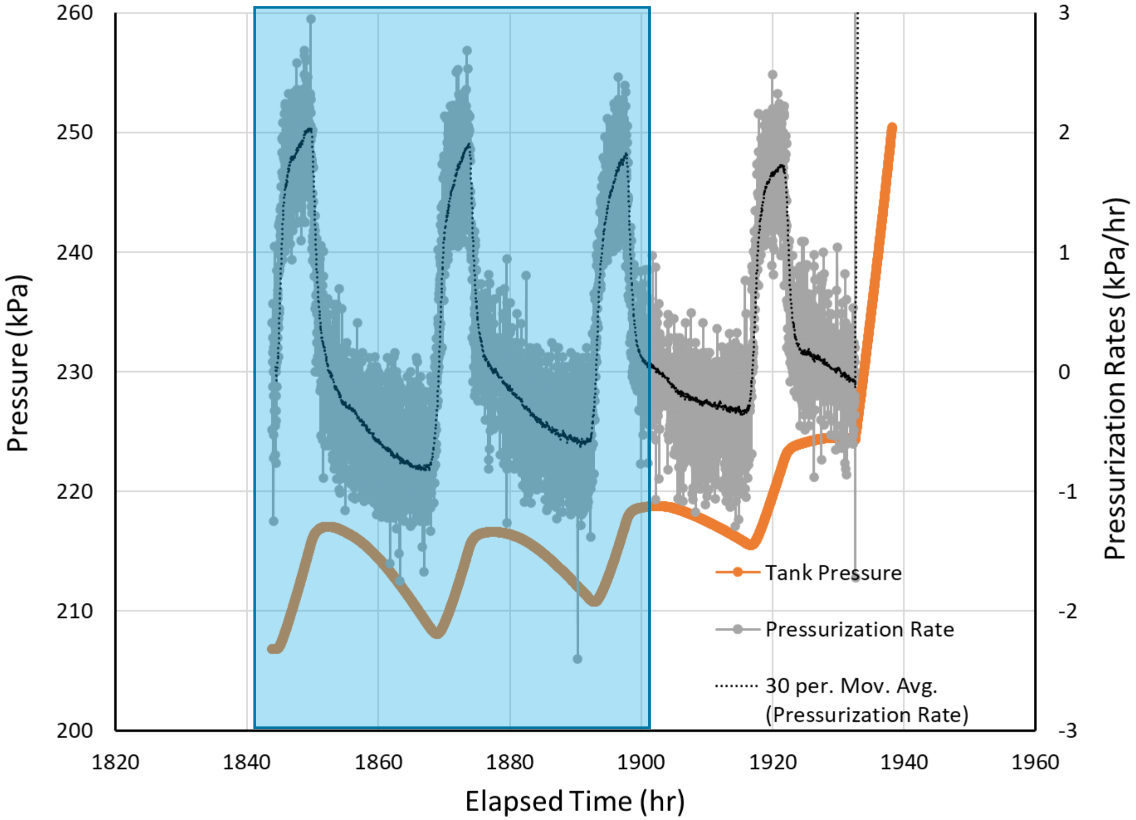
- Avg Pressurization Rate: 6.0 kPa/hr
- Avg Depressurization Rate: - 5.2 kPa/hr
- All repeatable within 7% over the four cycles

Varied heater settings on cryocooler system to simulate effect of power availability cycles for cryocooler on tank pressure during constant liquefaction.
Note: overnight ran separate test.

Fill level between 0 and 10 percent

ENVIRONMENTAL TEMPERATURE TRANSIENTS (PHASE 3)





Varied the environmental temperature to simulate day/night cycle temperature swings in Lunar/Martian environment and their impact on tank pressure with constant liquefaction flow (1.1 kg/hr)

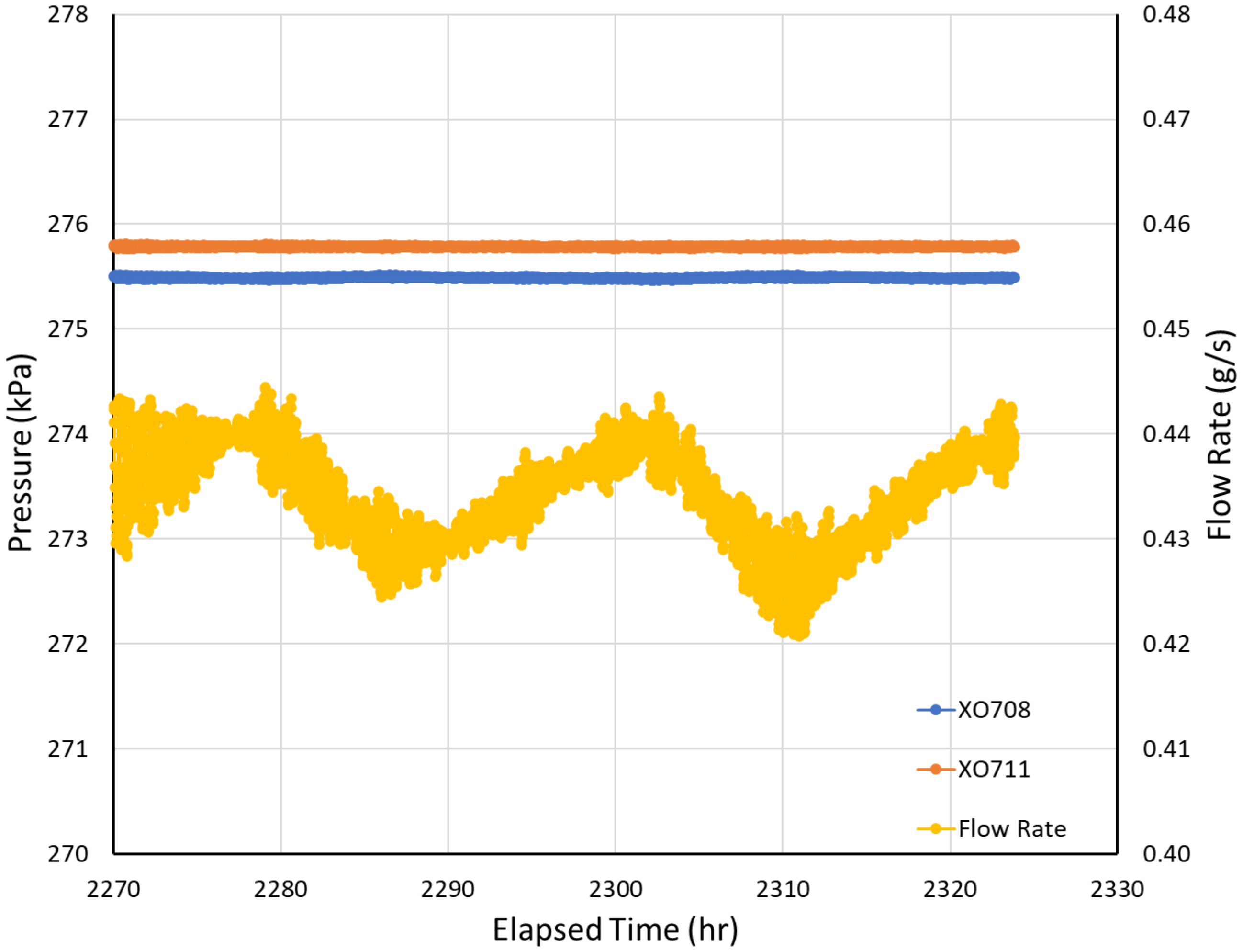
First ~2.5 days of testing repeatable

Pressure Response

- Avg Pressurization Rate: 1.7 kPa/hr
- Avg Depressurization Rate: - 0.5 kPa/hr
- Pressurization repeatable within 11%
- Depressurization repeatable within 45%

Fill level between 0 and 10 percent

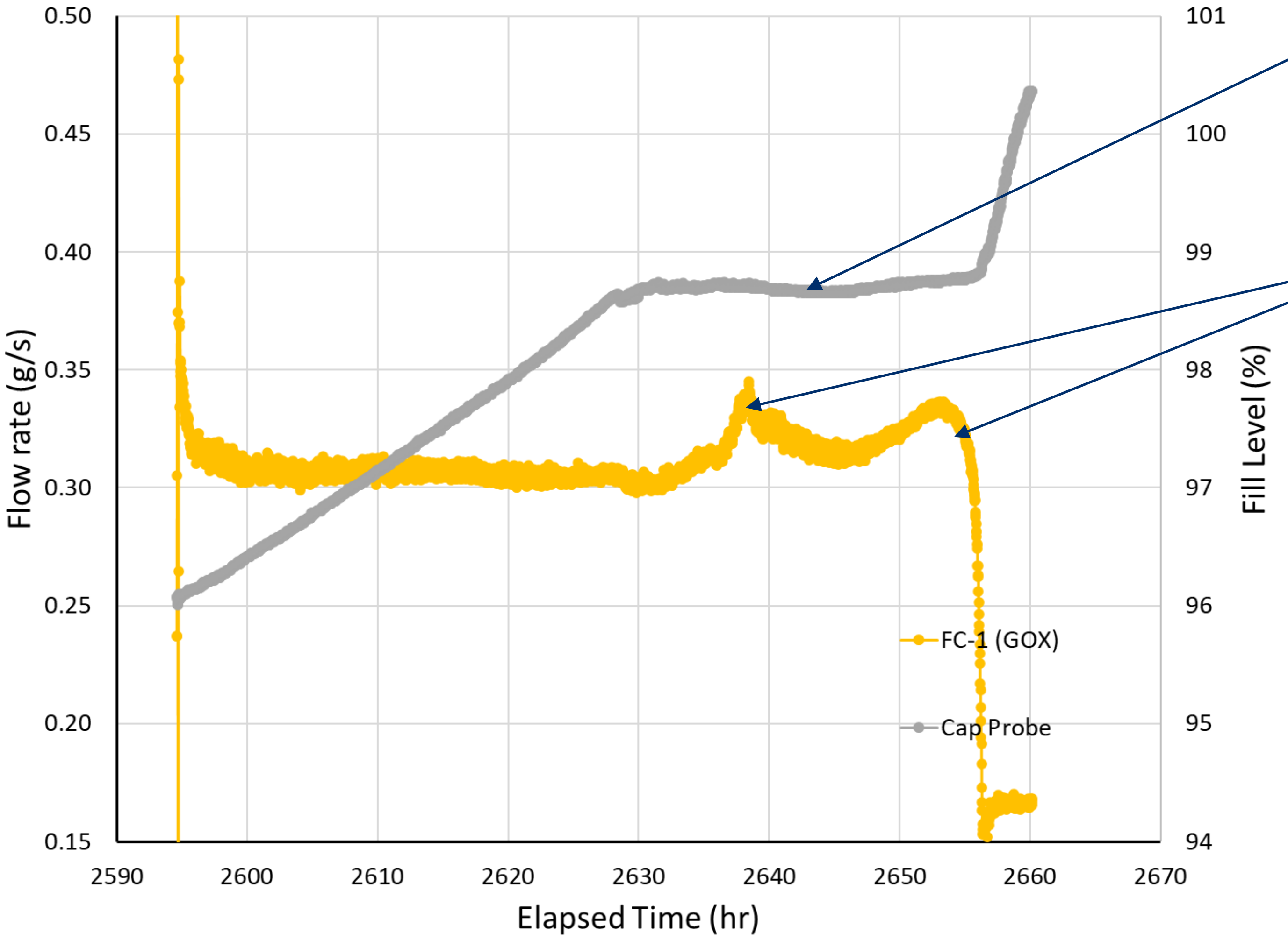
MAX FLOW RATE TESTING



Set tank pressure to 276 kPa and turned off the neon flow loop and tank heaters.

Achieved maximum liquefaction rate of 0.434 g/s (1.56 kg/hr) average over 48 hours.

MAX FILL LEVEL TESTING



Part where cap probe didn’t increase but flow was certainly coming in (and nothing going out).

Interesting events within the test flow. Second spike also seen in temperatures.

Wet/dry sensors indicated wet at the end of testing up to LL19 (95% full). LL19 was marginally wet at beginning of test.

Testing showed that fill level greater than 95% achieved prior to decreasing.

Probably due to design with inlet manifold around fill port on tank.

CONCLUSIONS

- Successful demonstration of oxygen liquefaction in a scalable lander tank and relevant lunar environments.
- Demonstration of liquefaction completed with successful filling to > 95% full without slowdown in liquefaction rate and maximum liquefaction rate of 1.56 kg/hr.
- Demonstrated benefits of liquefaction at higher pressures increases liquefaction rate by 17% between 137 kPa and 275 kPa.
    - Results show cryocooler efficiency (~12% change) is stronger influence than change in enthalpy (4% change) in effect of liquefaction pressure/temperature.
- Transients due to GOX Mass Flow Rate and Cryocooler Heat Removal were significantly more impactful than transients due to Environmental Temperature (factor of 4 lower pressurization rates).
- Used steady-state results to predict transient pressurization rates within 10%.
- Fill level not important in predicting liquefaction rates:
    - Changed pressurization rates slightly in transient tests.
    - Able to fill tank up to > 98% full before liquefaction rate started to decrease.
    - Cryocooler flow inlet manifold around tank vent line.
    - Pressurization rate very similar, depressurization rate increase by factor of 4 at high fill level.

REFERENCES

[1] Polsgrove T, Thomas H D, Stephens W and Rucker M A, "Mars Ascent Vehicle Design for Human Exploration," in AIAA-2015-4416, 2015.

[2] Metzger P T, "Space development and space science together, an historic opportunity.," Space Policy, vol. 37, pp. 77-91, 2016.

[3] Hoffman J A, Hecht M H, Rapp D, Hartvigsen J J, SooHoo J G, Aboobaker A M, McClean J B, Liu A M, Hinterman E D, Nasr M, Hariharan S, Horn K J, Meyen F E, Okkels H, Steen P, Elangovan S, Graves C R, Khopkar P, Madsen M B, Voecks G E, Smith P H, Skafte T L, Araghi K R and Eisenman D J, "Mars Oxygen ISRU Experiment (MOXIE) - Preparing for hunan Mars exploration," Science, vol. 8, no. 35, 2022.

[4] Valenzuela J G, "Cryogenic In-Situ Liquefaction for Landers: "Brassboard" Liquefaction Test Series," NASA TM-20210010564, Huntsville, AL, 2021.

[5] Hartwig J, Johnson W, Bamberger H, Meyer M, Wendell J, Mullins J, Robinson R and Arnett L, "NASA Glenn Research Center Creek Road Cryogenic Complex: Testing between 2005-2019," Cryogenics, vol. 106, p. 103038, 2020.

[6] Chan H M, "Novel Fiber Optic Sensing Arrays with Enhanced Sensitivity in Cryogenic Temperatures, NASA TM-20205009645," Armstrong Flight Research Center, Edwards, CA, August 2021.

[7] Colozza A and Jakupca I, "Thermal System Sizing Comparison of a PEM and Solid Oxide Fuel Cell Systems on Mars," NASA TM-2019-220019, 2019.

QUESTIONS?