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

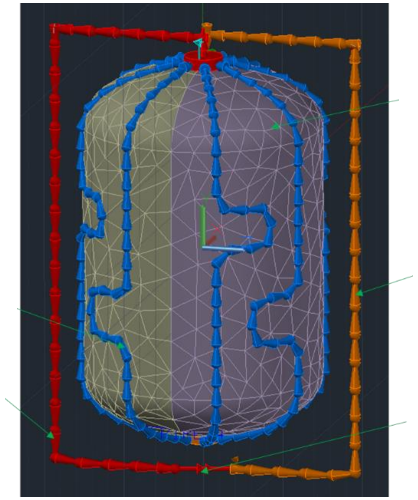
- Design, build, and test a prototypical lander tank with a liquefaction system capable of incorporating prototype flight components as they are developed.
- Demonstrate liquefaction processes in a relevant environment.
- Provide data for validation of two-phase cryogenic fluid models in development.

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 (Chan - C3Or3C-02)
- Final report to be published as NASA Technical Publication, draft completed
- Modelling of test data in progress (Kashani – C3Or2A-02)
- 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

CRYOFILL LIQUEFACTION TEST PROGRESSION

Completed 2019

Brassboard:

- Liquid nitrogen
- Uses as much existing hardware as possible
  - Tank
  - Other hardware
- Vacuum
- Industrial cryocooler
- Focused on operational variations

TRL 4

Testing Just Completed!!!

Prototype Block 1:

- Liquid oxygen
- New tank/ hardware
- Thermal vacuum
- Industrial cryocooler
- Focused on operational variations
- Changes between nitrogen and oxygen

TRL 5

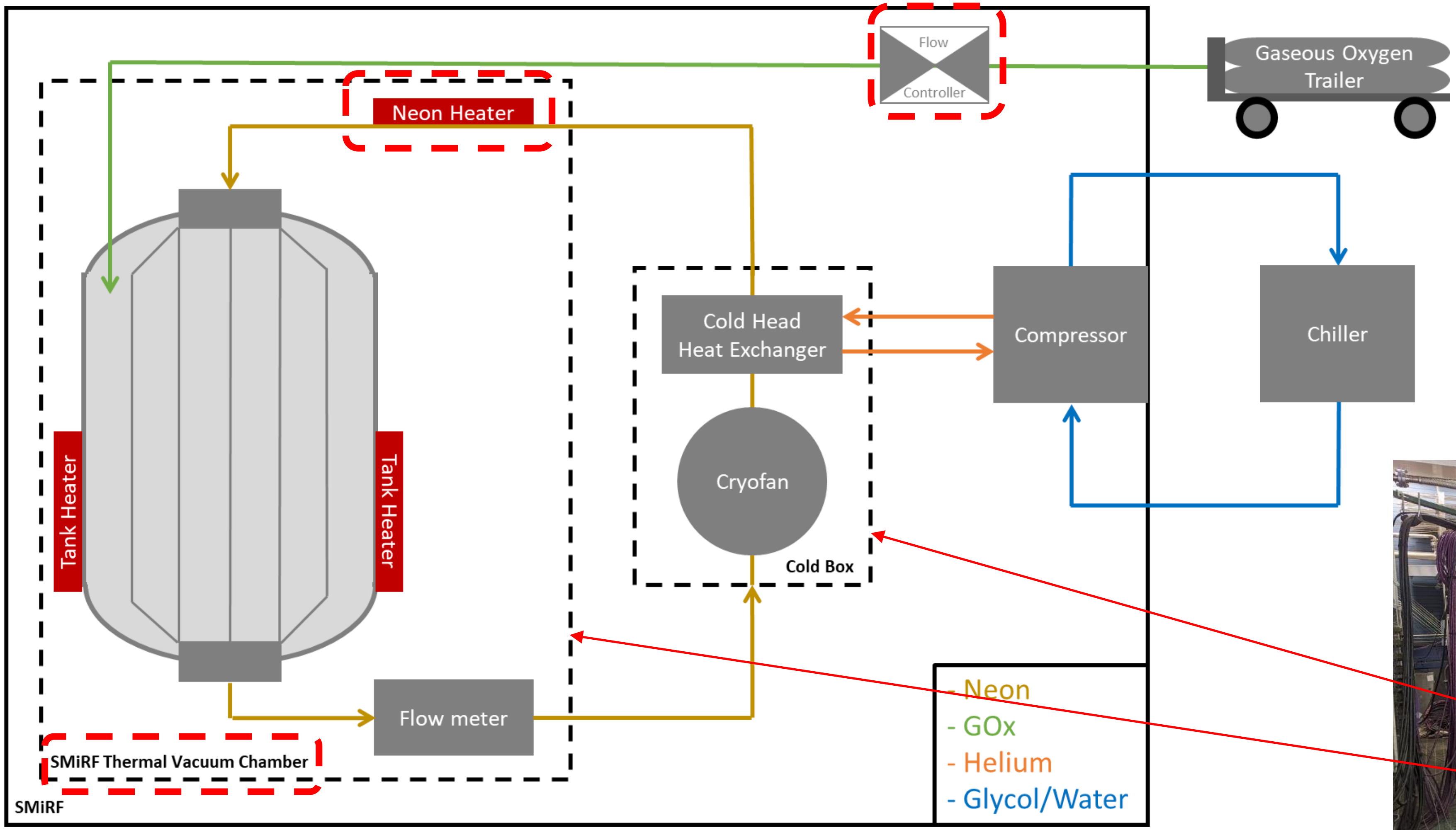
Planned starting 2025

Prototype Block 2:

- Liquid oxygen
- Block 1 hardware
- Thermal vacuum
- Incorporate prototype flight cryocooler (150 W at 90 K)
- Aspects of infusion customer's Concept of Operations
- Verify operability for ISRU

TRL 6

PROTOTYPE TEST SCHEMATIC



Test setup using industrial integrated cryocooler system

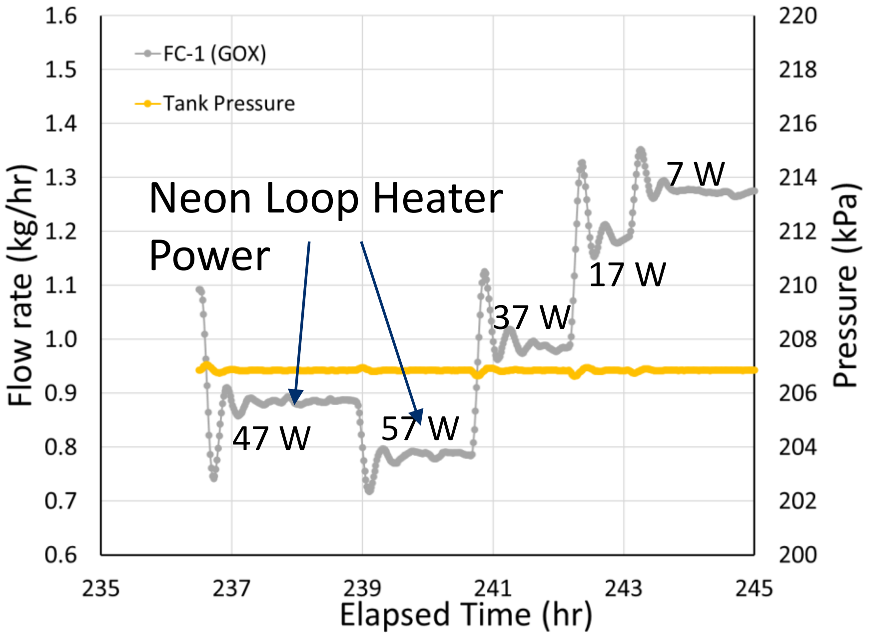
- Plan to incorporate flight-like cryocooler system in future.
- For transient operations, varied neon heater power, oxygen flow rate, and thermal vacuum environment.

PROTOTYPE BLOCK 1 TEST OVERVIEW

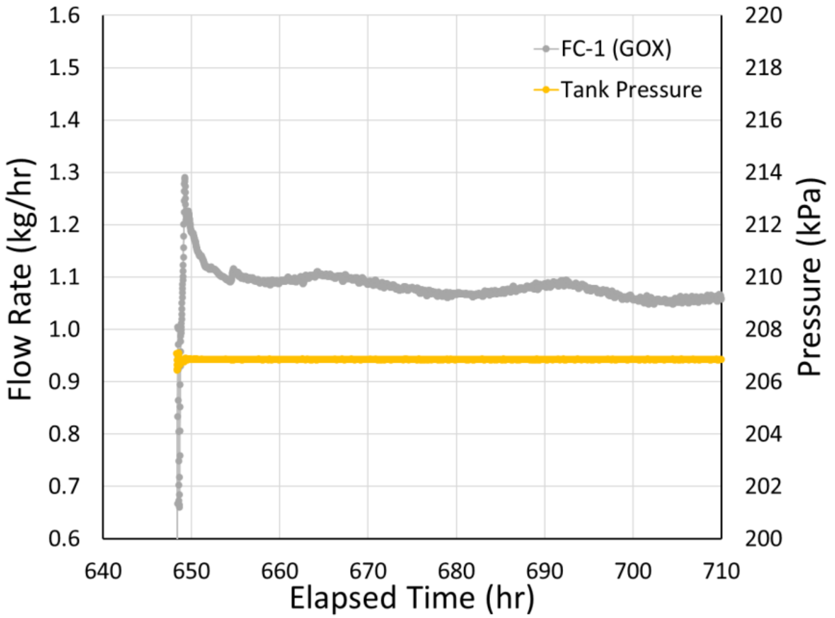
- Nitrogen checkout testing completed
  - Grotenrath - C4Or1B-06
- Three Phases of oxygen testing:
  1. Evaluation of Nominal Performance Determination
  2. Constant Liquefaction Operations
  3. Transient Liquefaction Operations

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

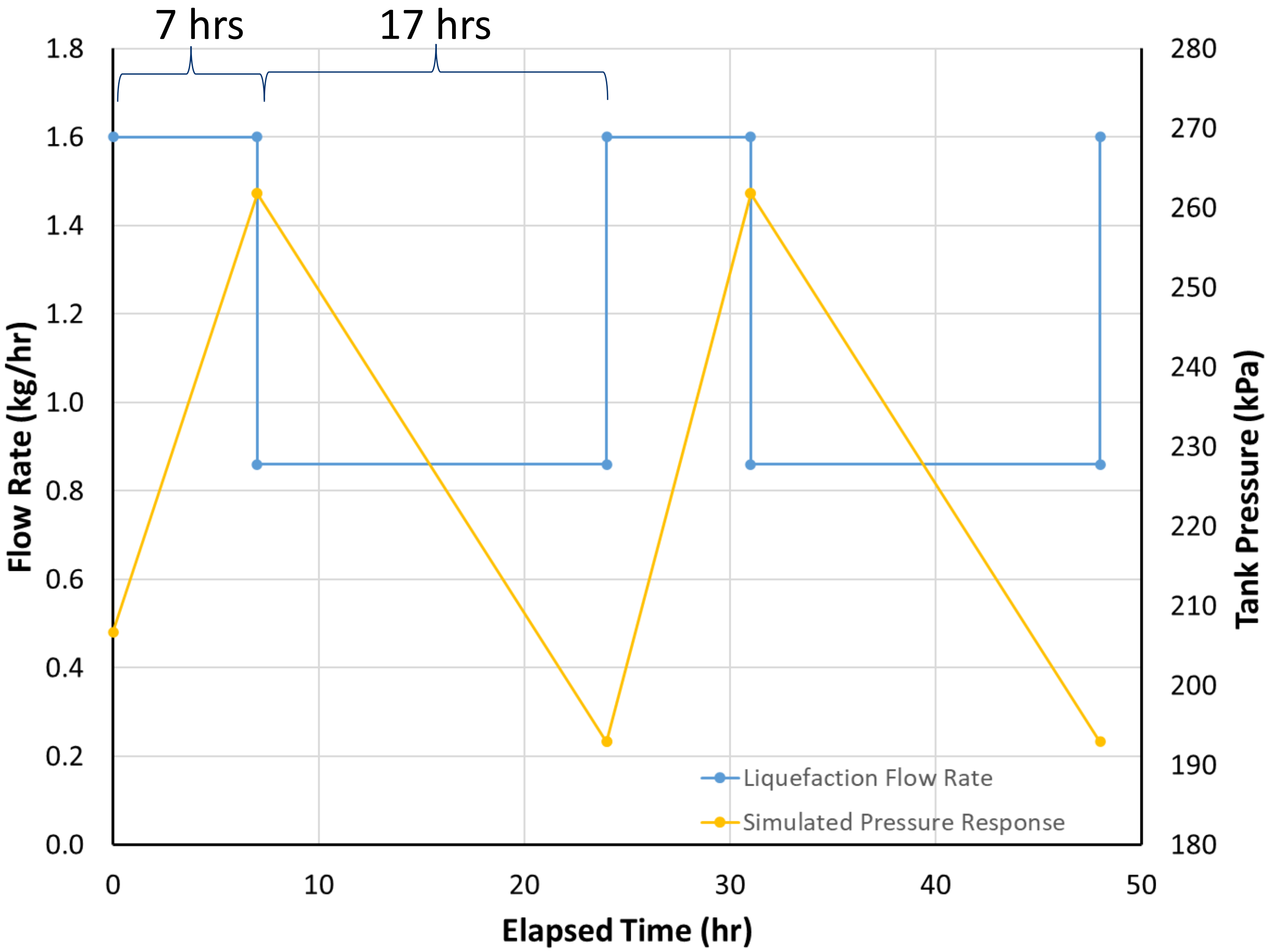
Characterizing system response to cryocooler power levels

Constant liquefaction with pressure set to 30 psia

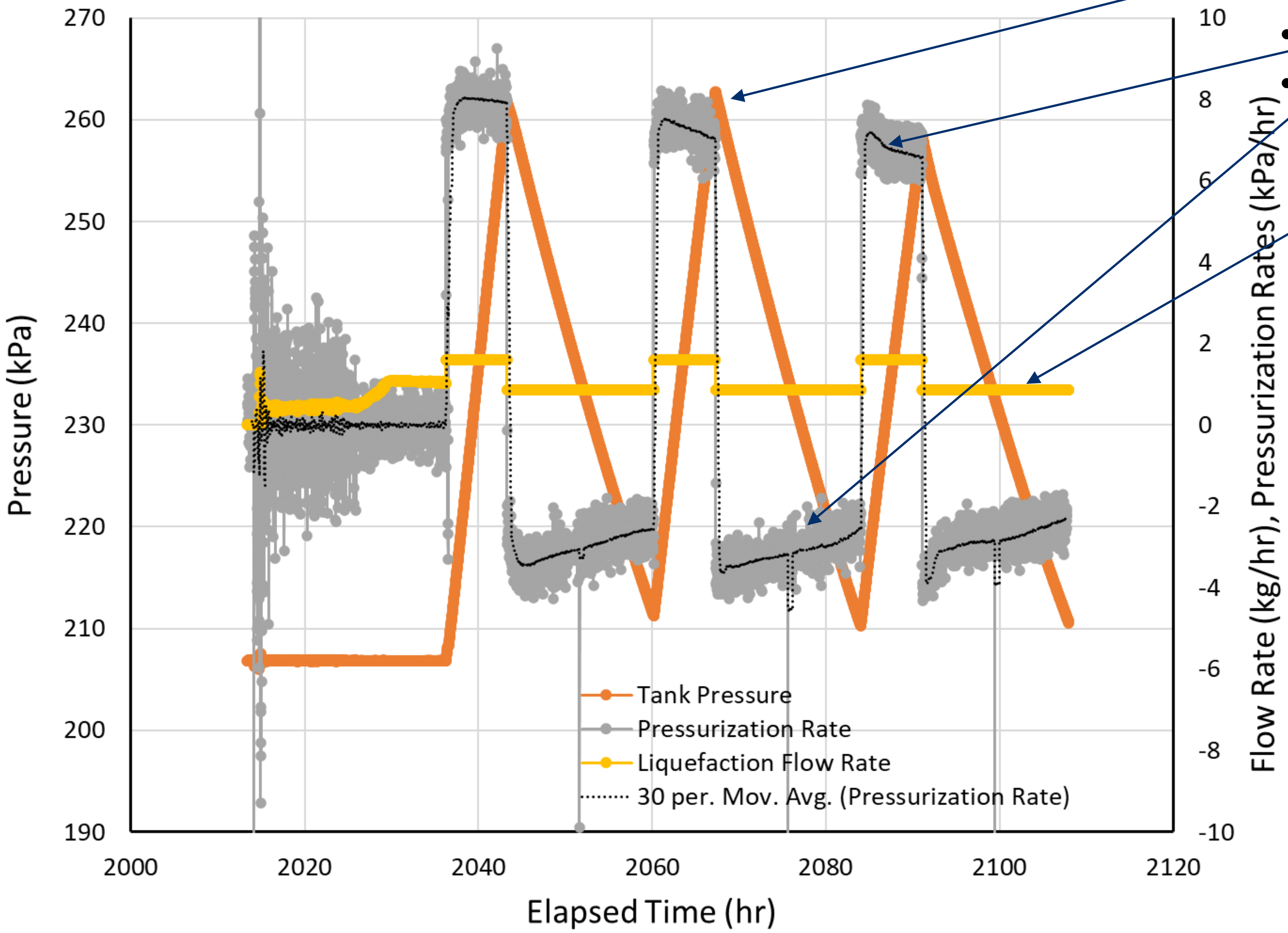
TYPICAL TRANSIENT OPERATIONS

Transient operations set up to allow for one portion to be completed during the day (test operators present) and the inverse completed overnight (no operators present).

The cycles were repeated at least three times over a multi-day period of time.



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%

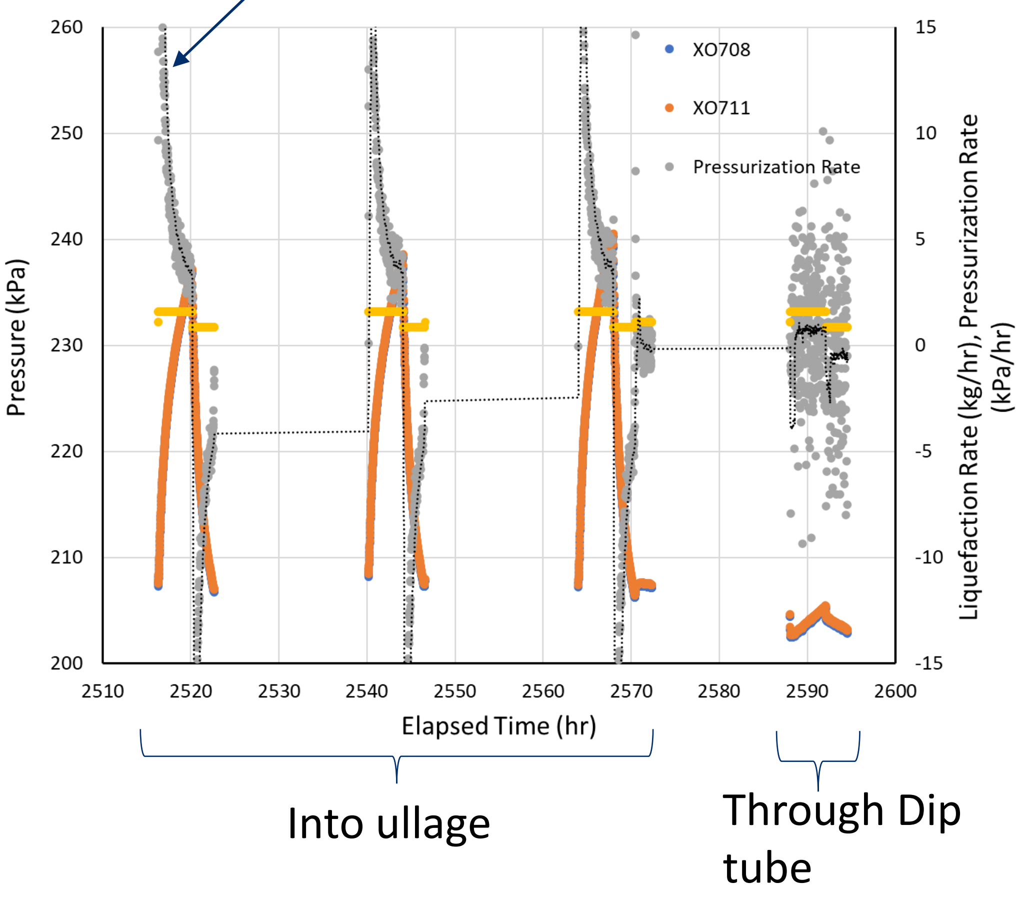
Cycle oxygen flow rate between 1.6 kg/hr and 0.9 kg/hr to simulate oxygen production and pressure swings with constant cryocooler settings.

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

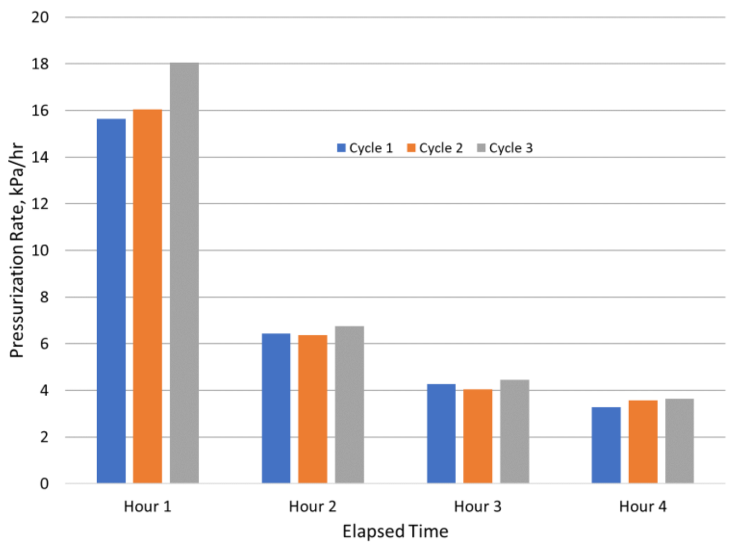


Average Pressurization rates:

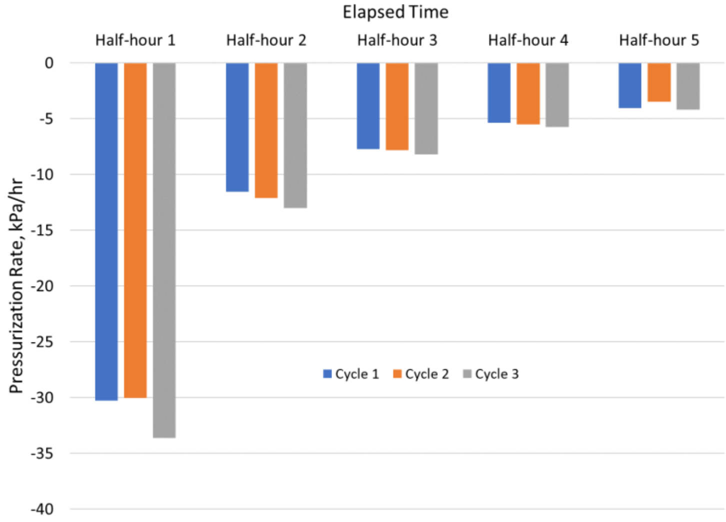
- 7.86 kPa/hr
  (7.2 at low fill)
- - 12.5 kPa/hr
  (-3.0 at low fill)
- Repeatable within 6%

Average Pressurization Rates with Dip Tube:

- 0.68 kPa/hr
- - 0.71 kPa/hr

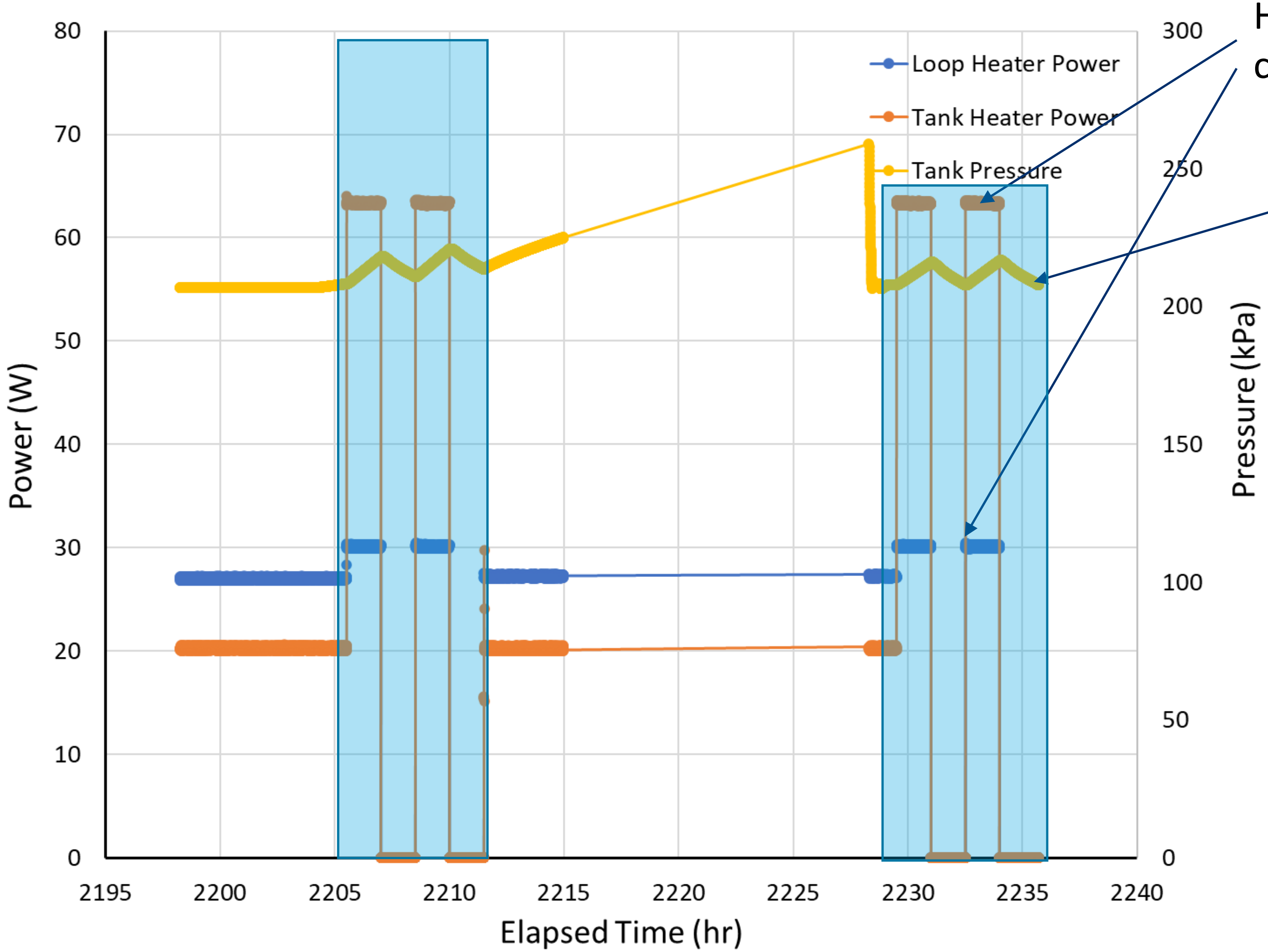


Pressurization rates (top) and depressurization rates (bottom) over defined periods within test data shown on left.



Fill level greater than 90 percent

CRYOCOOLER POWER TRANSIENTS (PHASE 3)



Heater variations to simulate cryocooler power changes

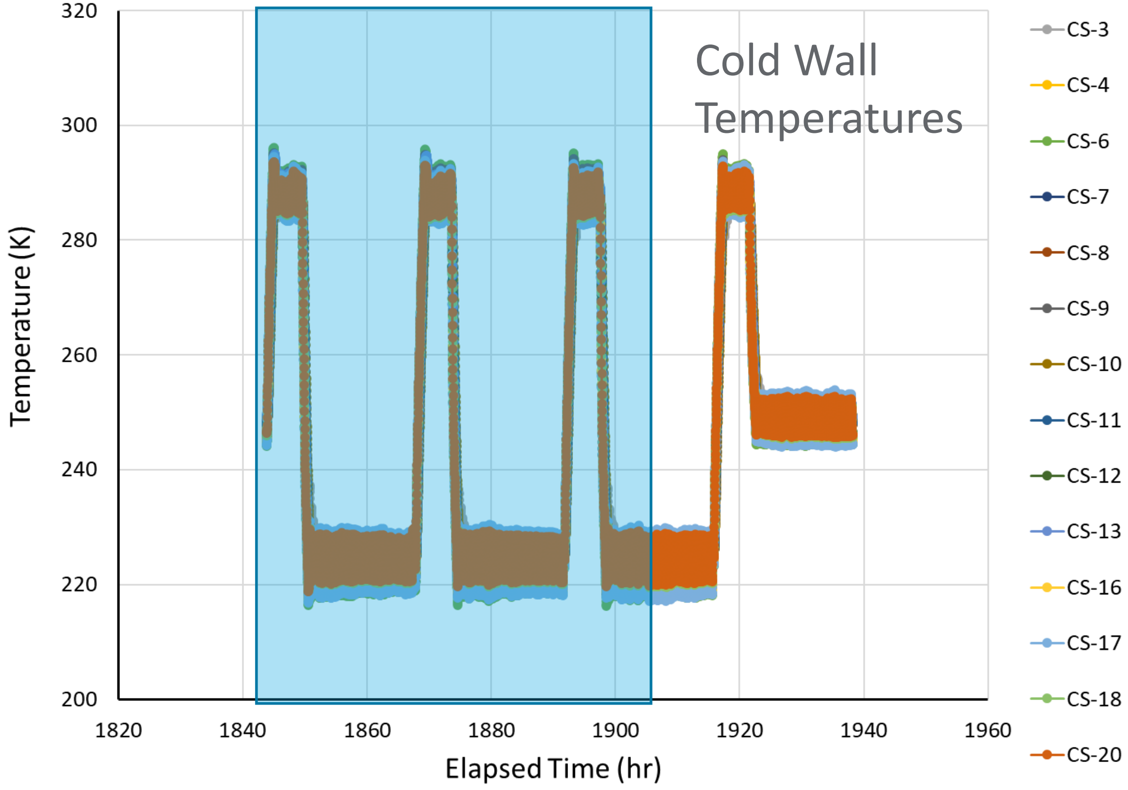
Pressure Response

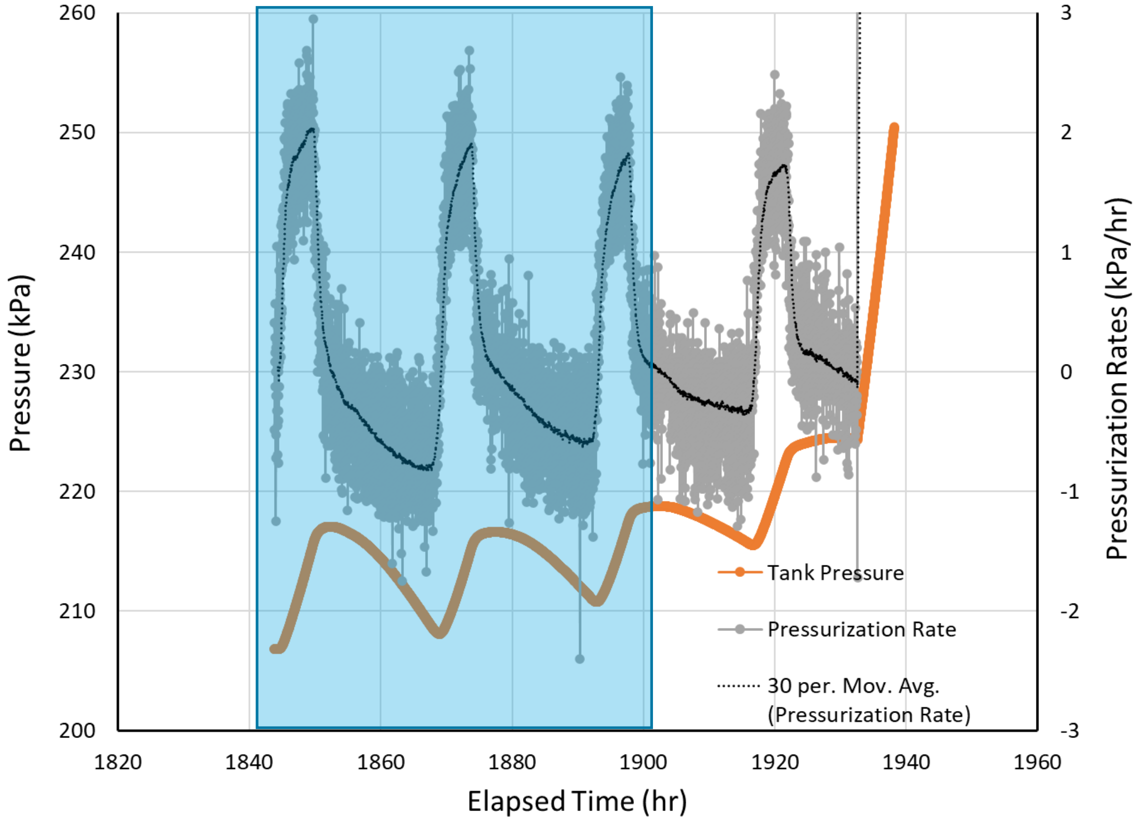
- Avg Pressurization Rate: 6.0 kPa/hr
- Avg Depressurization Rate: - 5.2 kPa/hr
- All repeatable within 7% over the four cycles

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

CONCLUSIONS

- 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.
  - Pressurization rate very similar, depressurization rate increase by factor of 4 at high fill level.
- At high fill levels, the pressurization rate was about 10x higher through ullage insertion than dip tube insertion.
  - Dip tube could be preferable during operational transient activities to decrease the pressurization rates, especially at higher fill levels.

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QUESTIONS?