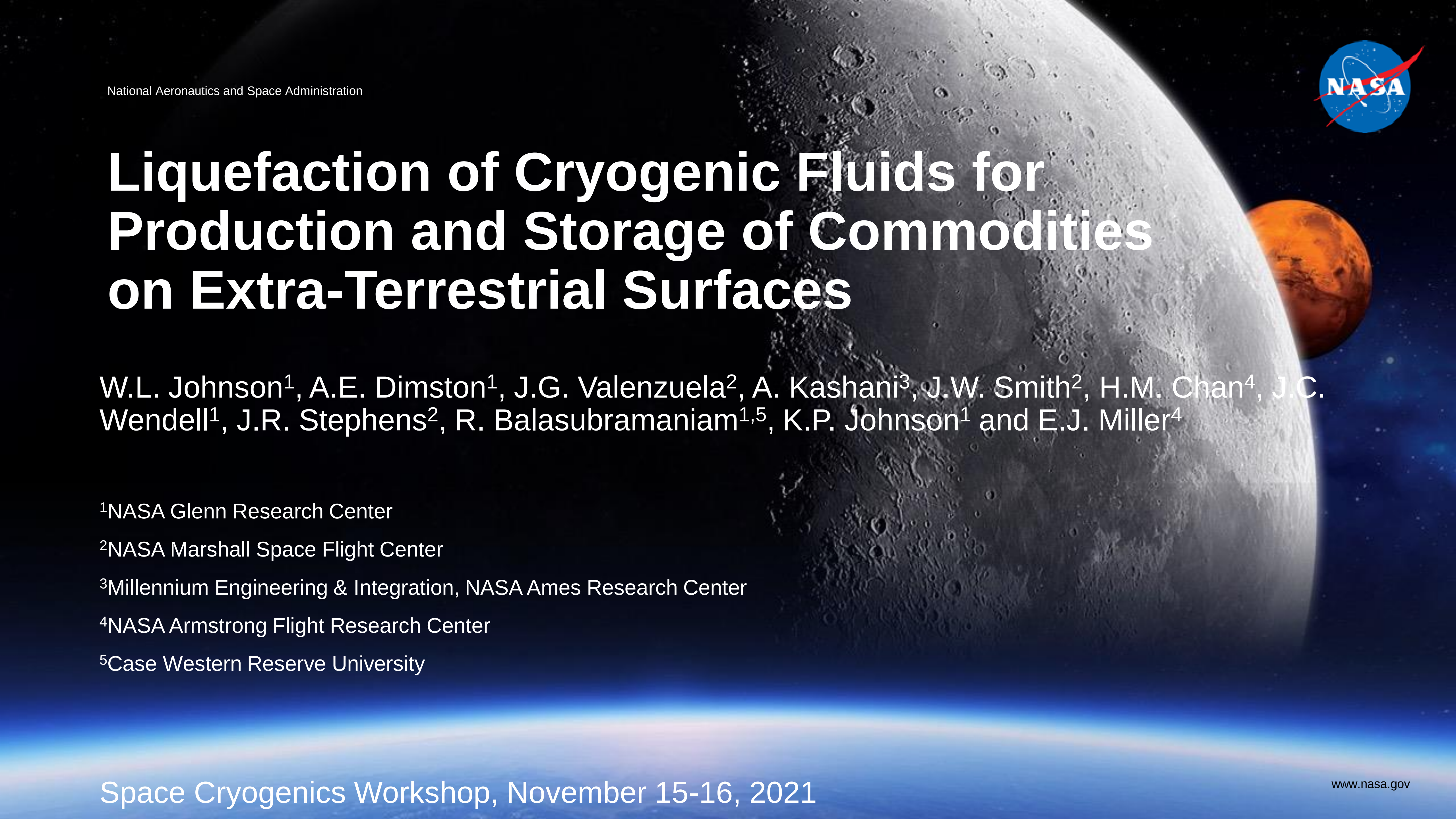

Liquefaction of Cryogenic Fluids for Production and Storage of Commodities on Extra-Terrestrial Surfaces

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Space Cryogenics Workshop, November 15-16, 2021

Cryogenic Fluid In-Situ Liquefaction for Landers (CryoFILL)

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 Sustainable Lunar Architecture
- In-Situ Resource Utilization (ISRU)

Objectives

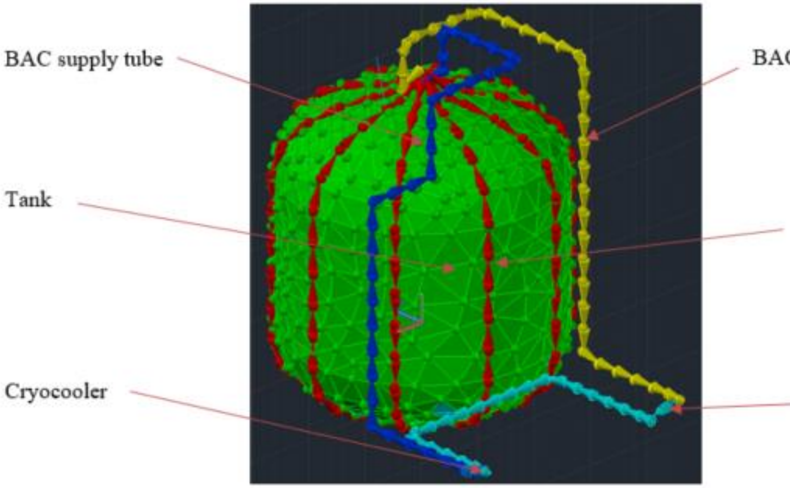
- Design, build, and test a prototypical lander tank with liquefaction system capable of incorporating prototype flight components as they are developed.
- Demonstrate liquefaction processes in a relevant environment.
- Develop and demonstrate lightweight cryogenic insulation systems for Mars Environments.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

Key Performance Parameters

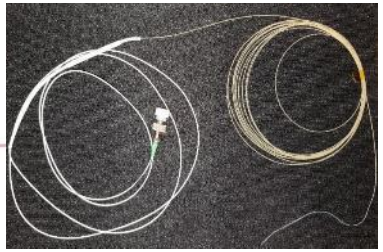
- Liquefaction of average of 1.1 kg/hr oxygen (input at 300 K, 1 bar)
    - Tank sized at nominally half surface area of lander tank
- Assess hardware in two types of transient cases
- Demonstrate fill level sensitivity of oxygen liquefaction using tube-on-tank cryocooler integration

Prototype Test Article being instrumented

Prototype Test Article with MLI



FOSS Sensors for Prototype



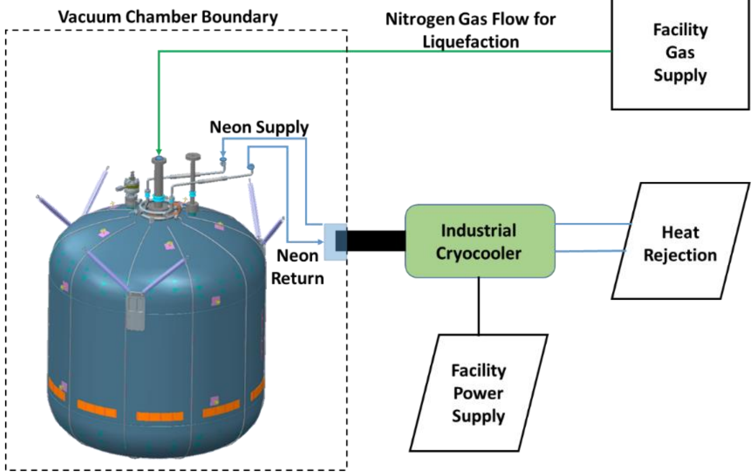
CryoFILL Philosophy

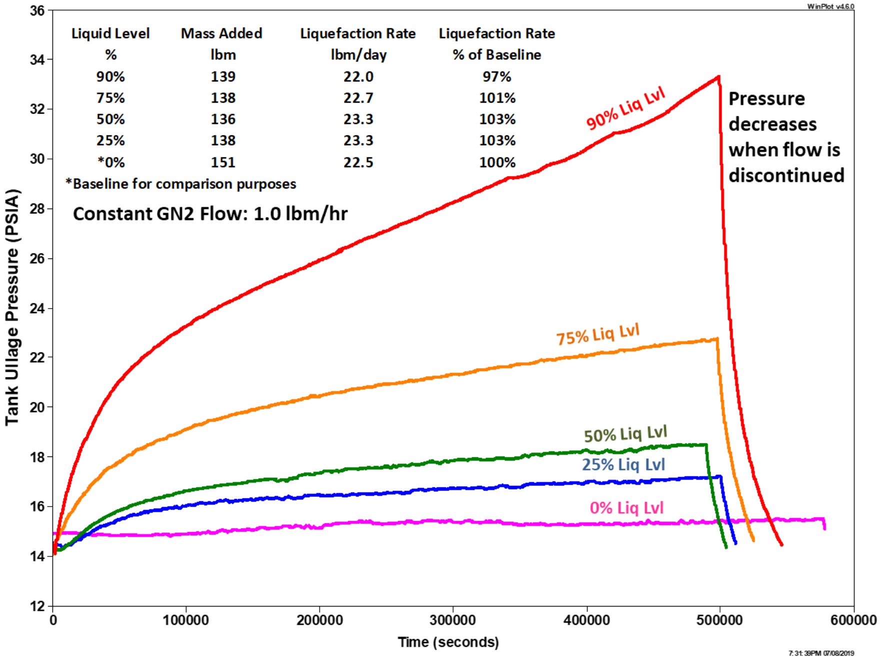
CryoFILL intentionally picked oxygen for liquefaction development first:

- Oxygen used as oxidizer with both hydrogen and methane
- Oxygen always makes up a large majority of the propellant mass:
  - 75% + for LOX/LCH4
  - 85% + for LOX/LH2
  - Thus, will provide the biggest initial bang for the mass carried
- NASA's Evolvable Mars Campaign (2016-2018 time frame) architecture analysis suggested oxygen only production as an initial first step for ISRU (ref 1)
  - Recent discussions elsewhere have indicated same possibility on the moon.
- Flight cryocooler development already underway for 90 K and 20 K
  - 90 K unit to be common for LOX and Methane (112 K)
  - 90 K cryocoolers much more energy efficient than 20 K cryocoolers
- Oxygen has many other uses: Life support, EVA, etc
- Hydrogen liquefaction system will be much more energy intense
  - 0.3 kg/hr hydrogen requires 10 – 30 kW input power (dependent upon environmental assumptions, para to ortho conversion approach, and cryocooler configuration)
  - 2.2 kg/hr oxygen requires 1.2 - 4 kW input power (dependent upon environmental assumptions and cryocooler configuration)

Brassboard Testing

- CPST Zero Boil-Off Propellant Tank (Ref 3)
  - Stainless Steel
  - Hangs from six low conductivity struts
  - Tube-On-Tank Heat Exchanger, 5 loops
  - Outfitted with 72 layers of MLI
- Gifford-McMahon 90K cryocooler
  - Custom build heat exchanger to integrate cryocooler cold head to Tube-On-Tank Heat Exchanger
  - Cryofan to circulate working fluid (neon) through the refrigeration loop.
- GN2 used as a surrogate for GOX
  - Facility supplied at ~ 292K
- Constant flowrate set via Mass Flow Controller
- Tested at high vacuum: ~4.0E-6 Torr
- Results published in NASA TM-20210010564 (Ref 4)
  - Available at https://ntrs.nasa.gov/search





Liquid Level %	Mass Added lbm	Liquefaction Rate lbm/day	Liquefaction Rate % of Baseline
90%	139	22.0	97%
75%	138	22.7	101%
50%	136	23.3	103%
25%	138	23.3	103%
*0%	151	22.5	100%

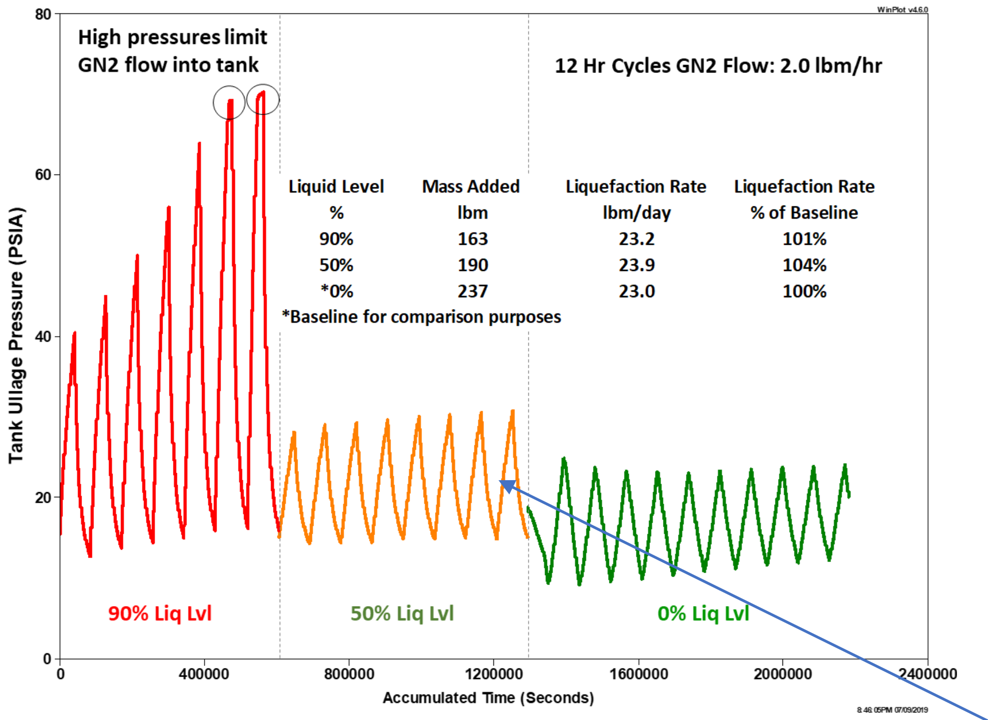
*Baseline for comparison purposes

Constant GN2 Flow: 1.0 lbm/hr

Pressure decreases when flow is discontinued

Liquefaction at Various Liquid Levels
Non-Constant GN2 Flowrate (12 hr cycles)

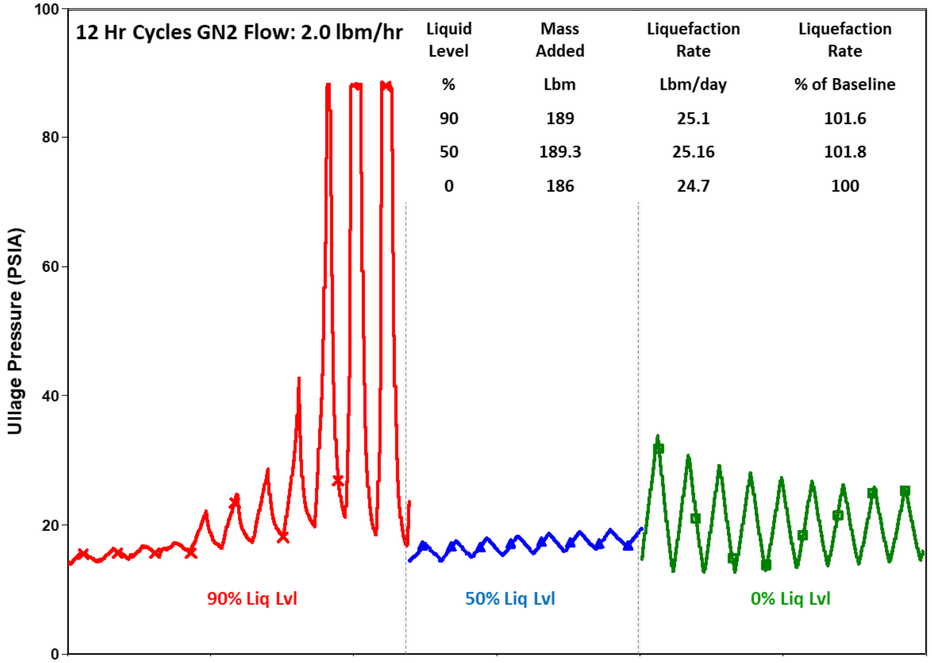
Injected Into Tank Ullage Space



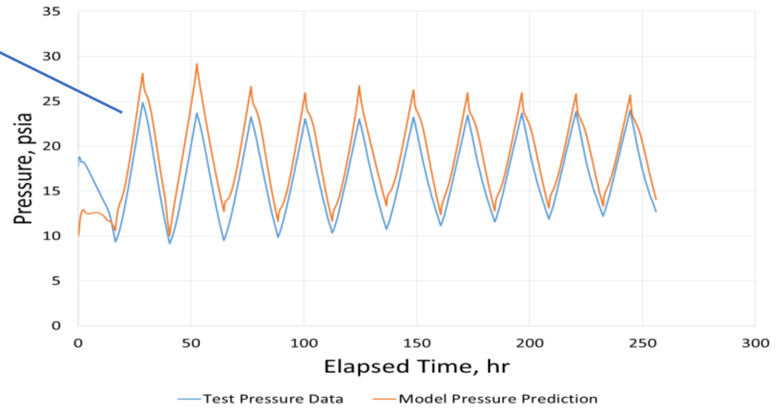
Liquid Level	Mass Added	Liquefaction Rate	Liquefaction Rate
%	lbm	lbm/day	% of Baseline
90%	163	23.2	101%
50%	190	23.9	104%
*0%	237	23.0	100%

*Baseline for comparison purposes

Injected Into Tank Liquid Space

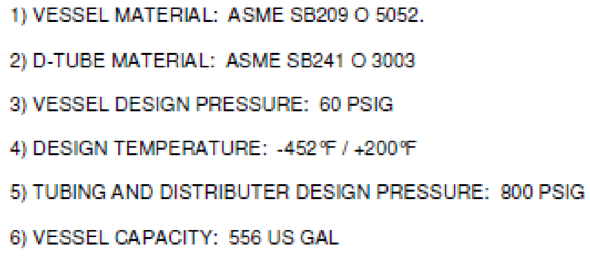


Liquid Level	Mass Added	Liquefaction Rate	Liquefaction Rate
%	Lbm	Lbm/day	% of Baseline
90	189	25.1	101.6
50	189.3	25.16	101.8
0	186	24.7	100



Transient flow test pressure and Thermal Desktop model predictions for Brassboard test, 50% full, 12 hours double flow, 12 hours no flow

Description of Prototype Test Hardware



1) VESSEL MATERIAL: ASME SB209 O 5052.

2) D-TUBE MATERIAL: ASME SB241 O 3003

3) VESSEL DESIGN PRESSURE: 60 PSIG

4) DESIGN TEMPERATURE: -452°F / +200°F

5) TUBING AND DISTRIBUTER DESIGN PRESSURE: 800 PSIG

6) VESSEL CAPACITY: 556 US GAL

Prototype Test Tank before and after insulation installation.

Liquefy Oxygen at 1.1 kg/hr approximately half scale Lunar or Martian architectures
(~ 10 mton/yr)

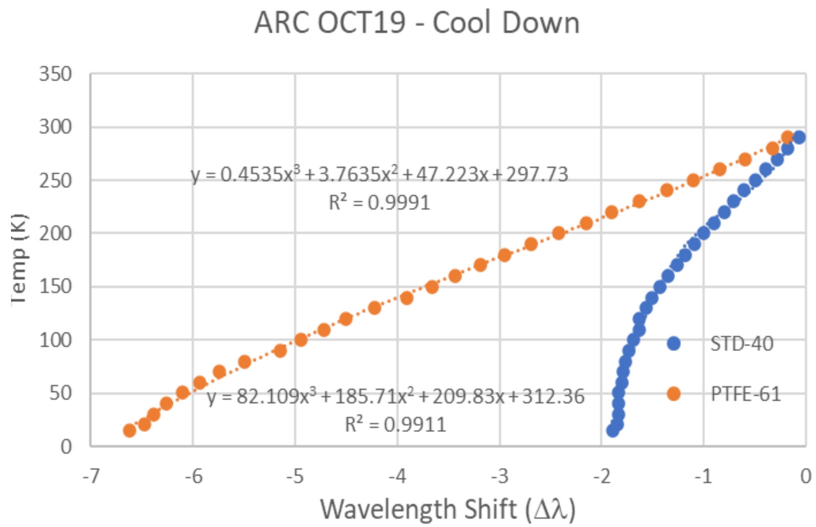
Industrial Cryocooler

Thermal vacuum testing planned for Spring 2022 at GRC

Prototype Generic Test Matrix

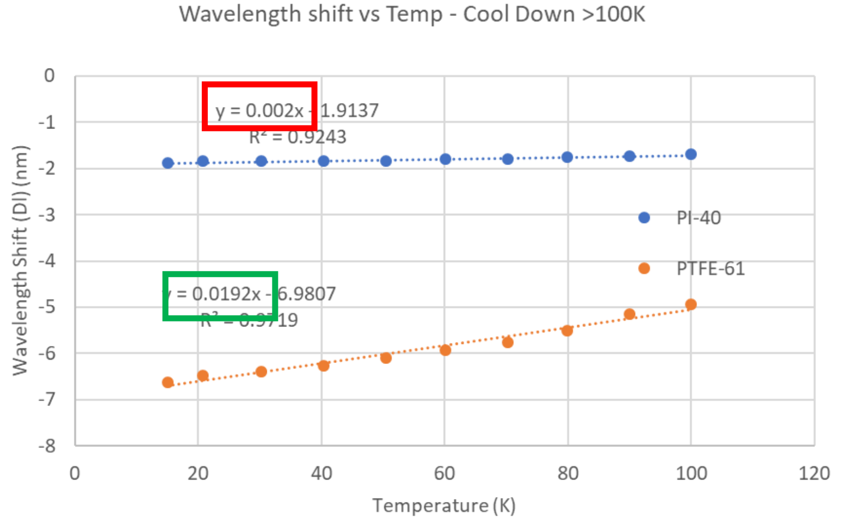
Variables	**Relative Importance**	**Min Value**	**Nominal**	**Max Value**
Fill Level (%)	High	5%		90%
Oxygen Flow Rate (kg/hr)	High	0.5	1.1	2.2
Cryocooler Power Levels (watt)	Med - Primary	0	120 W + Parasitic heat load	200
Environmental Temp. (K)	Med - Primary	150	250	350
Tank Pressure (psia)	Med - Secondary	18	25	45
GOX Injection method	Med-Secondary	Ullage	N/A	Diptube
Neon Loop Flow rate (g/sec)	Med-Secondary	TBD Low	16	TBD High
Oxygen contaminates (%)	Low	99.4%	99.5%	99.95%

Cryogenic Applications of Fiber Optic Sensor System



AFRC has been strategically advancing the FOSS temperature measurement:

1. Use of PTFE sleeve increases wavelength shift in total (see plot to left) and sensitivity at low temperatures (see bottom plot, 20x more sensitivity > 100 K).
2. Understanding the dispersion of the temperatures helps to understand and improve the uncertainty in the sensor.
3. Calibration testing performed at ARC gives more thorough temperature sweep than testing in fluid.
4. Update avionics for difference in cryo temp needs.

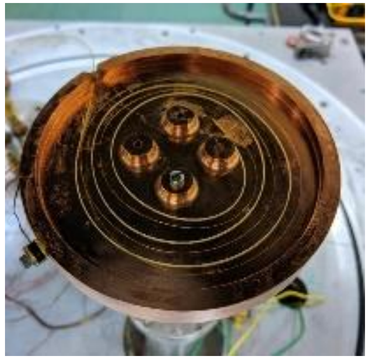


For PTFE-fiber (new):

PTFE	Δλ (nm)	Temp(K)
Average	-5.292	88.68
Avg+std	-5.224	91.66
Diff	0.068	2.99

For PI-fiber (original):

PI	Δλ (nm)	Temp(K)
Average	-1.83	47.09
Avg+std	-1.896	22.48
Diff	0.066	24.61



Ref 5, NASA TM-20205009645

MarVACS: NASA Partnership with Industry

NASA

- Requirements
- Risk Reduction
- Design Studies (Ref 2)

Quest Thermal Group

SBIR

High performing technology through MEMLI

- Suspension of MLI and Shell through polymer posts

Similar product line flown on NASA Green Propellant Mission

Lockheed Martin

Procurement

High chance of successful construction at the cost of performance

- MLI blanket with a structurally supported vacuum shell

A similar design flew on Gravity Probe-B and Wide Field Infrared Survey Explorer (WISE)

Quest MarVACS Concept

- Use Quest Thermal Group’s discrete micro-molded insulation spacers to provide structural support to the vacuum shell.
  - Vacuum shell, at 0.016” thick, required unique fabrication methods, both forming and welding.
- NASA provided structural analysis and testing support.
- Performed life testing for erosion via sandblasting and regolith blasting.
- Thermal Demonstration on a 400-liter tank
  - Heat load not as low as predicted, but better than required.
  - Didn’t fully eliminate leaks in welds, used attached vacuum pump to shell.

Ref 6

Lockheed Martin MarVACS Concept

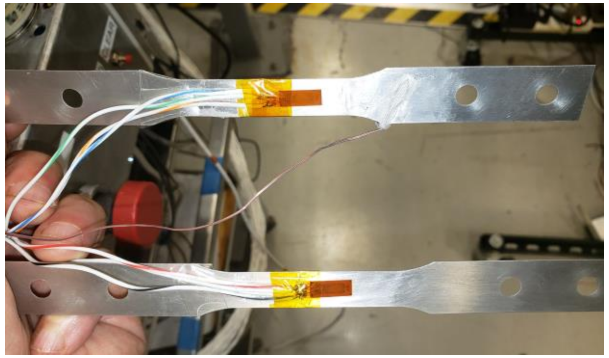
- Flight cryogenic storage systems have historically utilized hard metallic vacuum shells driven by external 1 atm pressure during ground servicing
- The LM MarVACS concept extends these designs with similar but lower weight approach taking advantage of lower external pressure
  - NASA Trade studies drove Mars external pressure requirement
  - Design for a large approach being demonstrated on smaller ZBO ground test unit (from Ref 3)
- Completed design reviews, manufacturing drawings in development
  - Mass competitive with Quest solution

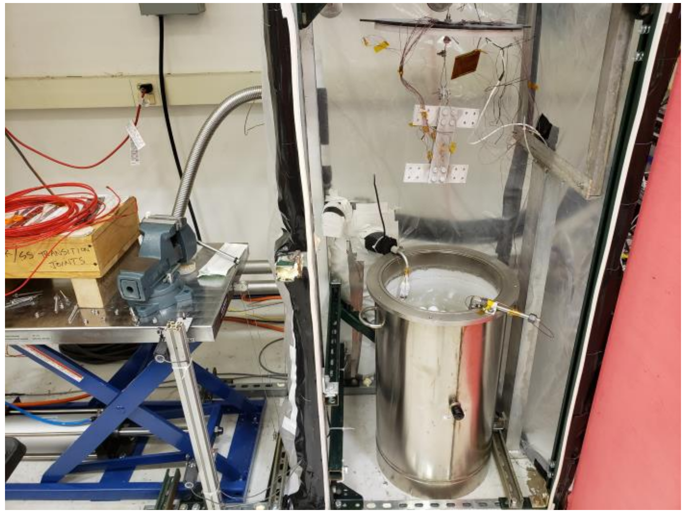
Lockheed ZBO MarVACS concept (ref 7)
(liquid Oxygen and Methane)

Risks and NASA Internal Risk Reduction

Several concerns/risks identified internally:

- Sustained impact due to wind/dust storms.
  - Any standards for dust impact/erosion for beach/desert locations on Earth?
- Impact due to orbital debris falling from the sky.
  - Analysis of statistical data available suggested that this was not worth concern now.
- Failure of welds/epoxy seams due to repeated thermal cycling (i.e. day/night)
  - Vacuum pump development of interest to mitigate failure scenarios.





Conclusions

- A plan to demonstrate the capability to liquefy propellants in a manner appropriate for near term use is defined.
  - Initial testing with liquid nitrogen has answered key questions in the performance of these system types.
    - TM-20210010564 available at https://ntrs.nasa.gov/search
  - Follow-on oxygen testing will be performed starting early next calendar year.
  - Tracking transient system performance will be key to being able to understand integrated system performance.
- Multiple lightweight vacuum jacketed systems for soft vacuum insulation applications have made significant progress in maturation.

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Questions