Liquid Nitrogen Testing of ISRU Liquefaction Methods in Unsteady Applications

Space Cryogenics Workshop

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ISRU Liquefaction Brassboard Testing

Acknowledgments

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JSC	Banker	Brain	F	NASA
MSFC	Black	Markston	W	Yetispace, Inc.
MSFC	Burtts	Harold	W	Yetispace, Inc.
JSC	Desai	Pooja	S	NASA
MSFC	Harper	Roger	T	ESSCA
GRC	Hauser	Daniel	M	NASA
GRC	Johnson	Wesley	L	NASA
GRC	Plachta	David	W	NASA
MSFC	Reid	Tommy	W	MLSS
MSFC	Rhys	Noah	O	Yetispace, Inc.
JSC	Robison	Inhey		NASA
MSFC	Schoenfeld	Michael	P	NASA
MSFC	Smith	James	W	NASA
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GRC	Wang	Xiao-Yen	J	NASA
MSFC	Webster	Kenneth	L	NASA

ISRU Liquefaction Brassboard Testing
Introduction

Objective(s):

- **Demonstrate the liquefaction and storage of "In-Situ like" propellant via a Tube-On-Tank Heat Exchanger integrated with Active Cooling (cryocooler)**
  - **Verify proof of concept**
  - **Obtain relevant data for model validation**

- **Gather lessons learned from "brassboard" testing which will be applied to future liquefaction system prototype testing, then eventually to an end-to-end demonstration.**

Background:

- **To enable NASA's planned long duration missions, the agency is putting emphasis on reusable cryogenic systems**

- **Such systems will require replenishing of cryogens on-orbit via a cryogenic tanker or refueling depot, and potentially on the lunar or Martian surfaces with the utilization of in-situ resources.**

- **Surface replenishing requires the in-situ production of gaseous oxygen (and hydrogen if on the lunar surface), followed by liquefaction and storage.**

- **Funded by NASA's Advanced Exploration Systems, and managed under the Advanced Cis-Lunar Space Capability Project, the Cryogenic Fluid In-Situ Liquefaction for Landers (CryoFILL) multi center team was formed to develop a liquefaction and storage system that is efficient, reliable and scalable.**

ISRU Liquefaction Brassboard Testing
Introduction

Background (continued):

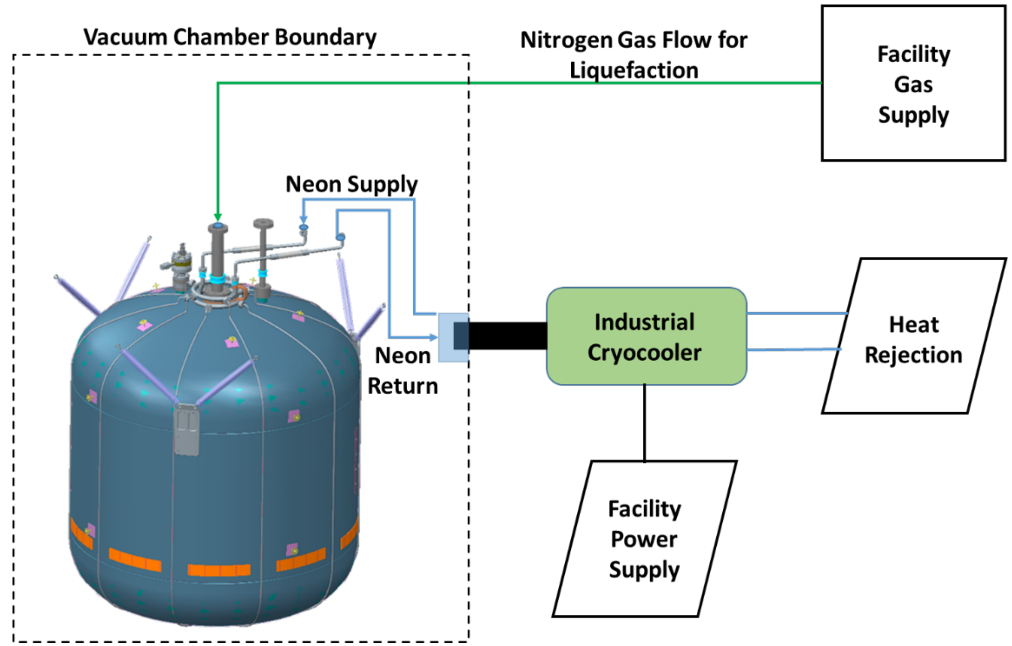
- **The CryoFILL team conducted trade studies on various system level concepts including multiple heat exchanger configurations to be integrated with active cooling (cryocoolers).**
- **When the trades concluded, the team settled on a configuration which includes a Tube-On-Tank Heat Exchanger integrated with Active Cooling**
- ***See W.L. Johnson, D.M. Hauser, B.F. Banker, J.R. Stephens, D.W. Plachta, P.S. Desai, A.M. Swanger and X-Y.J. Wang, "Comparison of Oxygen Liquefaction Methods for Use on the Martian Surface", presented at the 27th Space Cryogenics Workshop, July 2017***
- **Development plan includes:**
  - **Modeling of the liquefaction process**
  - **"Brassboard" Proof of Concept Testing**
    - **Data for model validation**
    - **Gather lessons learned**
  - **Design, build and test of a prototype surface liquefaction and storage system**
  - **Full end-to-end demonstration to include ISRU production, liquefaction, and long term storage**

Focus of today's discussion (bracketing "Brassboard" Proof of Concept Testing, Data for model validation, Gather lessons learned)

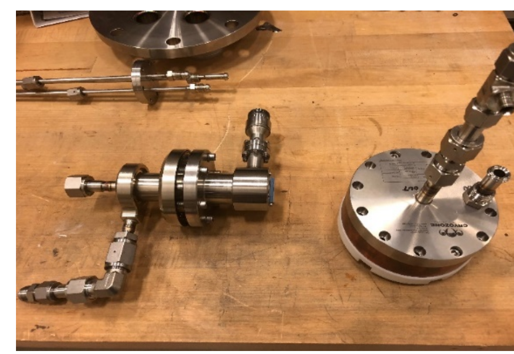
ISRU Liquefaction Brassboard Testing
Hardware and Experimental Setup

- *Glenn Research Center’s Zero Boil-Off Propellant Tank
  - Stainless Steel
  - 630 lbm dry mass
  - 48.5 ft^3 total volume
  - Hangs from six low conductivity struts
  - Tube-On-Tank Heat Exchanger
  - Outfitted with 80 layers of tMLI
- 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

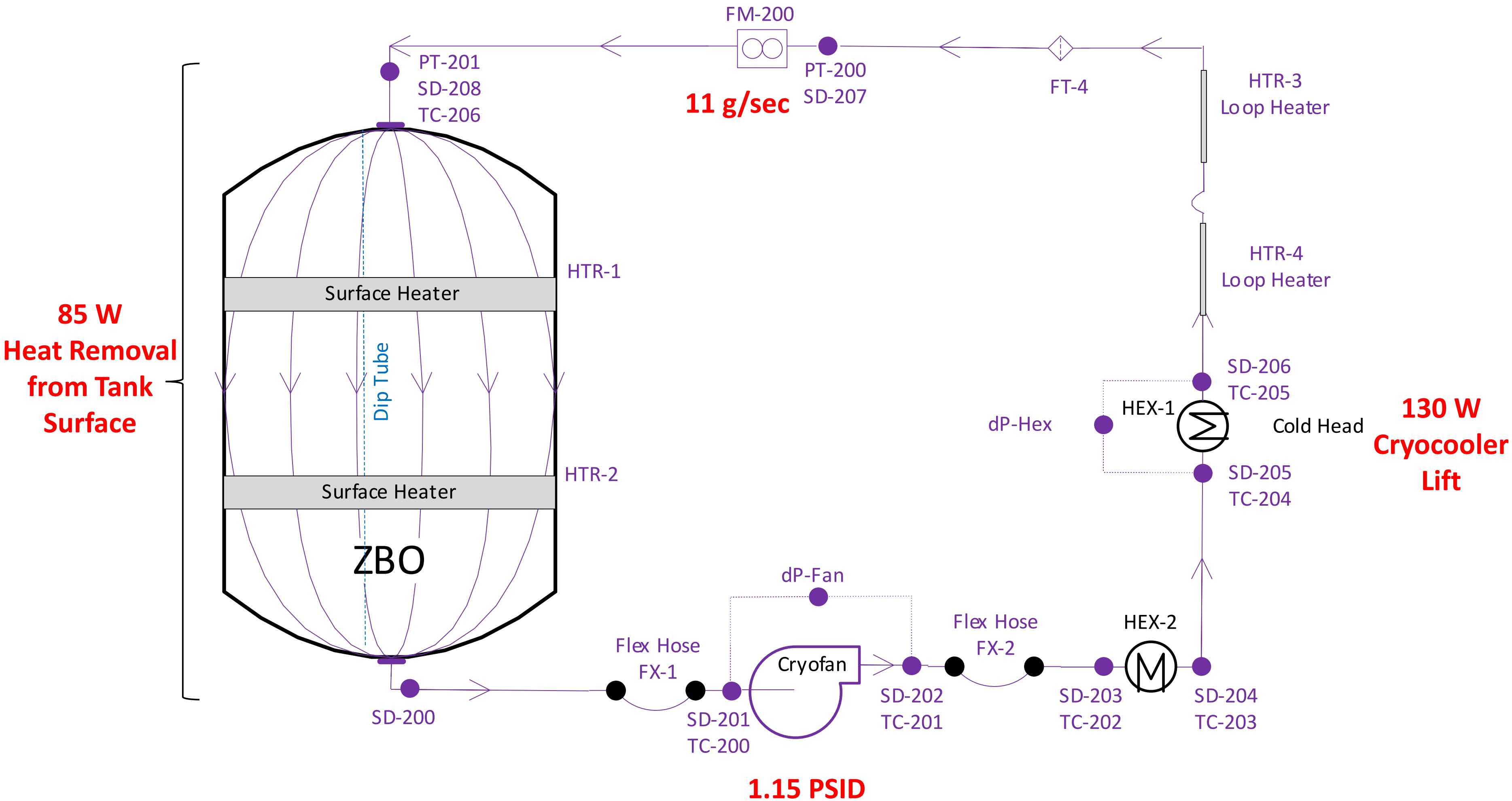
See D.W. Plachta, W.L. Johnson, and J.R. Feller, “Zero Boil-Off System Testing”, presented at the 26th Space Cryogenics Workshop, June 2015




PHPK Cryocooler


CryoZone Cryofan (left) and cold head Heat Exchanger (right)

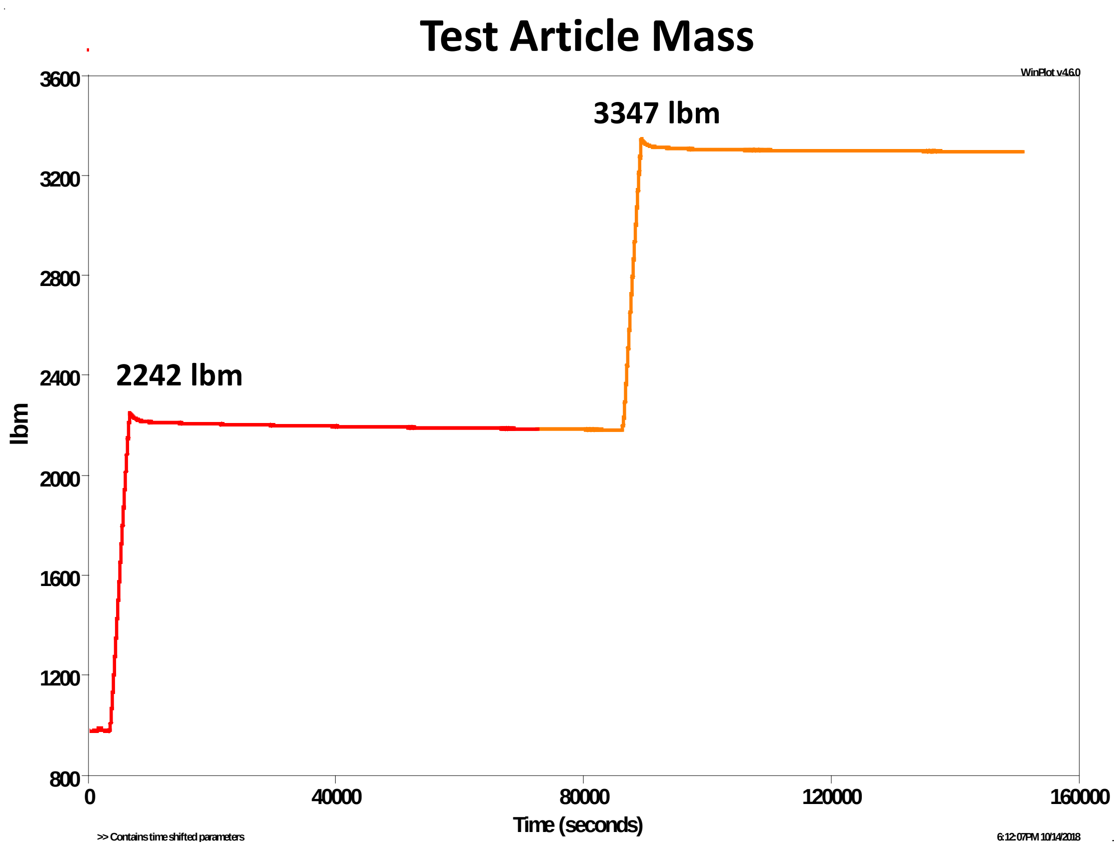
ISRU Liquefaction Brassboard Testing
Heat Exchanger Loop



ISRU Liquefaction Brassboard Testing

Tank Pre-Chill and Fill

- Filled ZBO with LN2 to 54% Initially, then topped off to 100% Liquid Level
  - Continued to fill until Vent SD read LN2 temperatures
- Allowed the test article, penetrations and insulation time to "cold soak"
- Tank pressure controlled to 18 PSIA during "cold soak" Steady-State Heat Load test



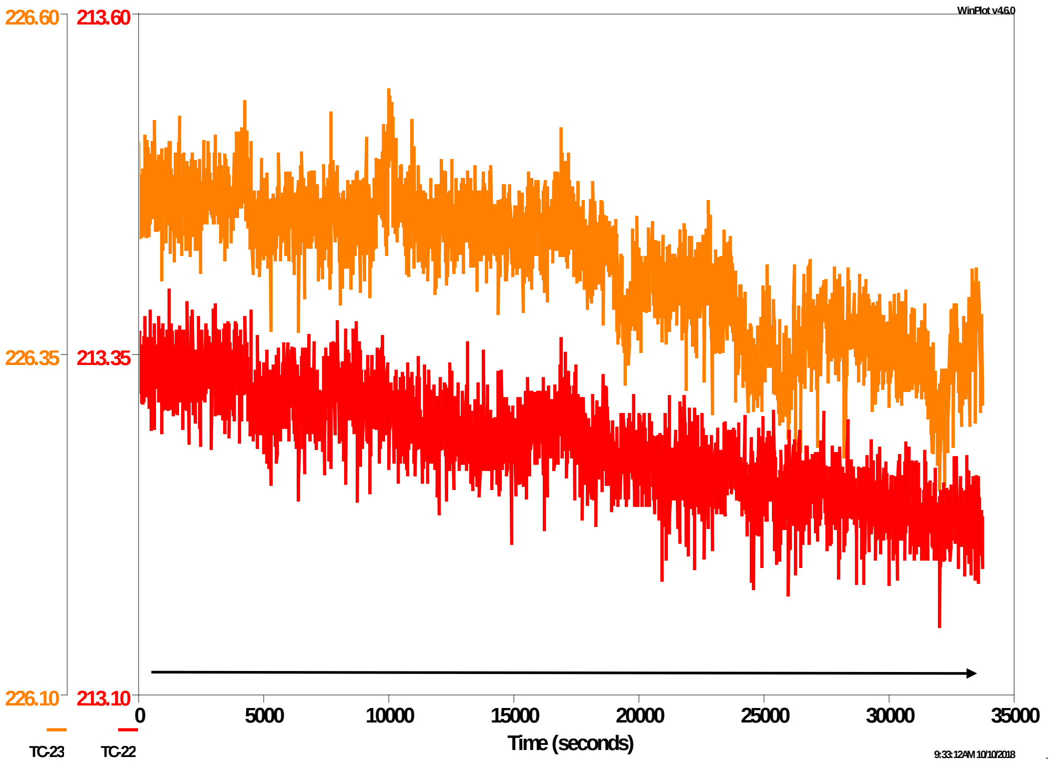
ISRU Liquefaction Brassboard Testing
Steady-State Criteria

- **Steady State will be declared for the Heat Load Test when either TC22 or TC23 demonstrate a temperature change of less than 0.5 K over a six hour period.**
  - **These TCs are located at MLI layers 15 and 20 respectively.**

- **Loaded Tank to 100% Liquid Level on September 4th, 2018**

- **Steady State Conditions shown here from September 13th, 2018**

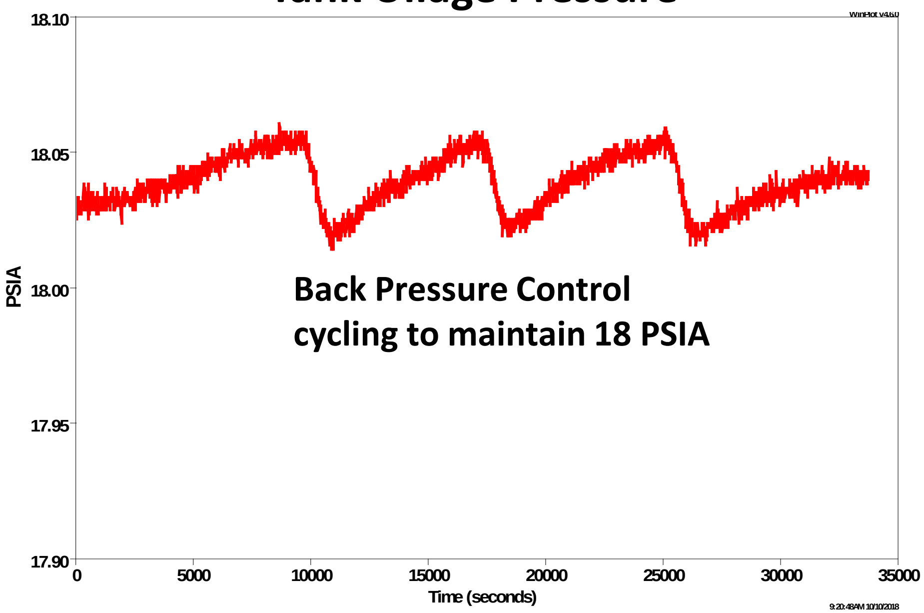
Temperatures at MLI Layers 15 and 20



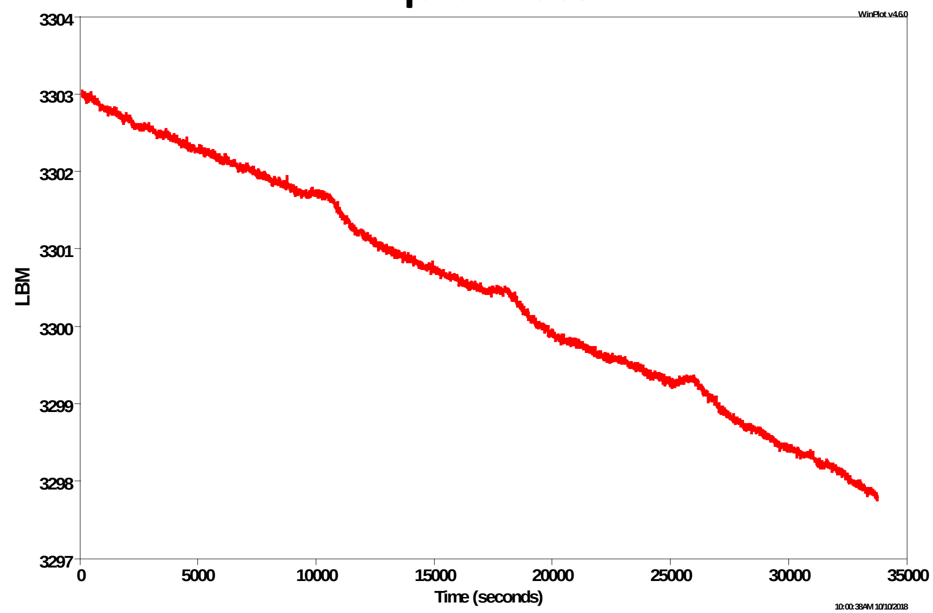
ISRU Liquefaction Brassboard Testing

Steady-State Heat Load

Tank Ullage Pressure



Liquid Mass



- ZBO Tank Loaded with LN2 to ~ 95%
- Venting with Back Pressure Control set to 18 PSIA

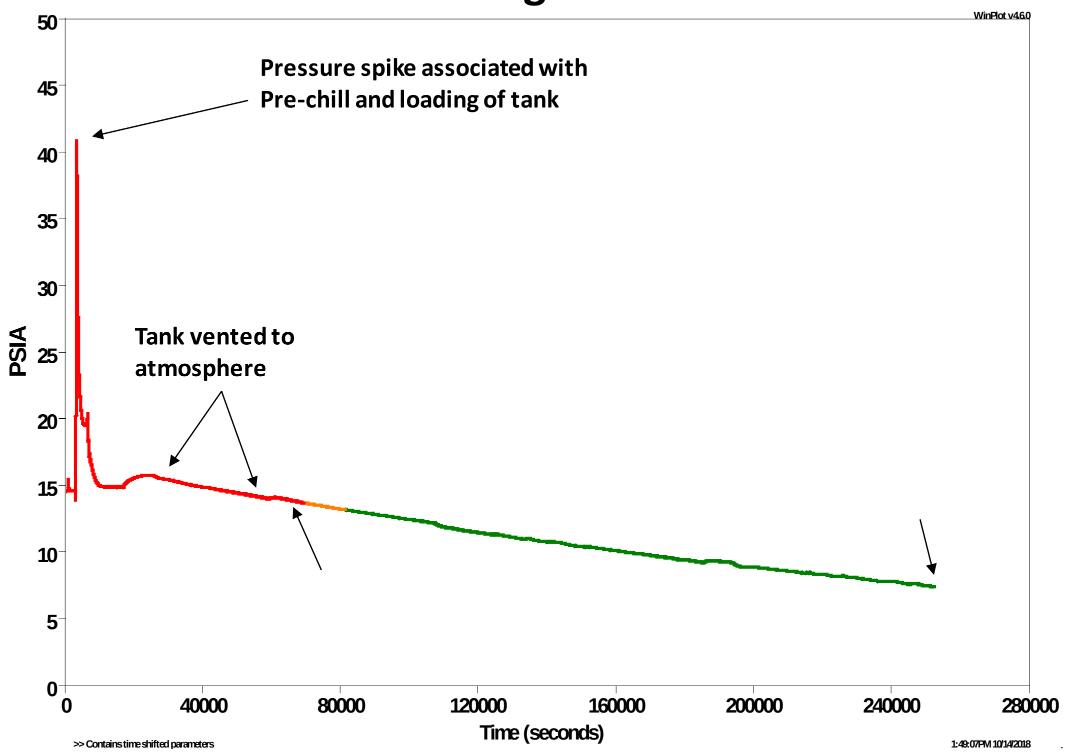
- Monitoring Vent Flowmeter and Load Cells
- Approximately 0.54 lbm/hr boil-off

Q_{total} = 18.9W
Q_{latent} = 13.404W
$Q_{sensible}$ = 5.522W

ISRU Liquefaction Brassboard Testing
Heat Exchanger Loop Checkout – ZBO Demonstration

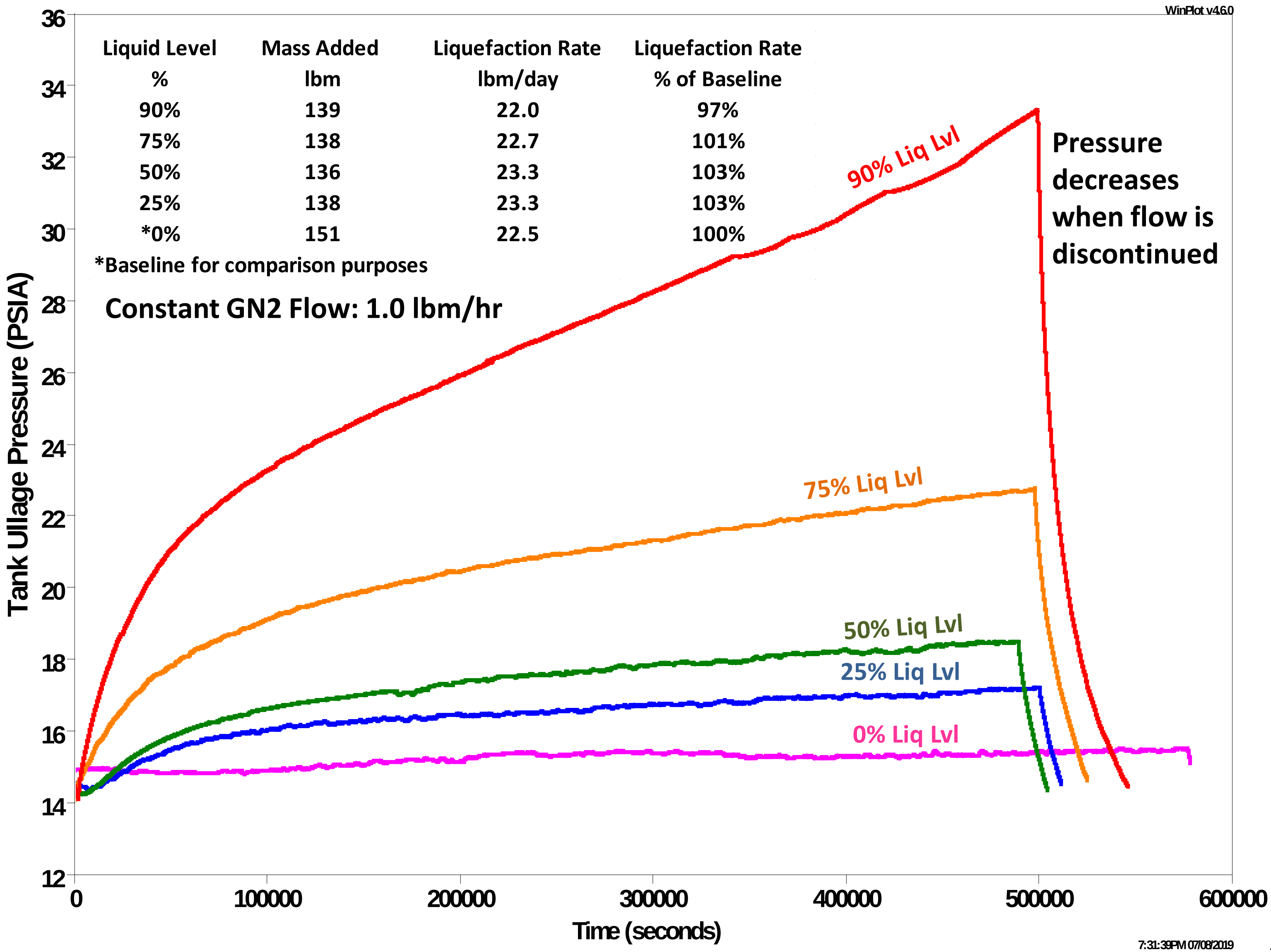
- **Tank filled to ~ 57% Liquid Level**
  - **Loaded at Atmospheric Pressure**
- **Neon Loop Checkout**
  - **Loop Pressure ~ 200 PSIA**
  - **Cryofan Speed ~ 15,000 RPM**
- **Tank Pressure Reduction**
  - **0.1314 PSI / hour**

Tank Ullage Pressure



Liquefaction at Various Liquid Levels

Constant GN2 Flowrate – Injected Into Tank Ullage Space

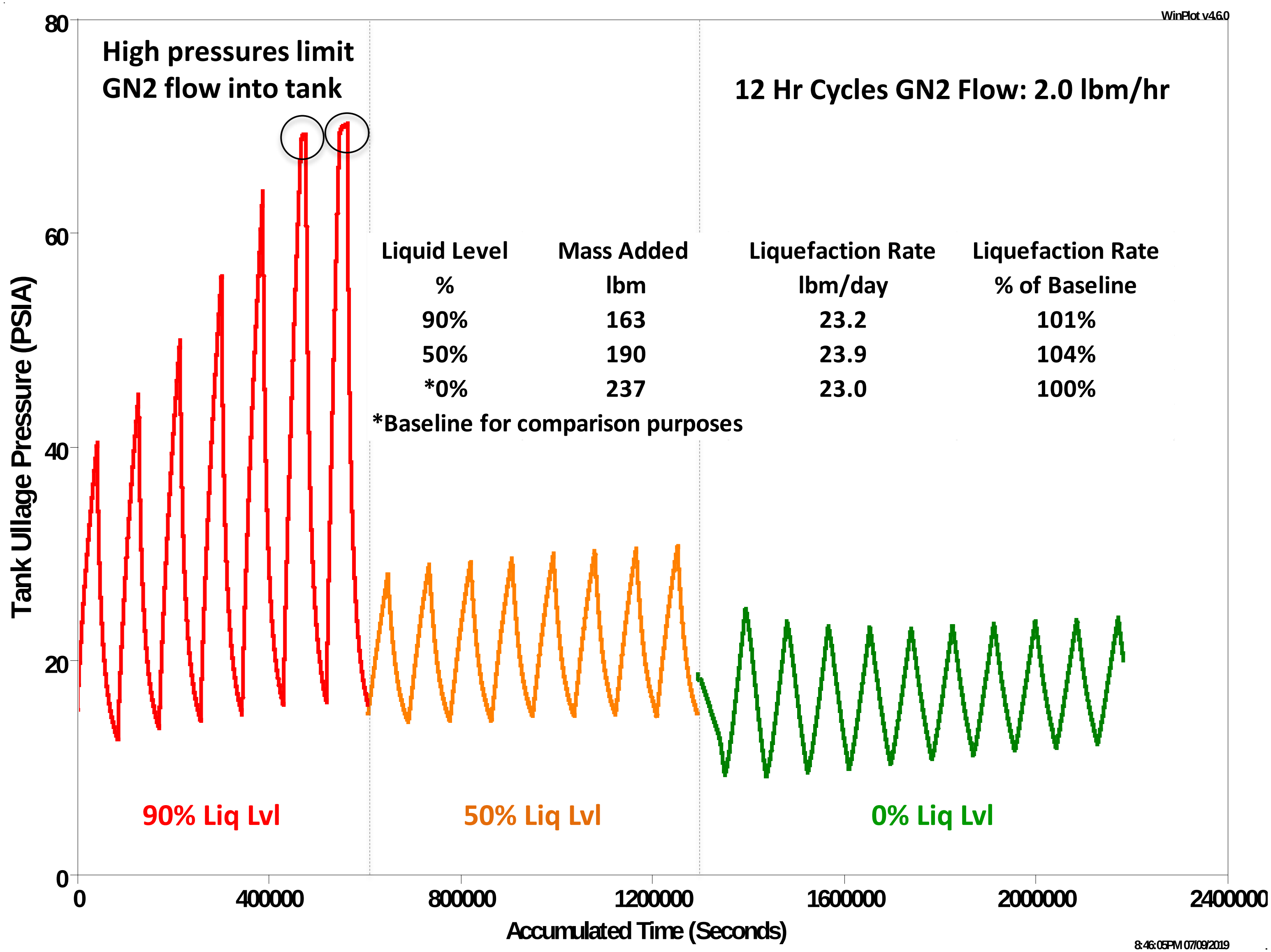


Liquid Level %	Mass Added lbm	Liquefaction Rate lbm/day	Liquefaction Rate % of Baseline
90%	139	22.0	97%
75%	138	22.7	101%
50%	136	23.3	103%
25%	138	23.3	103%
*0%	151	22.5	100%

*Baseline for comparison purposes

Liquefaction at Various Liquid Levels

Non-Constant GN2 Flowrate (12 hr cycles) – Injected Into Tank Ullage Space

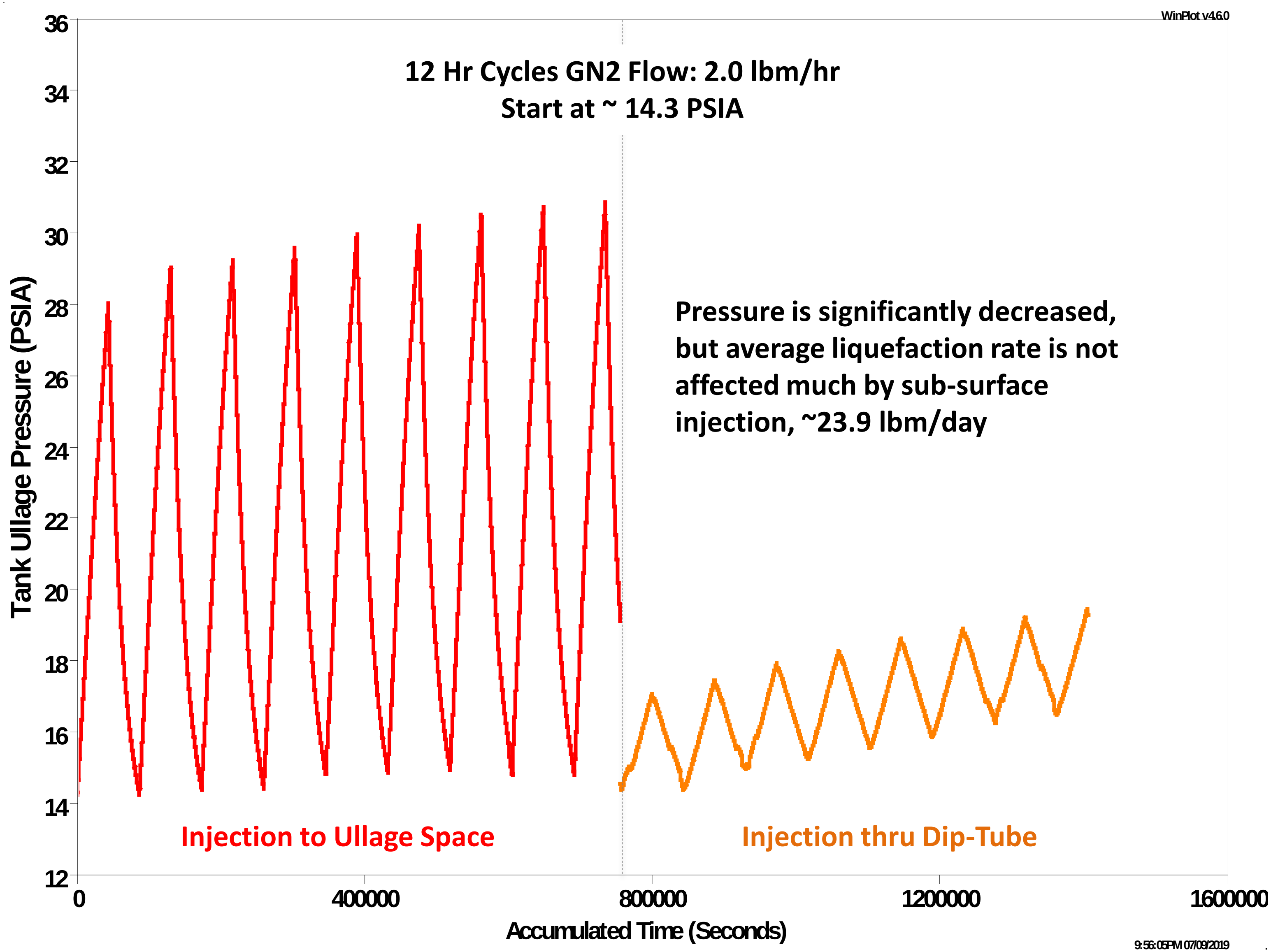


Liquid Level %	Mass Added lbm	Liquefaction Rate lbm/day	Liquefaction Rate % of Baseline
90%	163	23.2	101%
50%	190	23.9	104%
*0%	237	23.0	100%

*Baseline for comparison purposes

Effects of Sub-Surface Injection

Non-Constant GN2 Flowrate (12 hr cycles) – Tank at 50% Liquid Level



ISRU Liquefaction Brassboard Testing

Conclusions and Future Work

Conclusions:

- **Loaded with Liquid Nitrogen, the heat load into the test article is ~18.9 Watts at high vacuum**
- **The Cryocooler consistently removes ~ 130 W heat from the refrigeration loop which removes ~ 85 W from the test article**
- **Both Zero Boil-Off and Liquefaction were demonstrated with the Tube-On-Tank Heat Exchanger integrated with a Cryocooler**
- **Liquefaction at higher liquid levels results in higher pressures and reduced liquefaction rates due to smaller ullage volumes, and decreased surface areas available for liquefaction**
  - **Excessive pressures can reduce the inflow of propellant gas**
- **Changes in liquefaction rates were not very significant**
  - **Less than 6% change over liquid levels tested**
  - **Slightly increase, ~ 2% to 5%, when introducing flow in 12 hour cycles rather than a constant 24 hours.**
- **Sub-Surface Injection results in lower tank ullage pressures and will likely be the preferred method for prototype testing.**

Backup Charts