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
MSFC	Stephens	Jonathan	R	NASA
MSFC	Valenzuela	Juan	G	NASA
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**

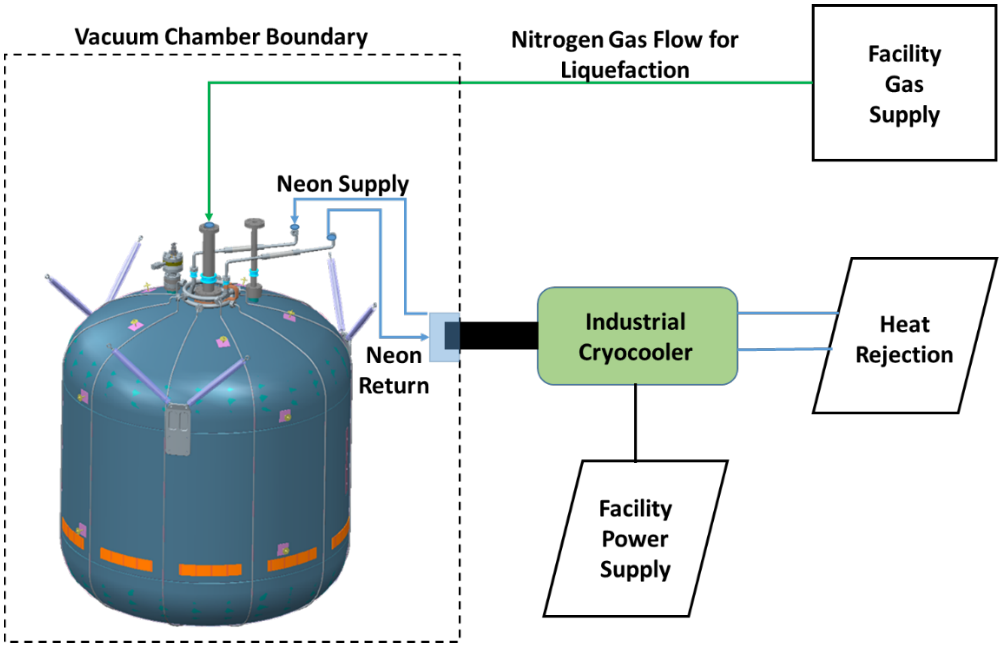
- ***See W.L. Johnson, D.M. Hauser, B.F. Banker, J.R. Stephens, D.W. Plachta, P.S. Desai, A.M. Swanger and X-Y.J. Wang, "Comparison of Oxygen Liquefaction Methods for Use on the Martian Surface", presented at the 27th Space Cryogenics Workshop, July 2017***

- **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**

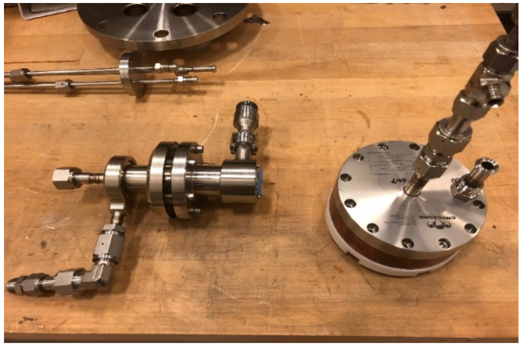
Focus of today's discussion (bracketing "Brassboard" Proof of Concept Testing, Data for model validation, Gather lessons learned)

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



PHPK Cryocooler

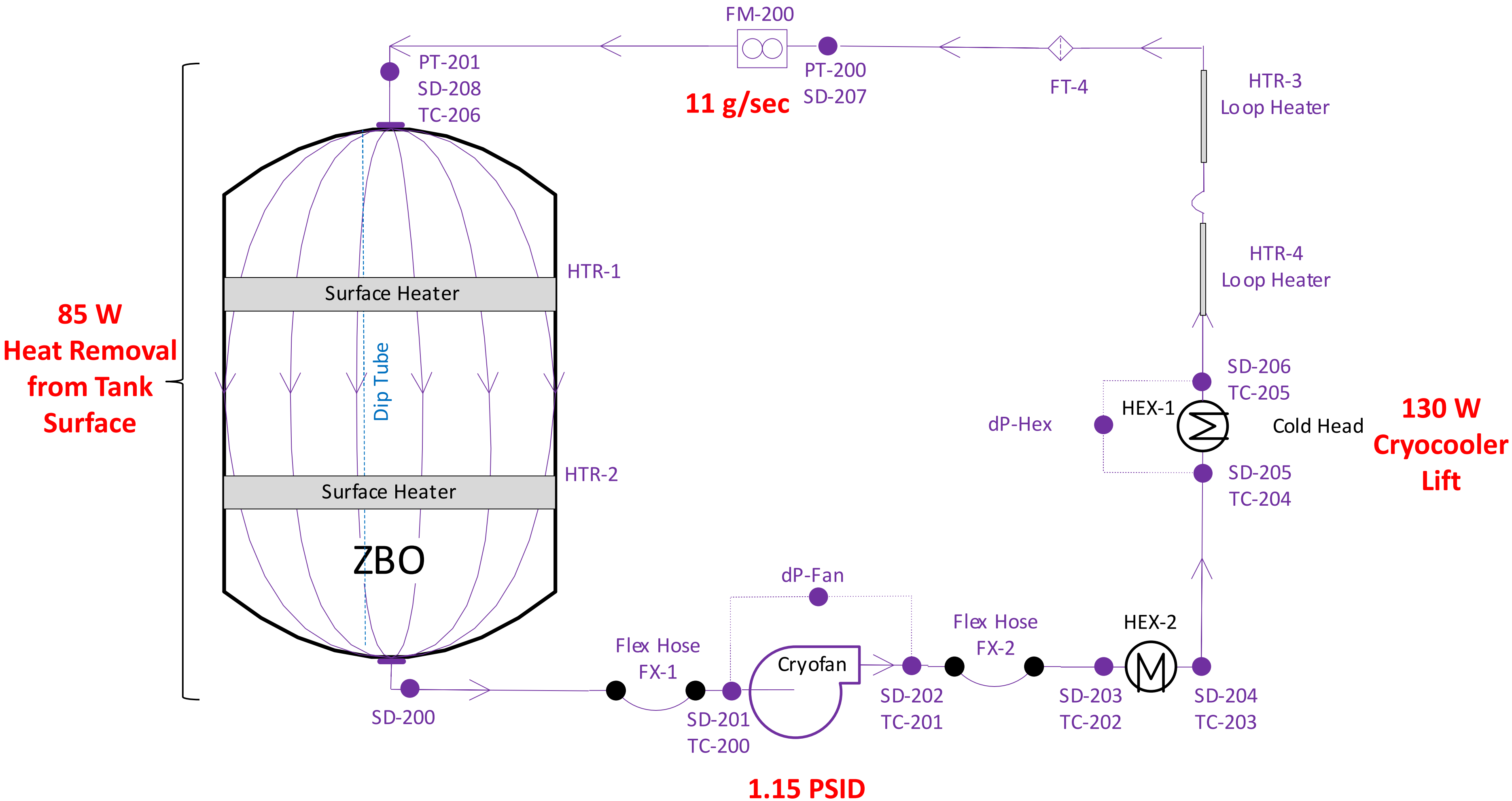


CryoZone Cryofan (left) and cold head Heat Exchanger (right)

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

ISRU Liquefaction Brassboard Testing

Heat Exchanger Loop

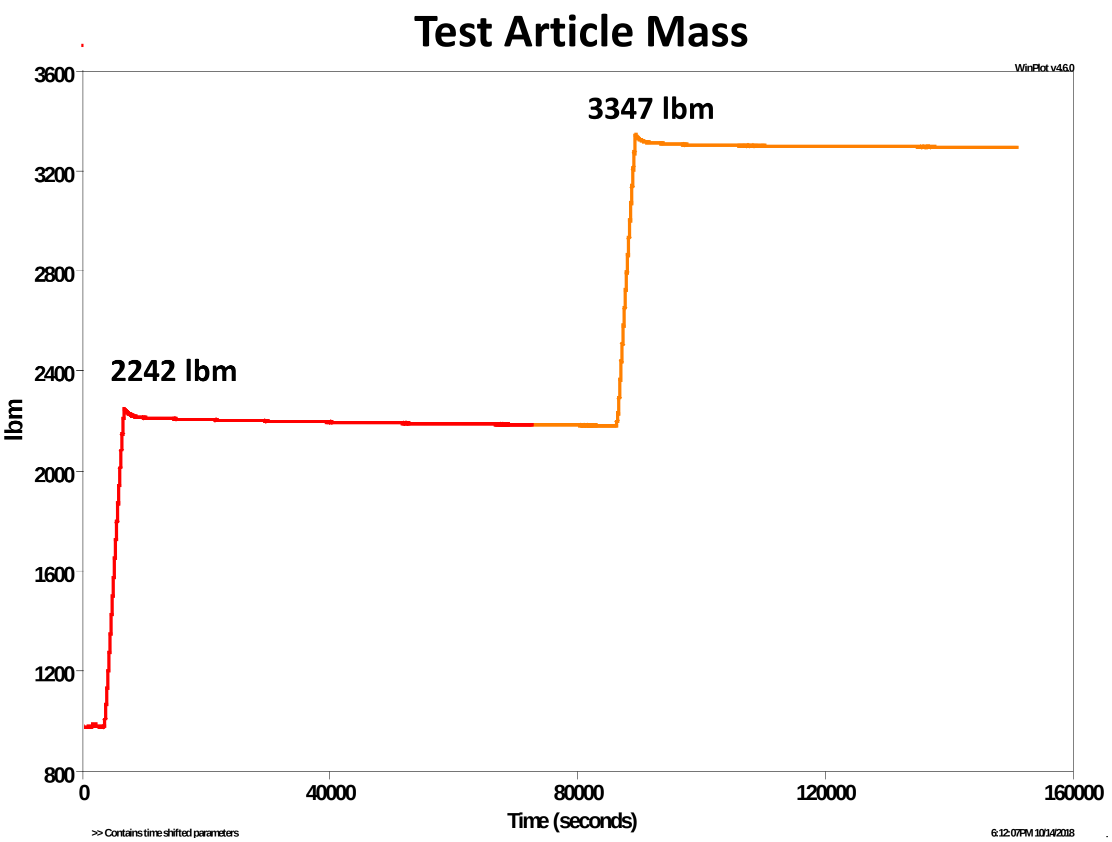


ISRU Liquefaction Brassboard Testing
Tank Pre-Chill and Fill

- **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**



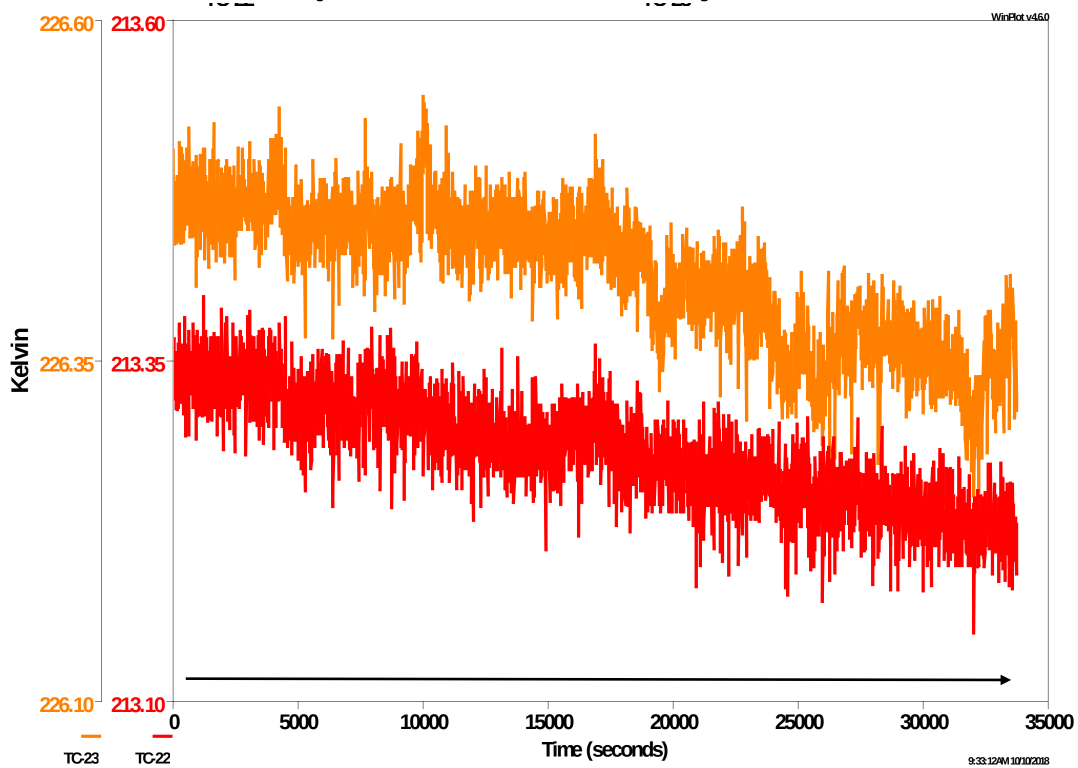
ISRU Liquefaction Brassboard Testing
Steady-State Criteria

- 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

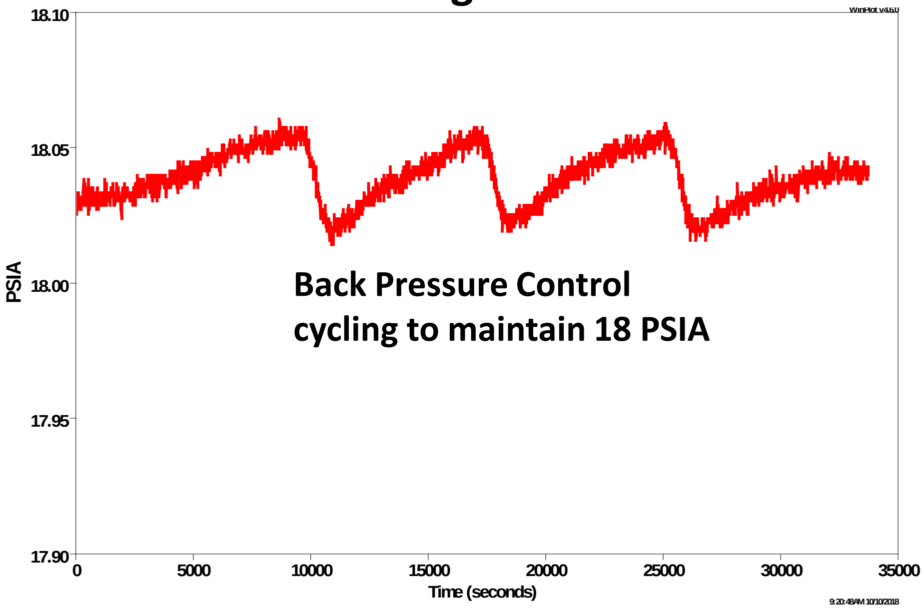
Temperatures at MLI Layers 15 and 20



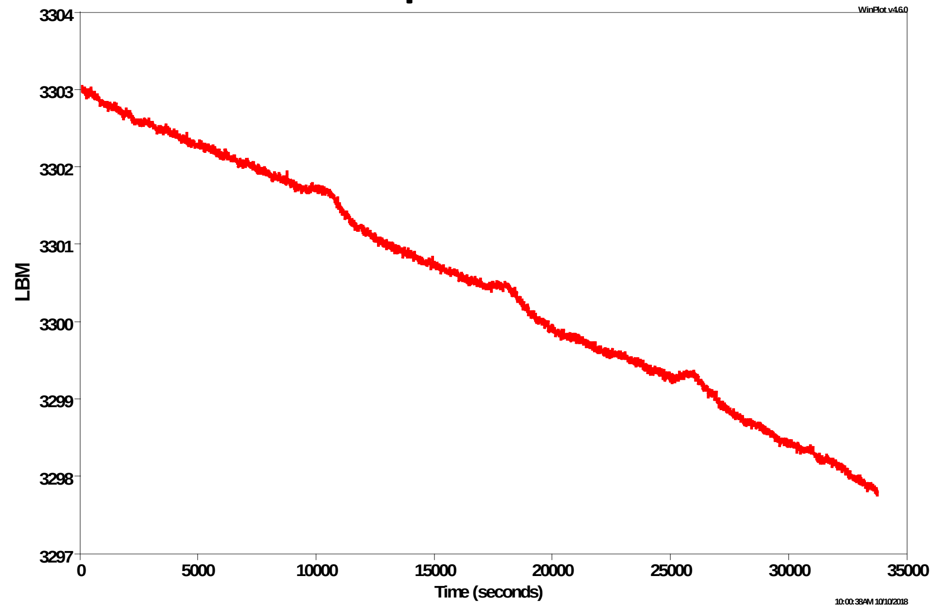
ISRU Liquefaction Brassboard Testing

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

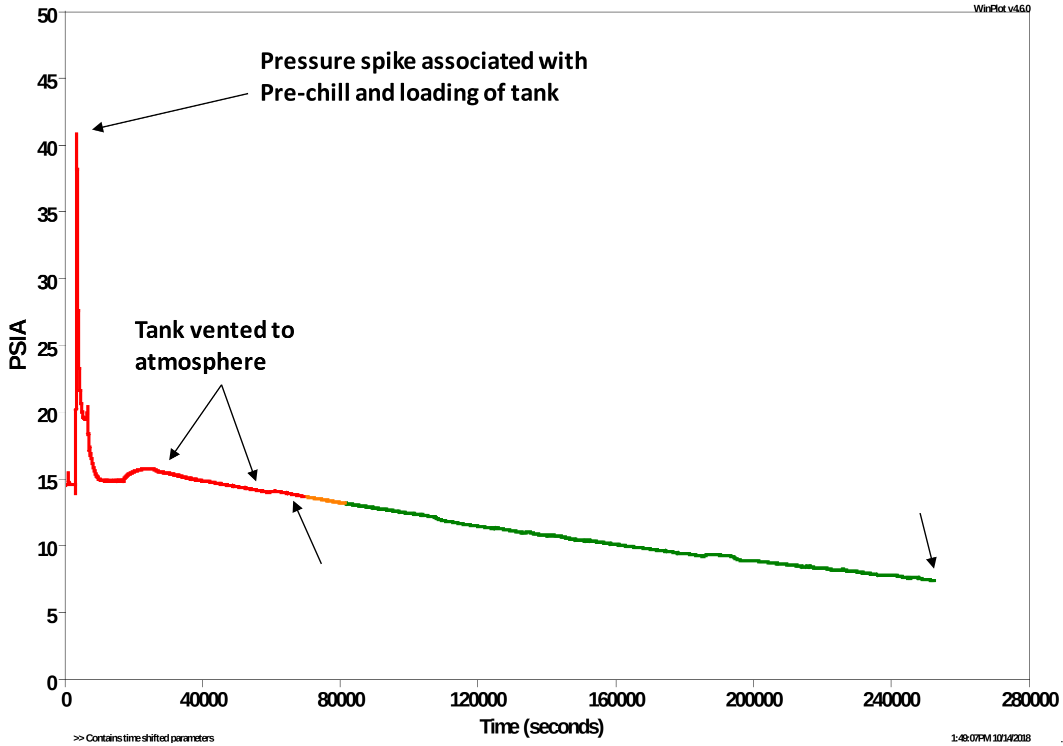
Q_{latent} = 13.404W

$Q_{sensible}$ = 5.522W

ISRU Liquefaction Brassboard Testing
Heat Exchanger Loop Checkout – ZBO Demonstration

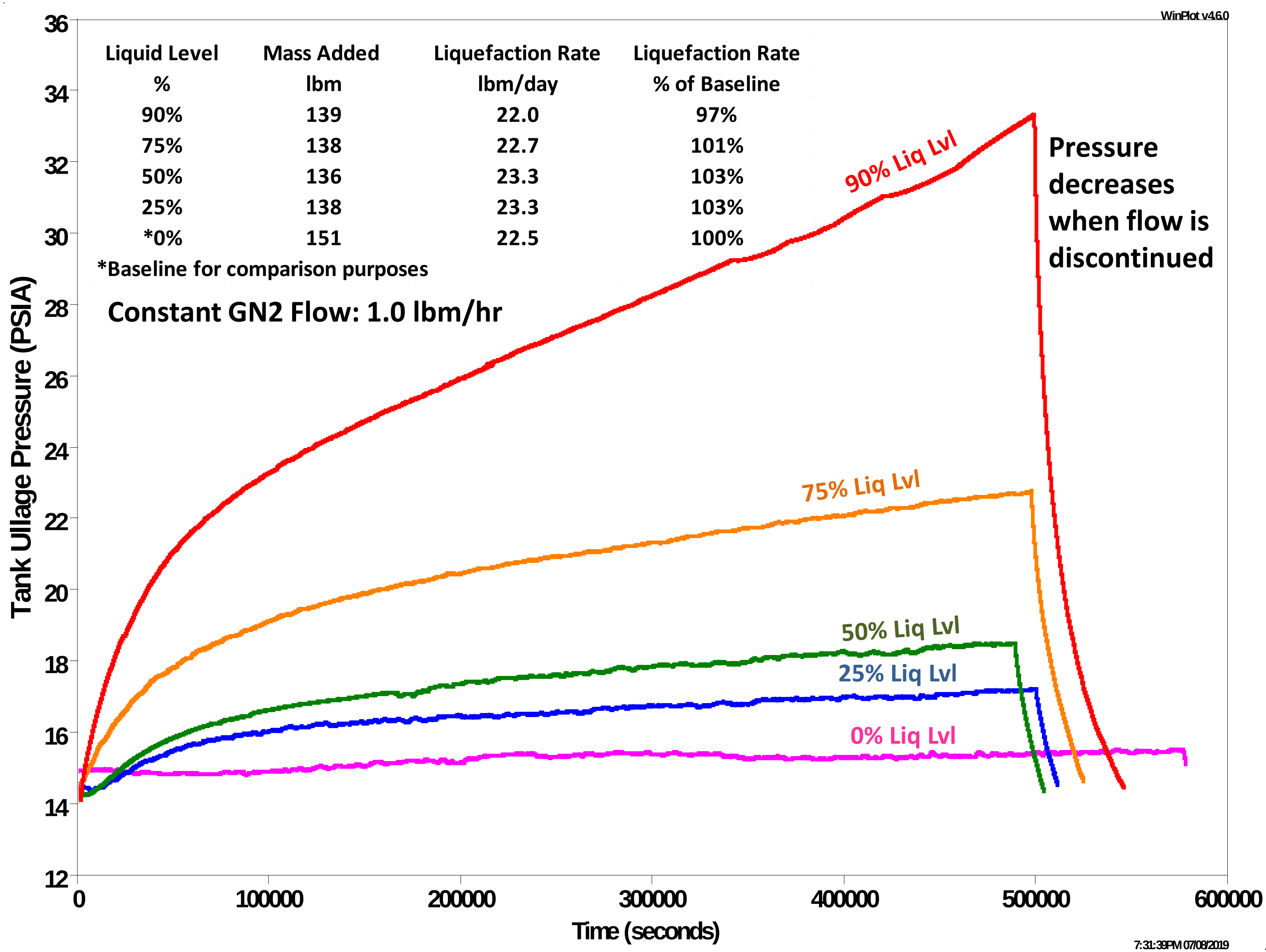
- Tank filled to ~ 57% Liquid Level
  - Loaded at Atmospheric Pressure
- Neon Loop Checkout
  - Loop Pressure ~ 200 PSIA
  - Cryofan Speed ~ 15,000 RPM
- Tank Pressure Reduction
  - 0.1314 PSI / hour

Tank Ullage Pressure



Liquefaction at Various Liquid Levels

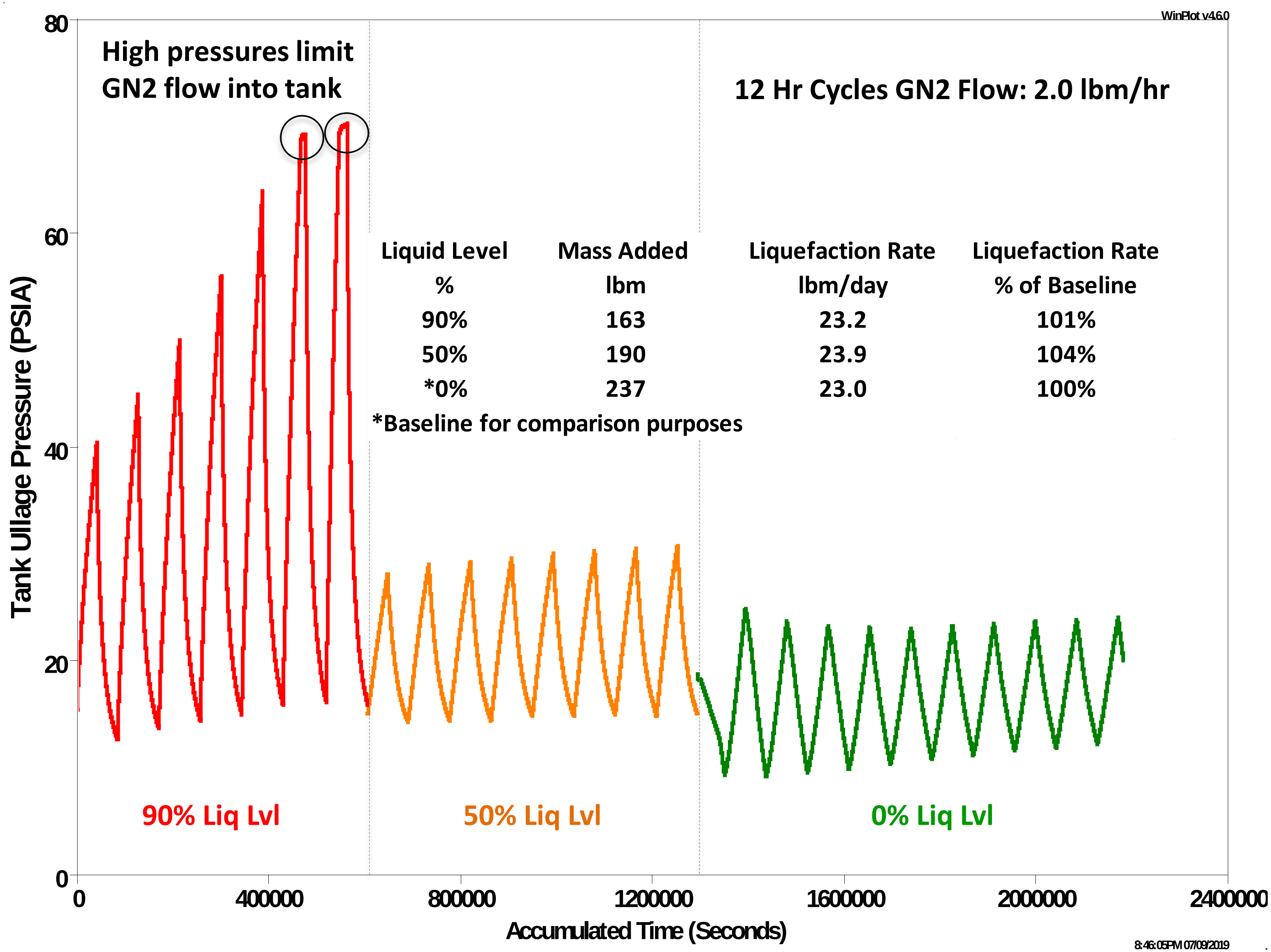
Constant GN2 Flowrate – Injected Into Tank Ullage Space



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%

Liquefaction at Various Liquid Levels

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

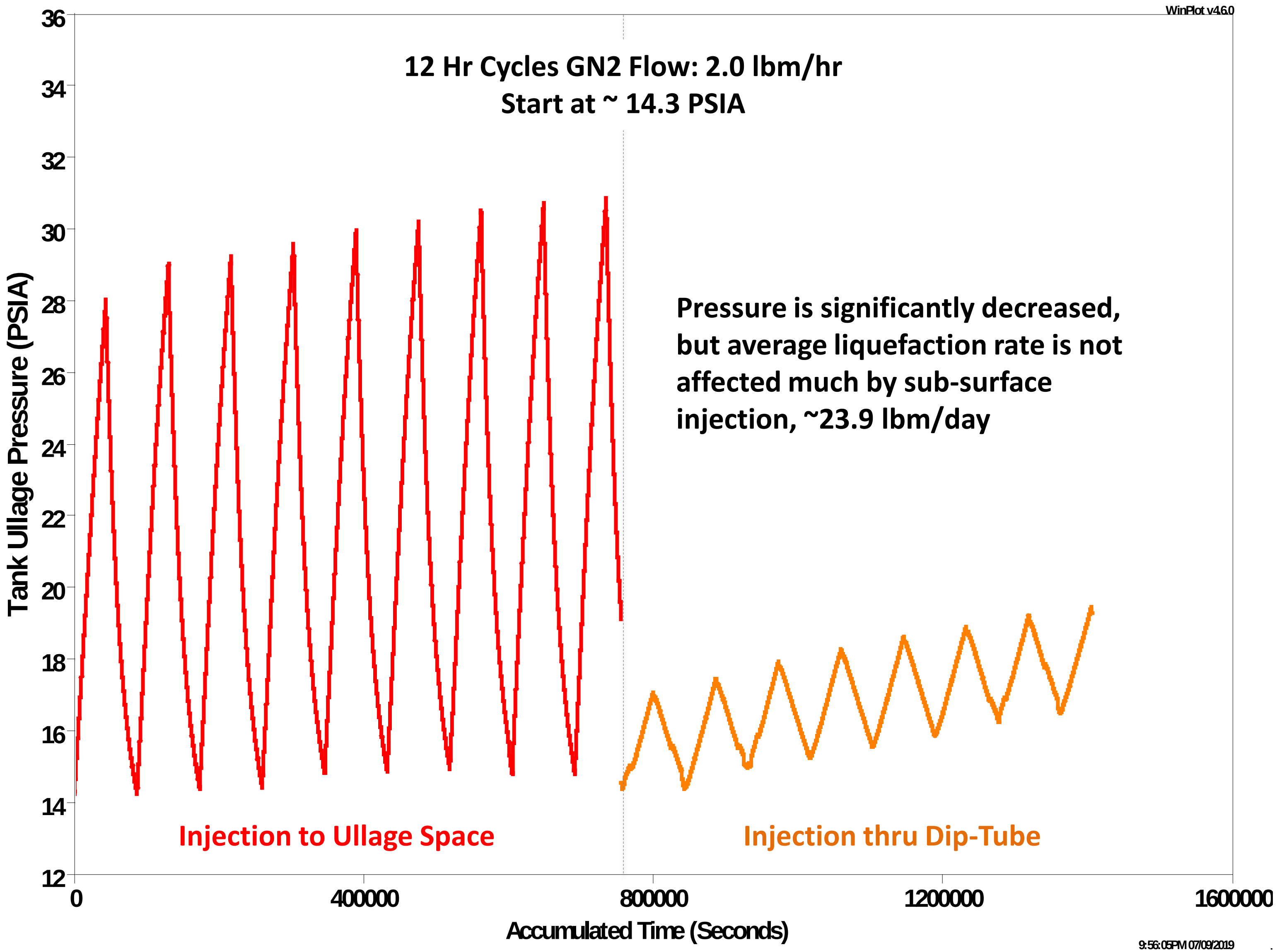


Liquid Level %	Mass Added lbm	Liquefaction Rate lbm/day	Liquefaction Rate % of Baseline
90%	163	23.2	101%
50%	190	23.9	104%
*0%	237	23.0	100%

*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