Cryogenic Propellant Tank Sub-Surface Pressurization with Bang-Bang Control

Jonathan R. Stephens

eCryo Industry Workshop
July 11th and 12th, 2016

ENGINEERING DEVELOPMENT UNIT

ENGINEERING DEVELOPMENT UNIT

- **The sub-surface pressurization tests were conducted on the Evolvable Cryogenics (eCryo) Engineering Development Unit (EDU)**

  - **The EDU is a ground based Cryogenic Fluid Management (CFM) test article managed by the eCryo Program at Glenn Research Center (GRC).**

  - **Sponsored by NASA's Science and Technology Mission Directorate, and led by GRC and Marshall Space Flight Center (MSFC)**

  - **Advanced insulation, Axial Jet mixing, Liquid Acquisition Devices, Radio Frequency Mass Gauging, and a Thermodynamic Vent System were all technologies to be demonstrated on the EDU.**

  - **Intended to be a precursor to a flight demonstration**
    - **The design and fabrication of EDU were completed.**
    - **Testing was conducted in 06/2014 and 09/2015.**
    - **Due to budget constraints, the flight demonstration was removed from the project portfolio.**

Sub-Surface Pressurization with Bang-Bang Control

OBJECTIVE

- **Evaluate the change in pressurization system performance when the pressurant diffuser becomes submerged beneath the liquid surface.**
  - **To establish a baseline case, run a test applying pressurant directly to the tank ullage space using the forward diffuser.**
  - **For comparison, repeat the baseline tests applying pressurant to the tank ullage space through the liquid by utilizing the aft (submerged) diffuser.**
- **The 2014 EDU test series included sub-surface pressurization with regulated ambient helium and the flow manually controlled.**
- **The focus of the 2015 EDU test series was to <u>implement a bang-bang control system to capture the dynamic effects and evaluate a pressurization system's ability to control to a predefined pressure range when the diffuser becomes submerged beneath the surface of the liquid.</u>**

BACKGROUND

- **A lot of data currently exist for pressurizing a propellant tank filled with a settled liquid.**
  - **Ground test articles**
  - **Vehicle propellant tank prepressurization on the ground**
  - **Vehicle propellant tank repressurization/pressurization while on ascent**
  - **Vehicle propellant tank repressurization after a settling maneuver**

BACKGROUND (continued)

- **No data is available for evaluating a pressurization systems performance in micro-gravity when the liquid is unsettled**
  - **Pressurization and expulsion of an unsettled propellant may be required:**
    - **Propellant depots for replenishing a vehicle on-orbit (tank-to-tank transfer).**
    - **Starting a liquid propellant engine or a Reaction Control System (RCS) from an unsettled state (engine restart after an extended coast).**

Sub-Surface Pressurization with Bang-Bang Control

BACKGROUND (continued)

- In a micro-g environment, the effects of Surface Tension dominate over Body Forces and the liquid no longer remains in a settled condition.
- Once unsettled and stabilized, the liquid remains attached to the tank inner wall and the ullage space forms a spherical shape in the center of the tank.

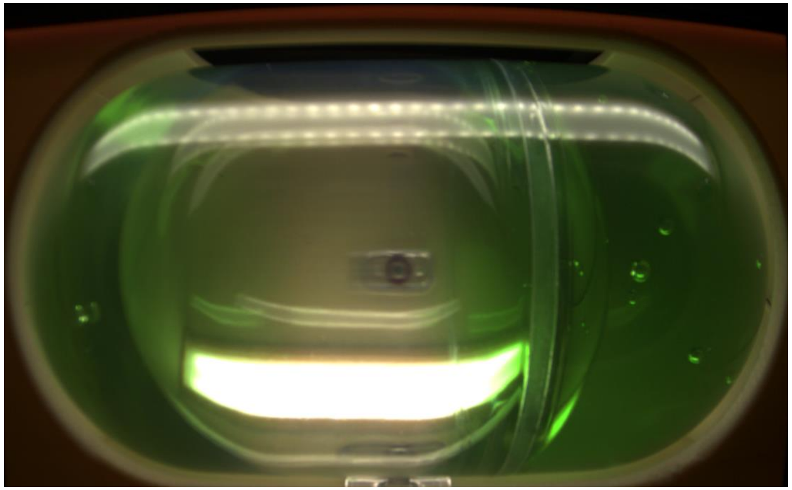


Photo of Slosh Experiment on ISS
Provided by KSC LSP – Tank 40% Full

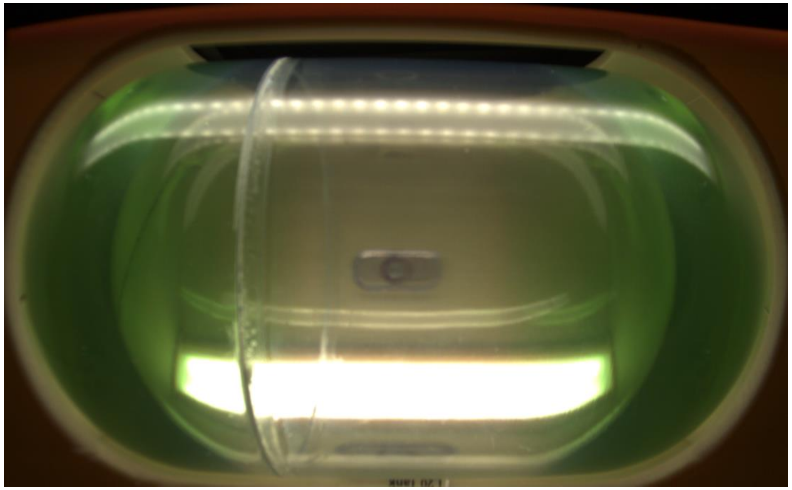


Photo of Slosh Experiment on ISS
Provided by KSC LSP – Tank 20% Full

- For a given pressurization system configuration, the diffuser may be exposed to the tank ullage when the propellant is settled, but submerged when the propellant is unsettled (flight demonstration).

Sub-Surface Pressurization with Bang-Bang Control

BACKGROUND (continued)

- **Potential issues associated with submerged diffuser pressurization:**
  - **Pressurant gas collapses as it passes through the liquid. As a result, more helium may be required.**
  - **Ability to control pressure within a specific range is unknown (focus of the EDU 2015 tests).**
  - **Helium can dissolve within the propellant leading to a reduction in propellant purity**
    - **Can potentially affect TVS performance**
    - **Will likely affect engine performance (thrust, flows, Isp)**
    - **Potential concern with ingestion of gaseous helium in turbo-pumps**

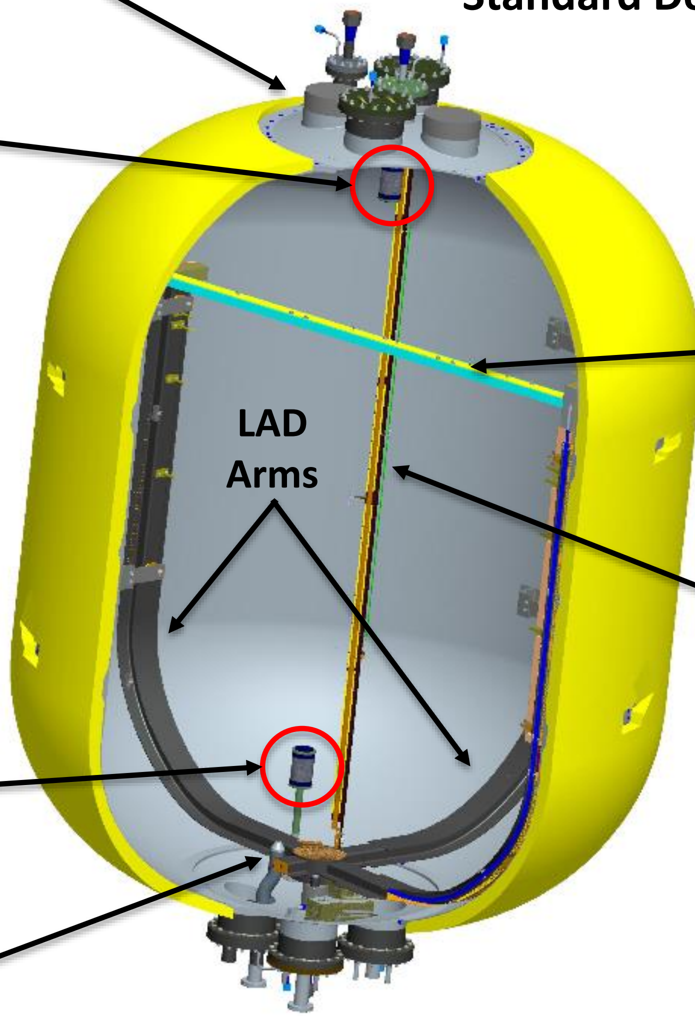
- **EDU is an excellent test article for evaluating pressurization system performance changes as a result of the diffuser becoming submerged beneath the liquid surface. <u>However, to capture all the effects of micro-gravity, a flight test article is required.</u>**
  - **A ground test cannot capture the bubble dynamics associated with sub-surface pressurization in micro-gravity.**
  - **The natural convection within the propellant tank cannot be simulated in ground test.**

Sub-Surface Pressurization with Bang-Bang Control

BACKGROUND (continued)

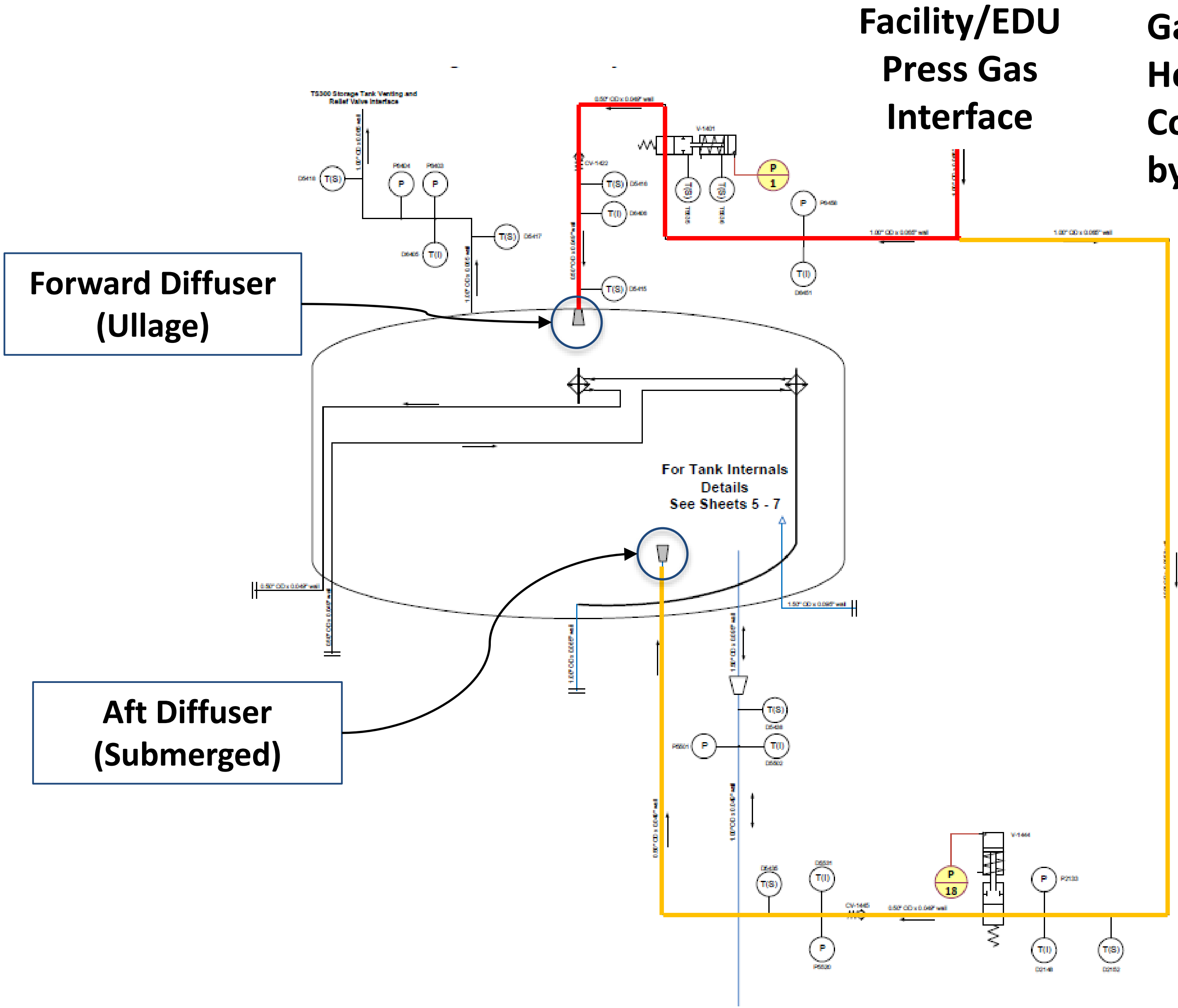
- EDU Pressurization System Configuration
  - EDU pressurization system has two <u>IDENTICAL</u> diffusers
    - Forward (ullage)
    - Aft (submerged)
  - Pressurant Gas
    - Gaseous helium regulated to ~ 500 PSIA at ambient temperature
    - Bang-bang control valves downstream of the pressure regulator set to control pressure within +/- 0.5 PSIA (09/2015 tests only)
    - Control orifice downstream of bang-bang valves to limit the flow during a pressurization cycle (09/2015 tests only)
      - GFSSP Model build of pressurization system to size orifice (Andre Leclair, NASA MSFC ER43)
      - Orifice Diameter: 5/32 inches
      - Flow Coefficient: 0.84

eCryo's Engineering Development Unit Propellant Tank Assembly

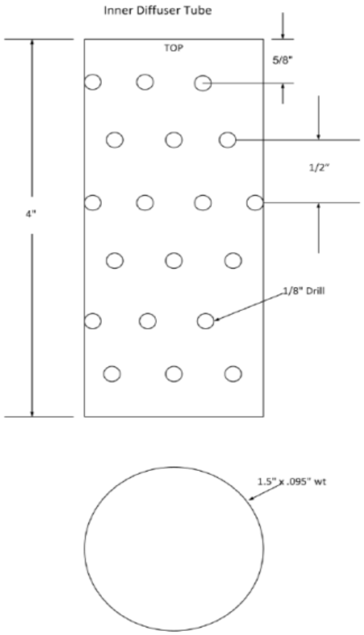


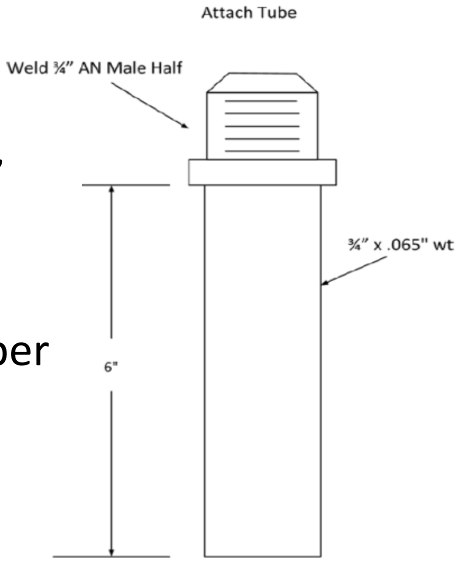
EDU Pressurization Sub-System

Gaseous Ambient Helium with Bang-Bang Control provided to EDU by the test facility.



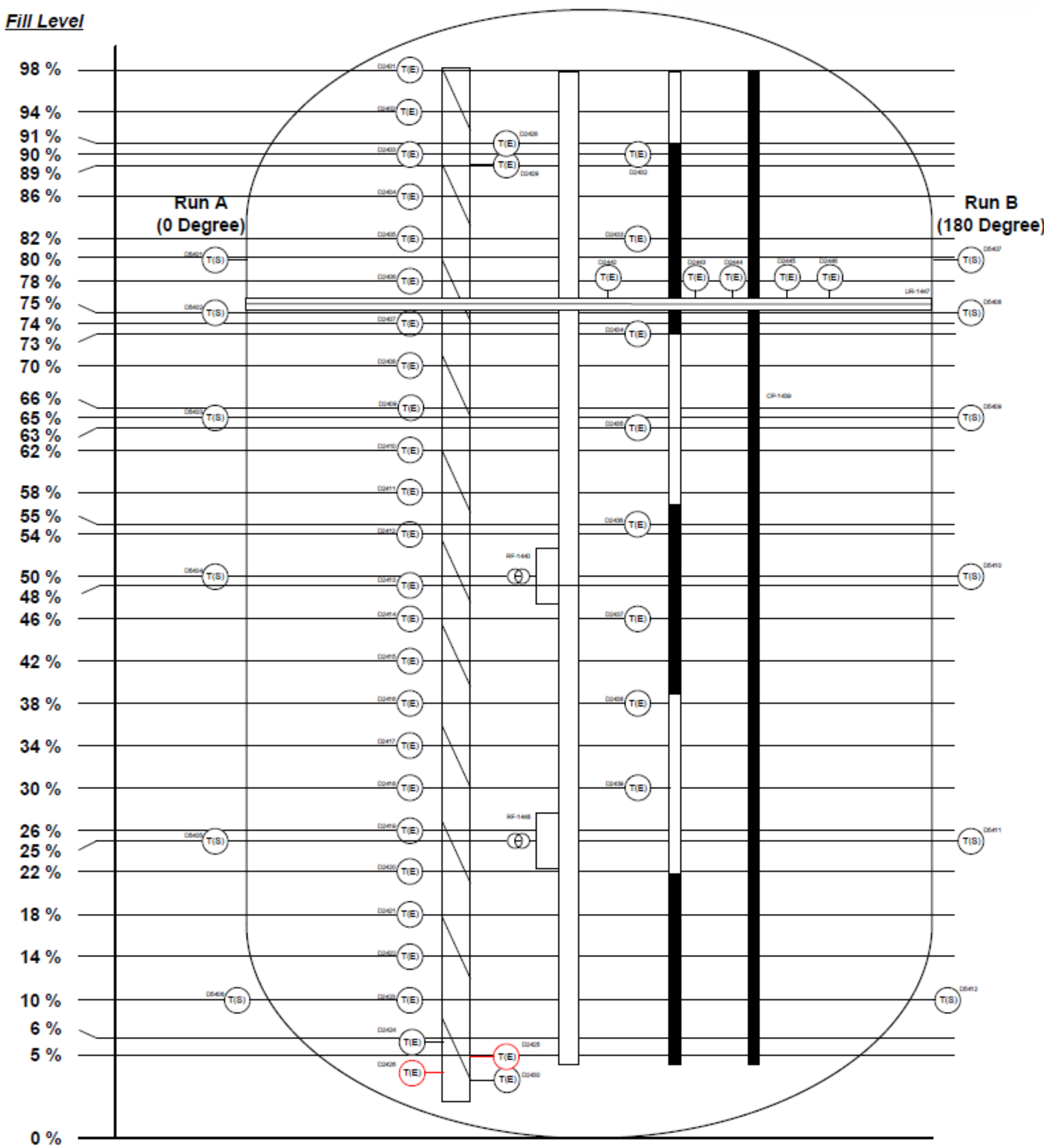
EDU Diffusers





- 4” X 2.5” can
- 6 rows
- 8 holes per row
- 1/8” Dia hole
- Rows are ½” apart
- 2 50X50 Mesh screens
- 30.3% open area

EDU Internal Temperatures and Mass Gauging



Fill Level (%)	Tank Station (in)	Temperature Rake
98	85.2	D2401
94	80.2	D2402
91	77.3	D2428
90	76.4	D2403
89	75.6	D2429
86	73.1	D2404
82	70	D2405
78	67	D2406
74	64	D2407
73	63.3	
70	61	D2408
66	58	D2409
63	55.7	
62	55	D2410
58	52	D2411
55	49.7	
54	49	D2412
50	46	
48	51.3	D2413
46	43	D2414
42	40	D2415
~~38~~	~~37~~	~~D2416~~
34	34	D2417
30	30.9	D2418
26	27.9	D2419
25	27.1	
22	24.9	D2420
18	21.9	D2421
14	18.8	D2422
10	15.5	D2423
6	11.7	D2424
5	10.6	D2425
	10.2	D2426
	9.8	D2430

Pressurization Testing Conducted at MSFC
in
June 2014

Cryogenic Liquid: Hydrogen
Pressurant Gas: Ambient Helium
Pressure Regulated, Flow Manually Controlled

Pressurization Tests Conducted

Forward Diffuser Pressurization Test 1 (Baseline Test)

Step 1 Pressurize tank from atmospheric to 27 PSIA using ambient helium and forward diffuser when tank liquid level is ~ 78%

Step 2 Once tank ullage pressure reaches 27 PSIA, discontinue pressurization and lockup tank. Allow tank to self pressurize to ~ 30 PSIA.

Step 3 Vent tank back down to atmospheric and allow at least 15 minutes to stabilize.

Aft Diffuser Pressurization Test 1 (Comparison Test)

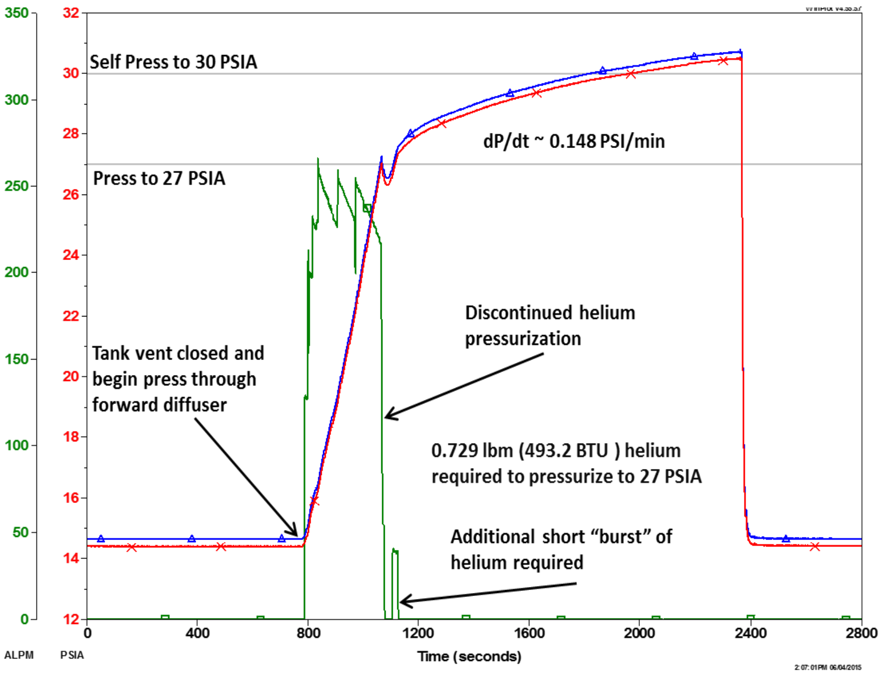
Step 1 Press tank from atmospheric to 27 PSIA using ambient helium and submerged diffuser when tank liquid level is ~ 78%

Step 2 Once tank ullage pressure reaches 27 PSIA, discontinue pressurization and lockup tank. Allow tank to self pressurize to ~ 30 PSIA.

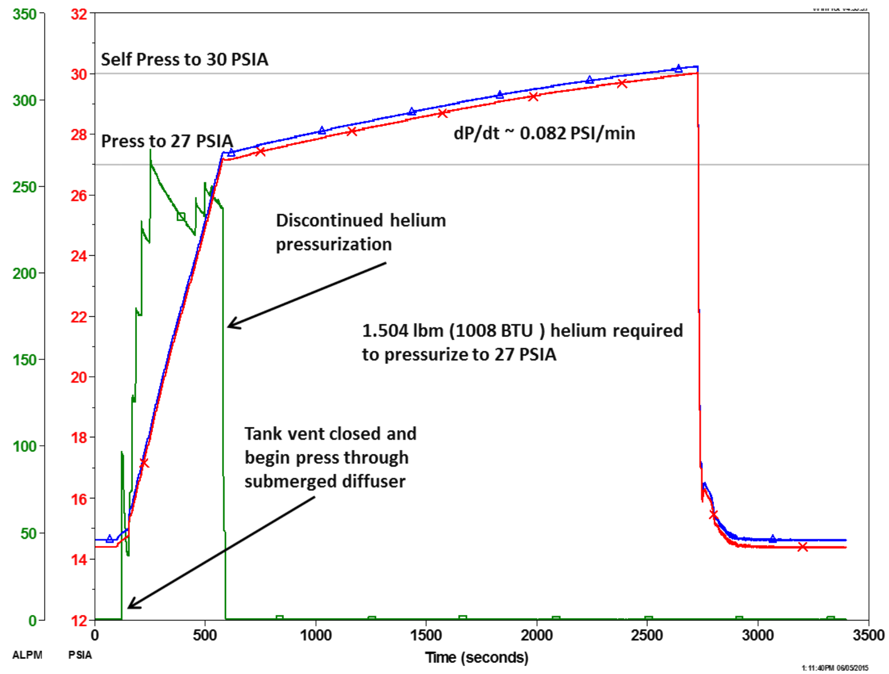
Step 3 Vent tank back down to atmospheric and allow at least 15 minutes to stabilize.

Tank Ullage Pressure & Pressurization Flowrate vs Time
Tank Liquid Level 78%

Baseline Test - Pressurant Gas to Ullage



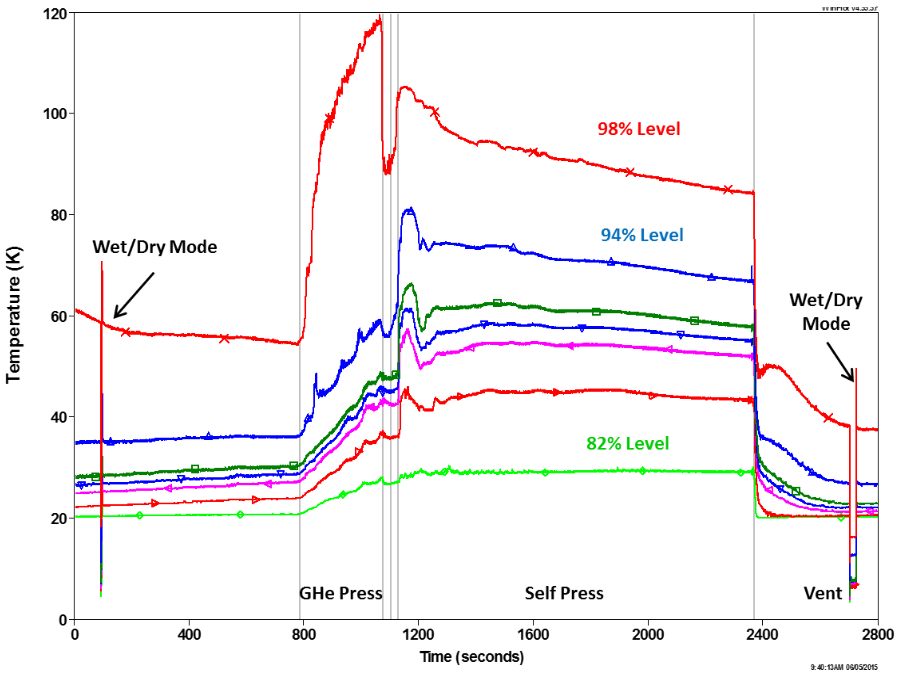
Comparison Test - Sub-Surface Pressurization



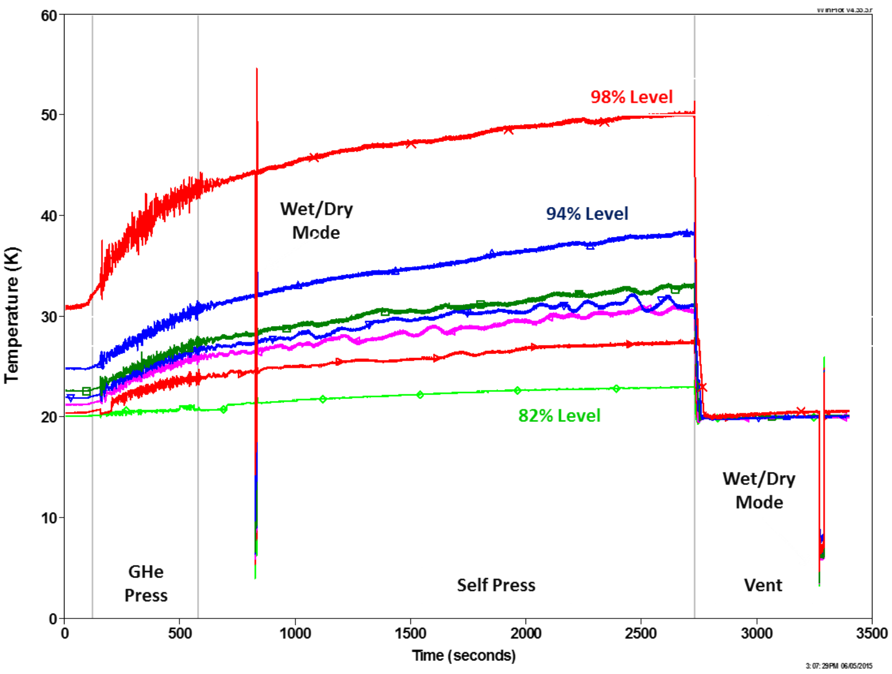
- The pressurant required to raise the tank pressure from ambient to 27 PSIA for the baseline test and submerged diffuser test where ~ 0.73 lbm (493.2 BTU) and ~ 1.504 lbm (1008 BTU), respectively.
- A pressurant gas mass increase of ~ 108% if the diffuser was submerged beneath the liquid surface.

Tank Ullage Temperature vs Time
Tank Liquid Level 78%

Baseline Test - Pressurant Gas to Ullage



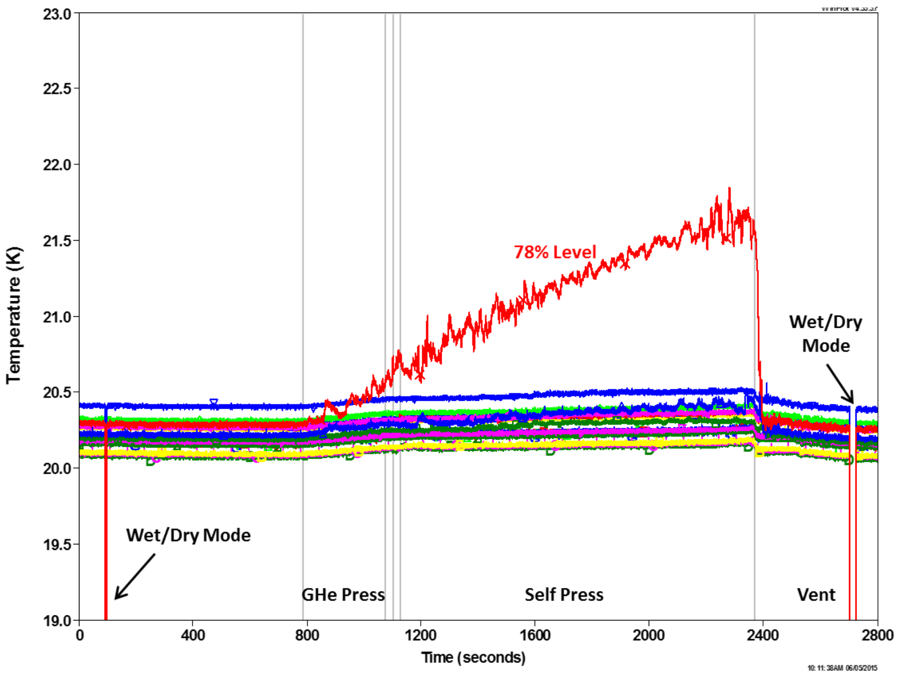
Comparison Test - Sub-Surface Pressurization



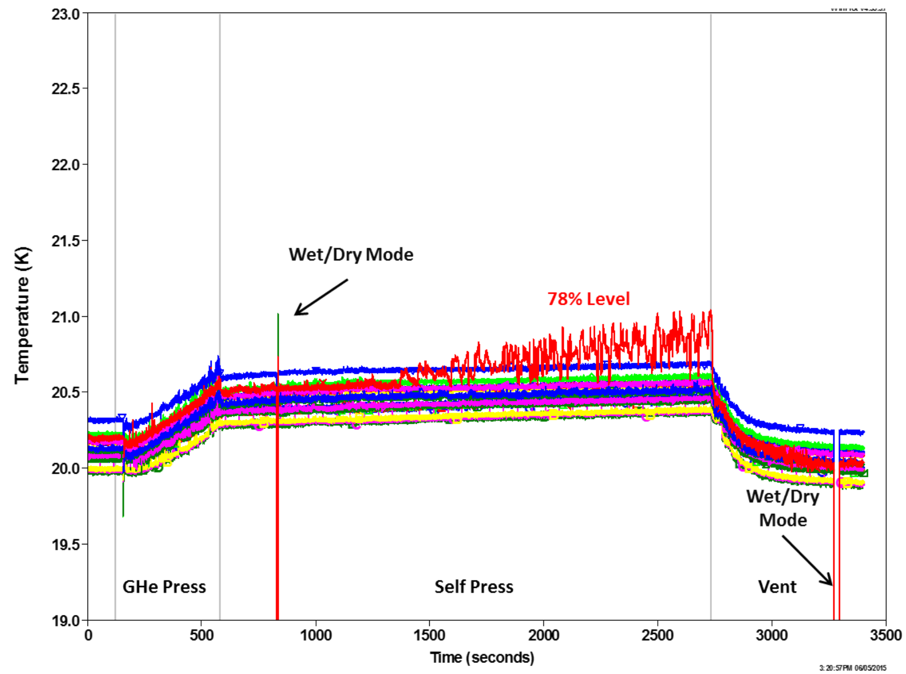
- The Tank Ullage Temperature was significantly warmer for the baseline test.
- The forward dome reached ~120 K and ~50K for the baseline test and submerged diffuser tests, respectively.
- Stratification was more evident in the baseline test, especially after venting.

Tank Liquid Temperature vs Time
Tank Liquid Level 78%

Baseline Test - Pressurant Gas to Ullage



Comparison Test - Sub-Surface Pressurization



- The Tank Liquid remained between 20K and 20.5K for both tests.
- Temperature increase during pressurization was noticed in the submerged diffuser test, but not the baseline test.
- Increase in temperature at the liquid surface was noted on both tests.

Pressurization Testing Conducted at MSFC
in
September 2015

Cryogenic Liquid: Nitrogen
Pressurant Gas: Ambient Helium
Automated Bang-Bang Pressure Control

Pressurization Tests Conducted

Day 1: Facility and test article checkouts, cold shock with LN2

- **Test #1**
  - **Filled EDU tank to 90% Liquid Level with LN2**
  - **Pressurized tank ullage space to 38+/-0.5 PSIA through the aft (submerged) diffuser using the bang-bang control system and gaseous helium**
  - **Conducted an outflow to 70% Liquid Level while maintaining ullage pressure at 31.5 +/- 0.5 PSIA**

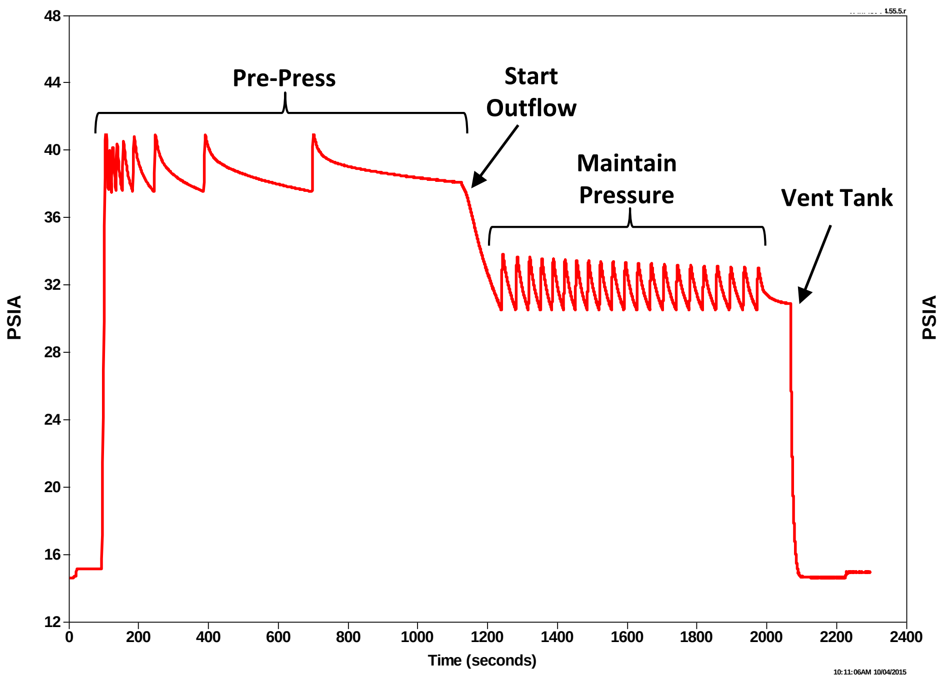
- **Test #2**
  - **Filled EDU tank to 90% Liquid Level with LN2**
  - **Pressurized tank ullage space to 38+/-0.5 PSIA through the forward (Ullage) diffuser using the bang-bang control system and gaseous helium**
  - **Conducted an outflow to 70% Liquid Level while maintaining ullage pressure at 31.5 +/- 0.5 PSIA**

- **Test #3**
  - **Repeat Test #2**

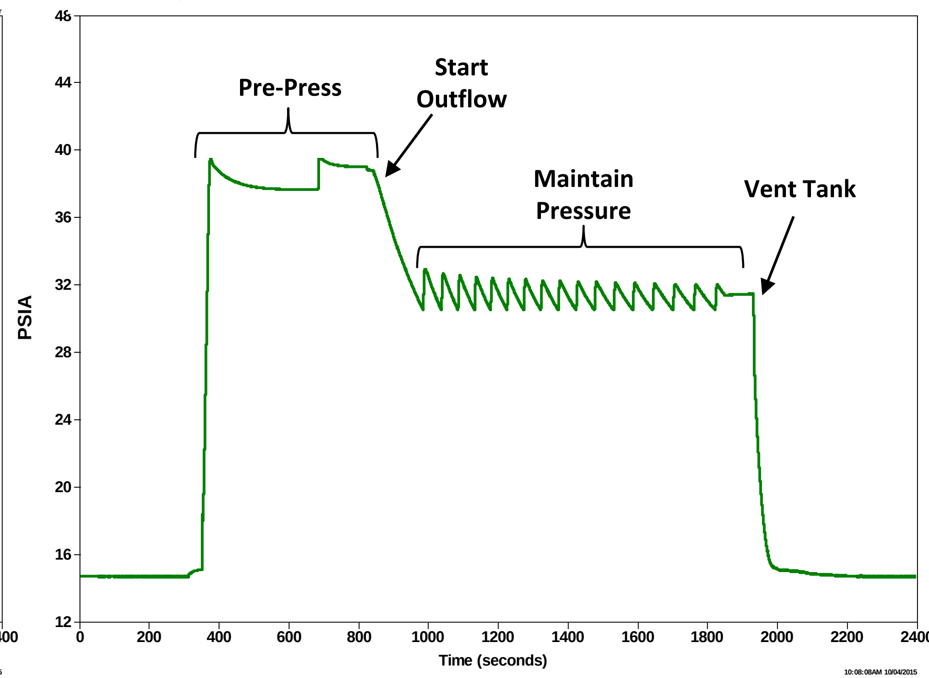
- **Test #4**
  - **Repeat Test #1**

Tank Ullage Pressure
Liquid Nitrogen and Gaseous Helium

Baseline Test - Pressurant Gas to Ullage

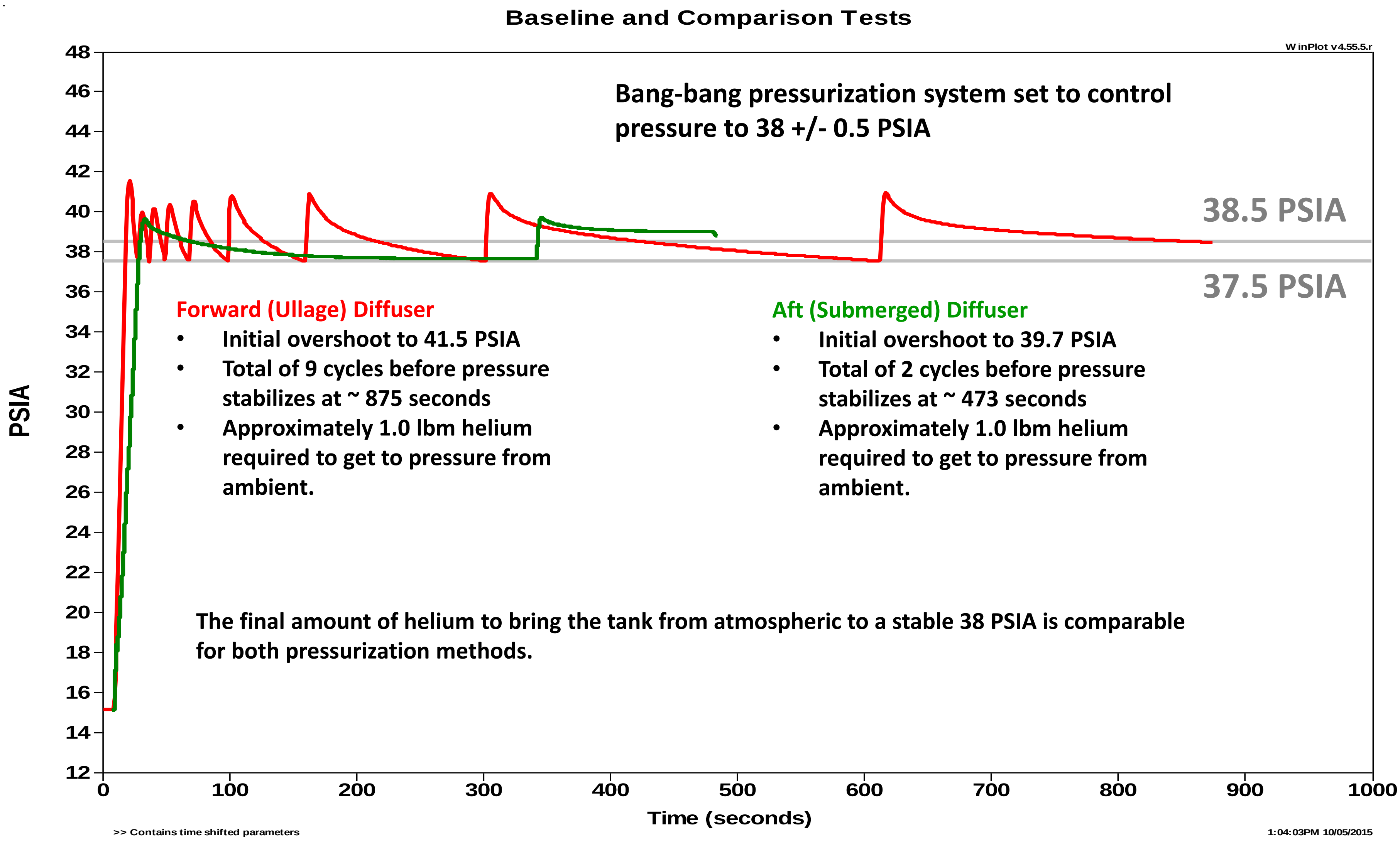


Comparison Test - Sub-Surface Pressurization



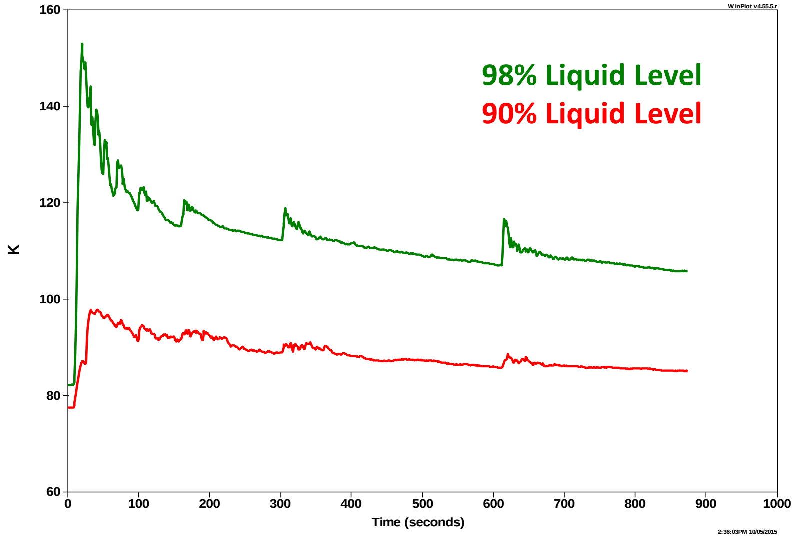
- Tank initially filled to 90% liquid level with liquid nitrogen
- Ambient Helium used as a pressurant gas
- Started with liquid and ullage saturated at 14.696 PSIA
- Prepressed to 38+/-0.5 PSIA
- Outflow to 70% liquid level
- Maintain pressure using bang-bang control to 31.5+/-0.5 PSIA
- Vented tank back down to atmospheric conditions

Tank Ullage Pressure - Pre-Pressurization
Liquid Nitrogen and Gaseous Helium

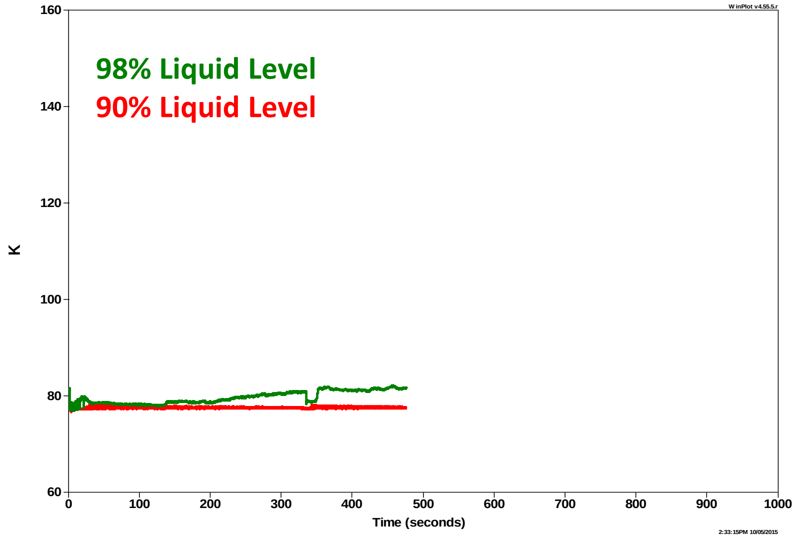


Tank Temperature - Pre-Pressurization
Liquid Nitrogen and Gaseous Helium

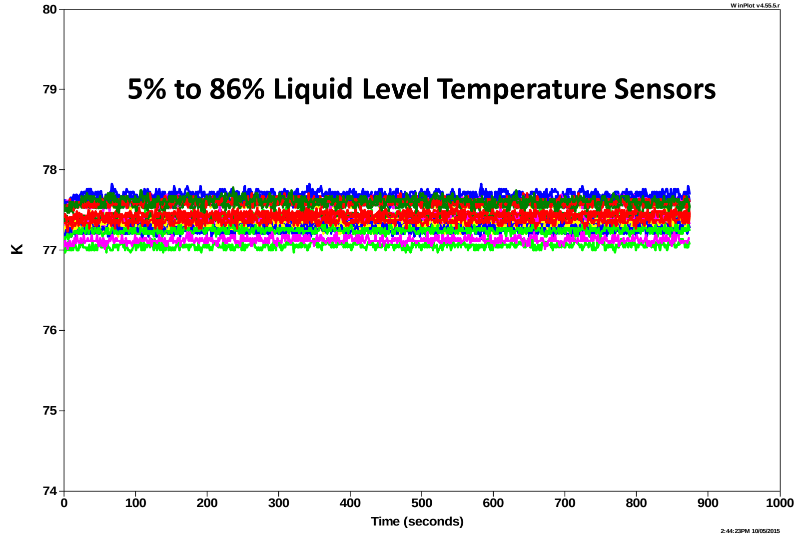
Pressurant Gas to Ullage – Ullage Temps



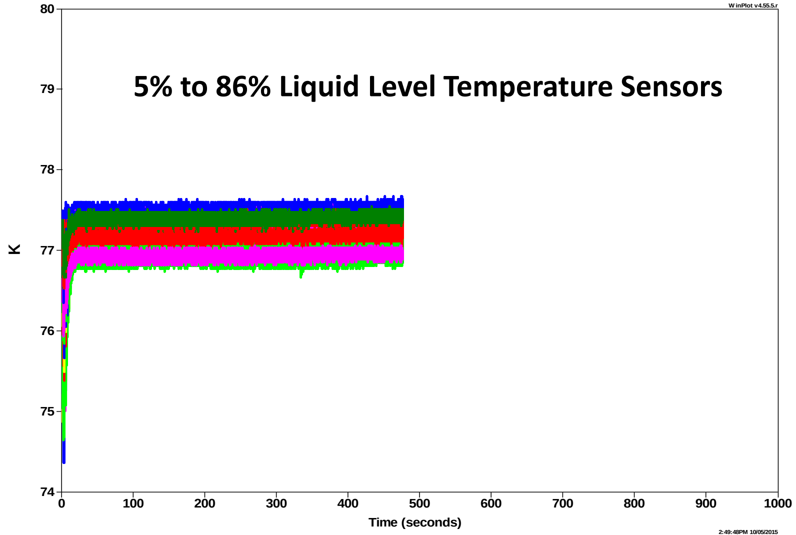
Sub-Surface Pressurization – Ullage Temps



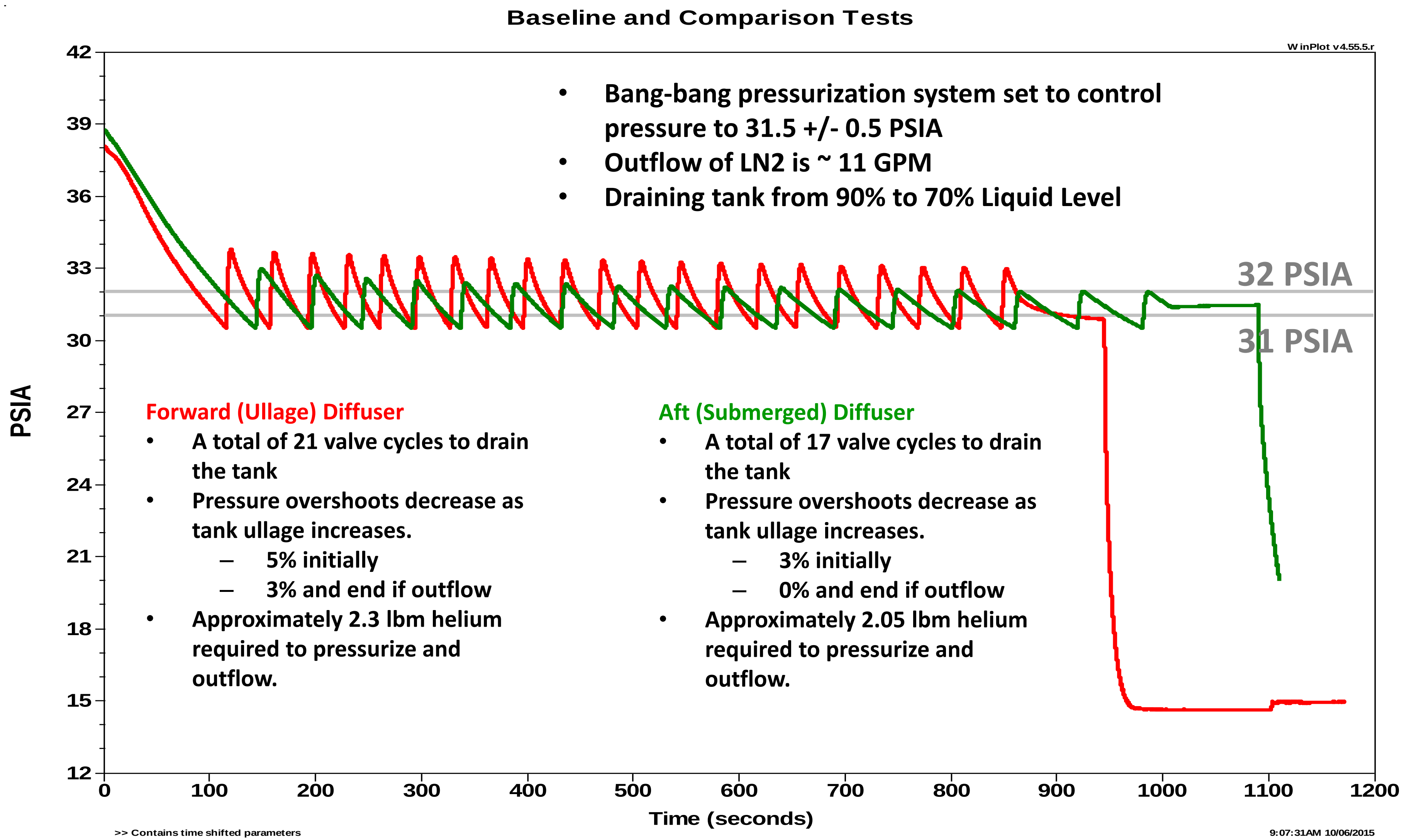
Pressurant Gas to Ullage – Liquid Temps



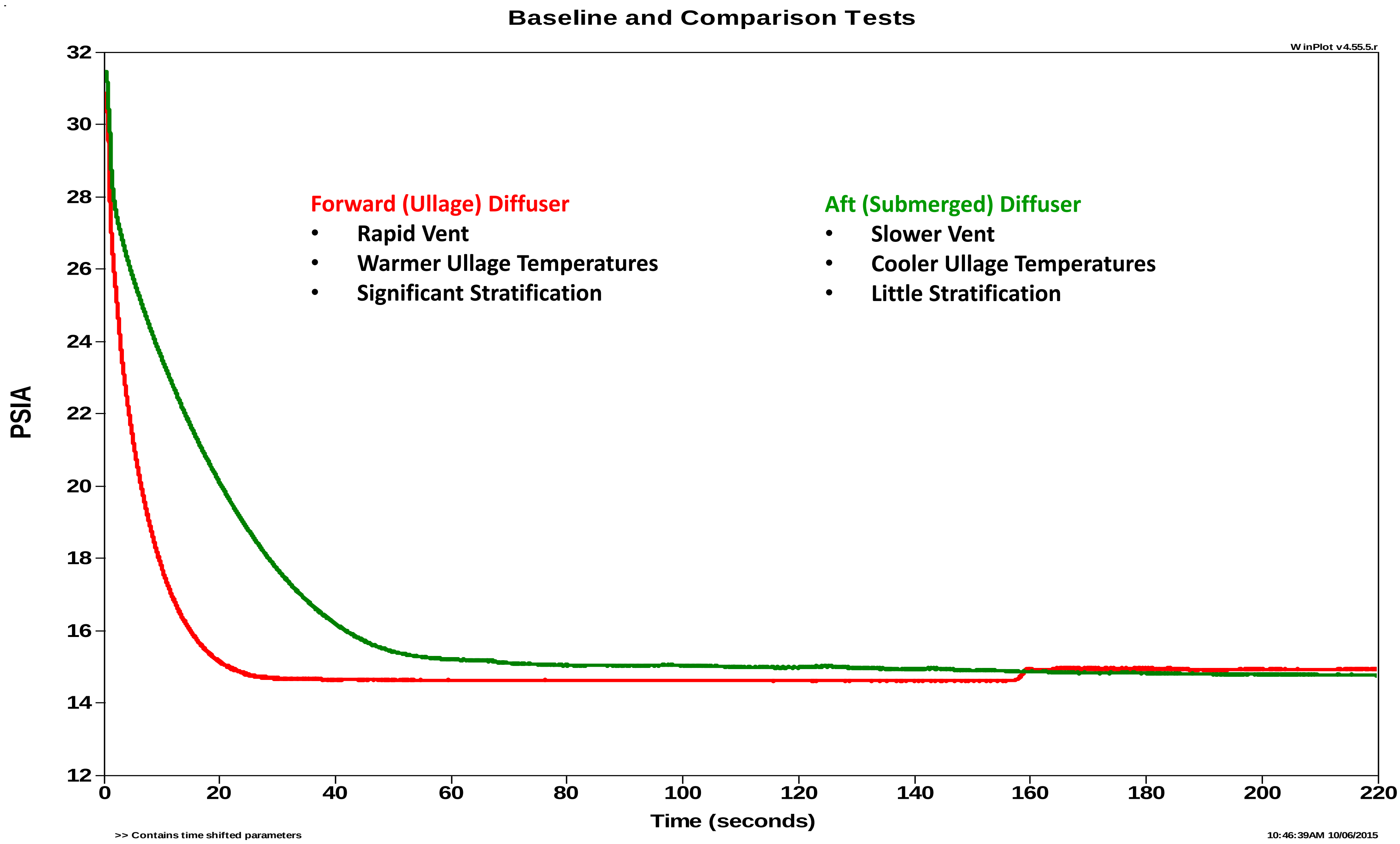
Sub-Surface Pressurization – Liquid Temps



Tank Ullage Pressure - Propellant Outflow
Liquid Nitrogen and Gaseous Helium

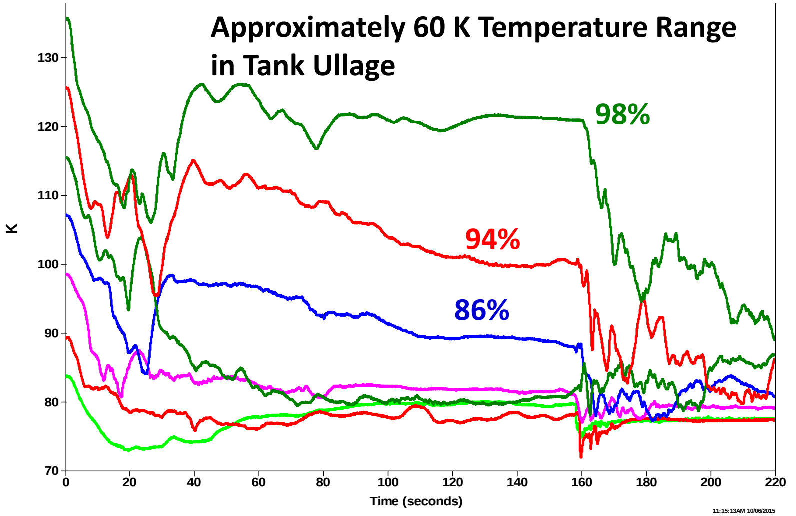


Tank Ullage Pressure - Tank Vent to Atmosphere
Liquid Nitrogen and Gaseous Helium

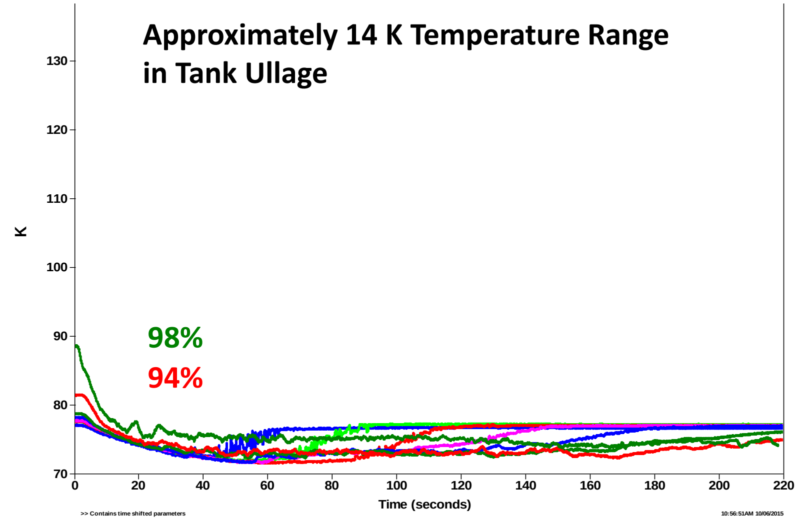


Tank Temperature - Tank Vent to Atmosphere
Liquid Nitrogen and Gaseous Helium

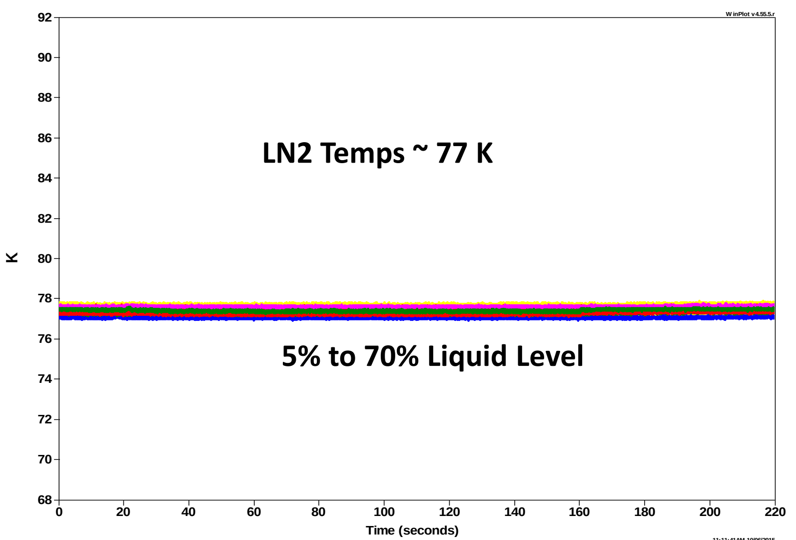
Pressurant Gas to Ullage – Ullage Temps



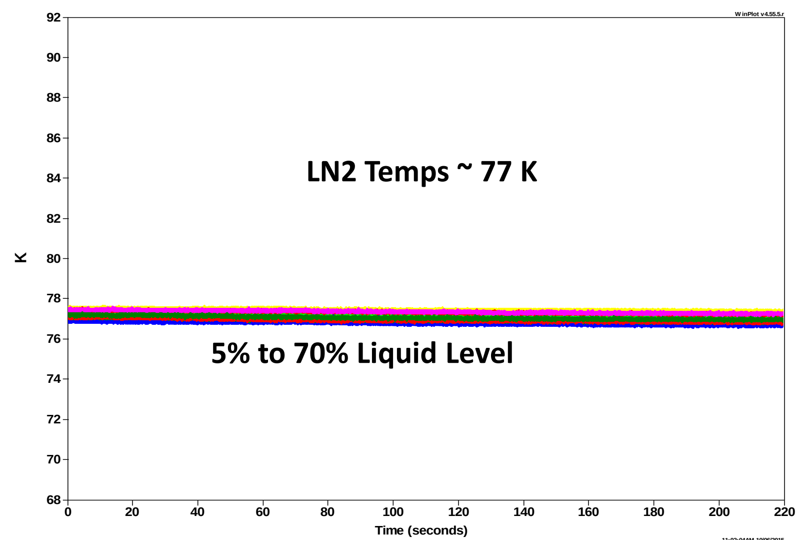
Sub-Surface Pressurization – Ullage Temps



Pressurant Gas to Ullage – Liquid Temps



Sub-Surface Pressurization – Liquid Temps



Pressurization Testing Conducted at MSFC
in
September 2015

Cryogenic Liquid: Hydrogen
Pressurant Gas: Ambient Helium
Automated Bang-Bang Pressure Control

Pressurization Tests Conducted

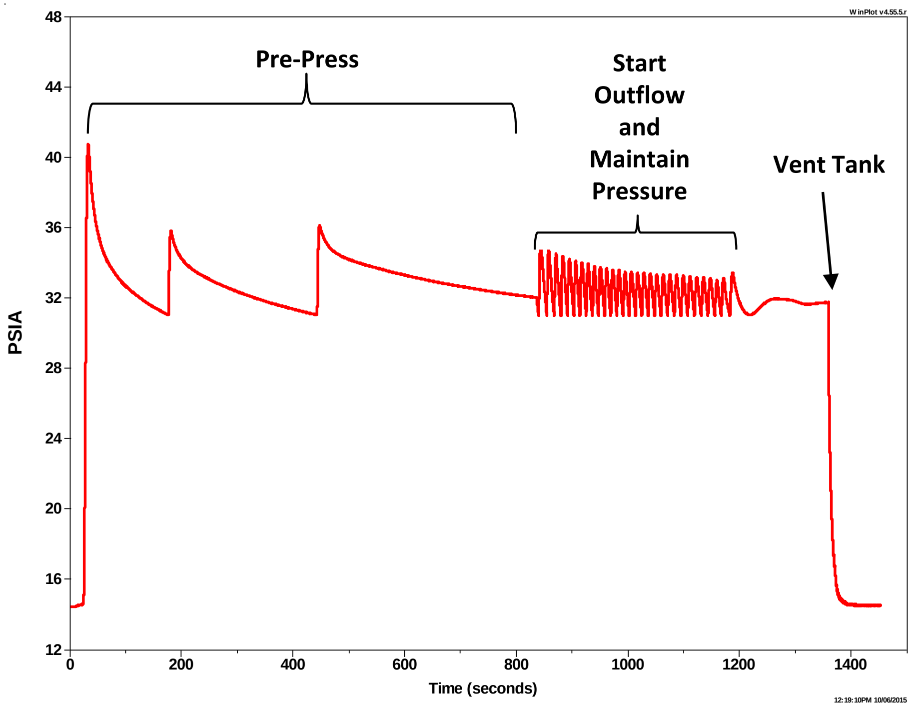
Day 4: Pressurization tests with LH2 and ambient gaseous helium

- **Test #1**
  - **Filled EDU tank to 94% Liquid Level with LH2**
  - **Pressurized tank ullage space to 31.5 +/- 0.5 PSIA through the aft (submerged) diffuser using the bang-bang control system and gaseous helium**
  - **Conducted an outflow to 70% Liquid Level while maintaining ullage pressure at 31.5 +/- 0.5 PSIA**

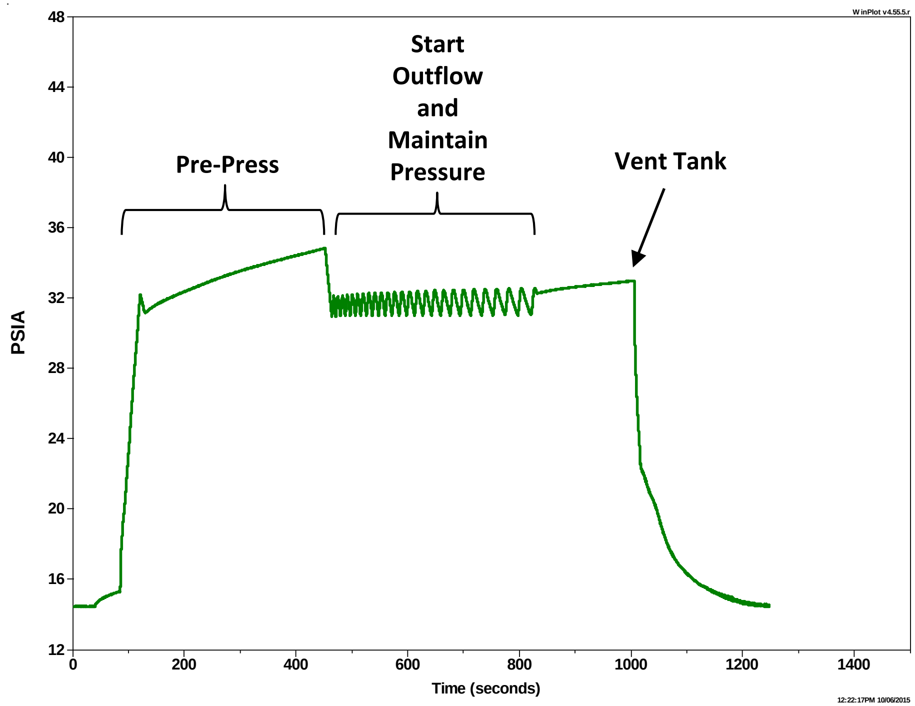
- **Test #2**
  - **Filled EDU tank to 94% Liquid Level with LH2**
  - **Pressurized tank ullage space to 31.5 +/- 0.5 PSIA through the forward (Ullage) diffuser using the bang-bang control system and gaseous helium**
  - **Conducted an outflow to 70% Liquid Level while maintaining ullage pressure at 31.5 +/- 0.5 PSIA**

Tank Ullage Pressure
Liquid Hydrogen and Gaseous Helium

Baseline Test Pressurant Gas to Ullage

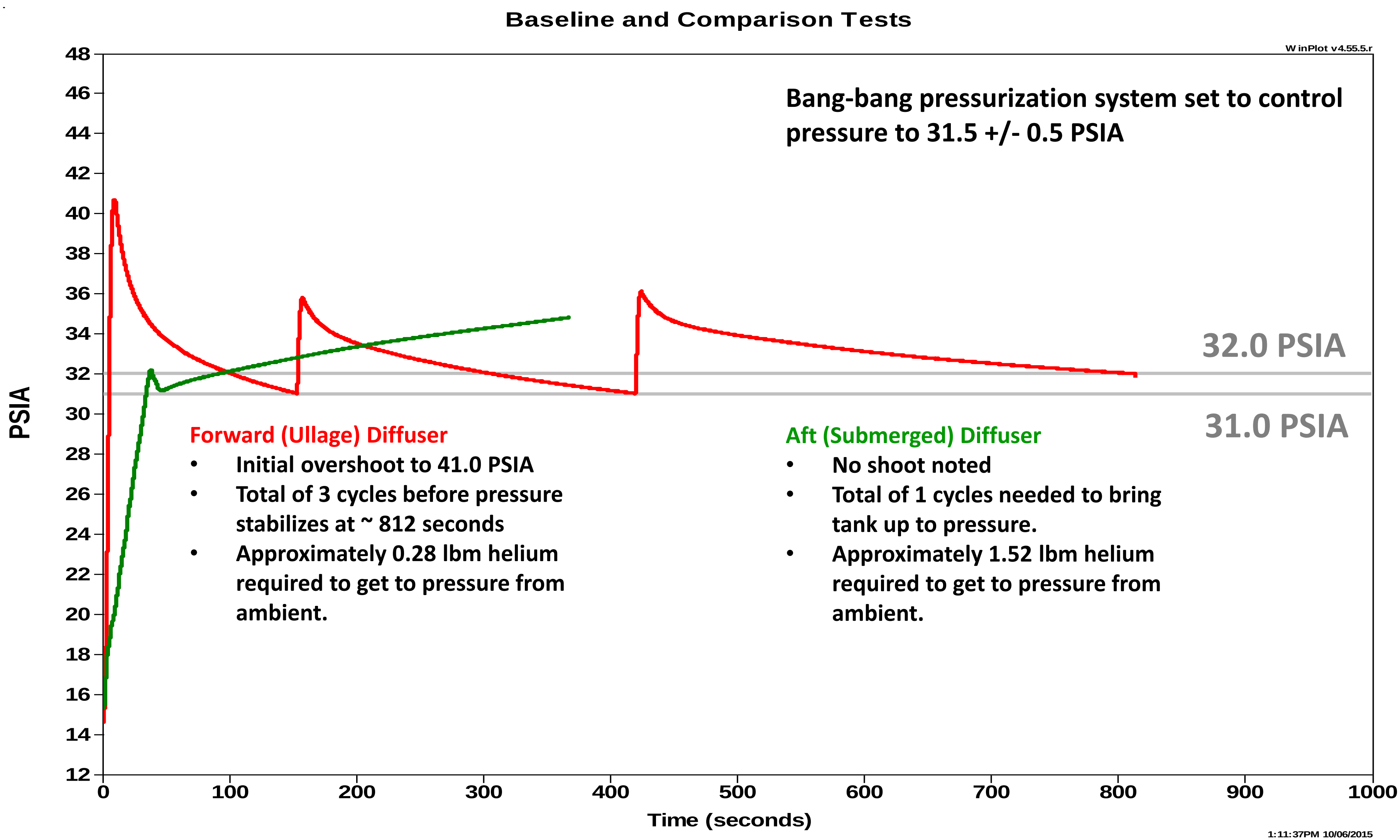


Comparison Test Sub-Surface Pressurization



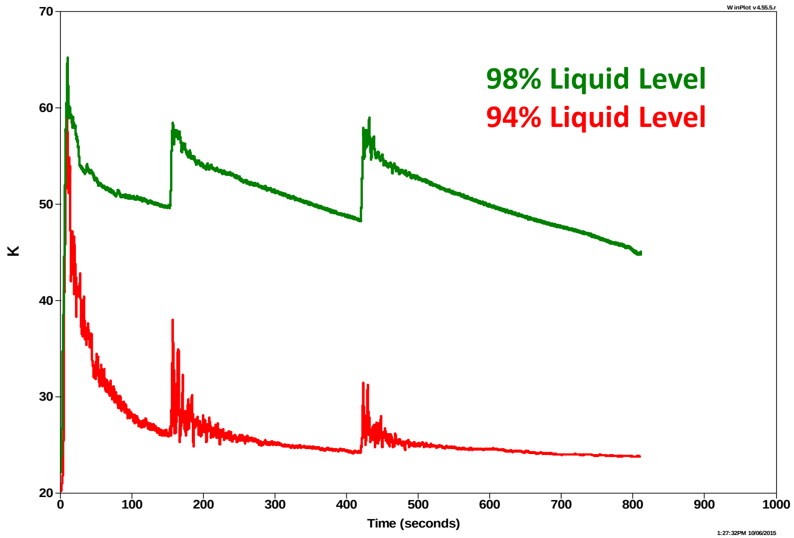
- Tank initially filled to 94% liquid level with liquid hydrogen
- Ambient Helium used as a pressurant gas
- Started with liquid and ullage saturated at 14.696 PSIA
- Prepressed to 31.5 +/- 0.5 PSIA
- Outflow to 70% liquid level
- Maintain pressure using bang-bang control to 31.5+/-0.5 PSIA
- Vented tank back down to atmospheric conditions

Tank Ullage Pressure - Pre-Pressurization Liquid Hydrogen and Gaseous Helium

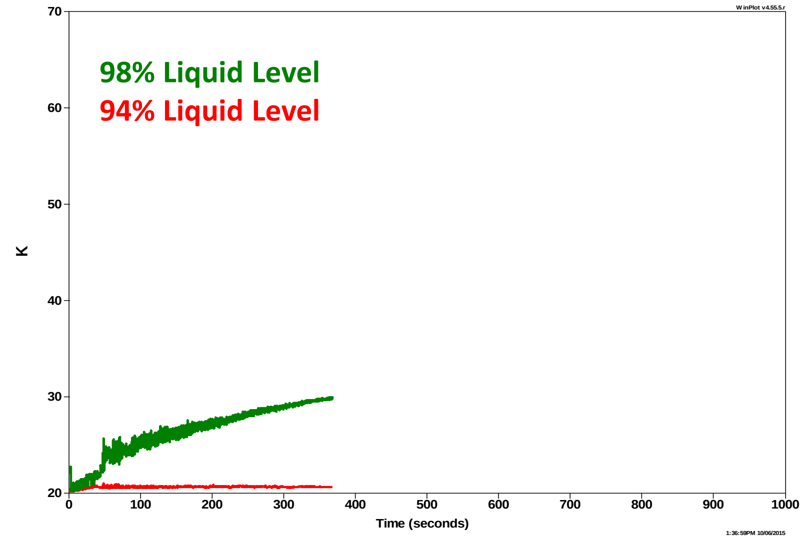


Tank Temperature - Pre-Pressurization
Liquid Hydrogen and Gaseous Helium

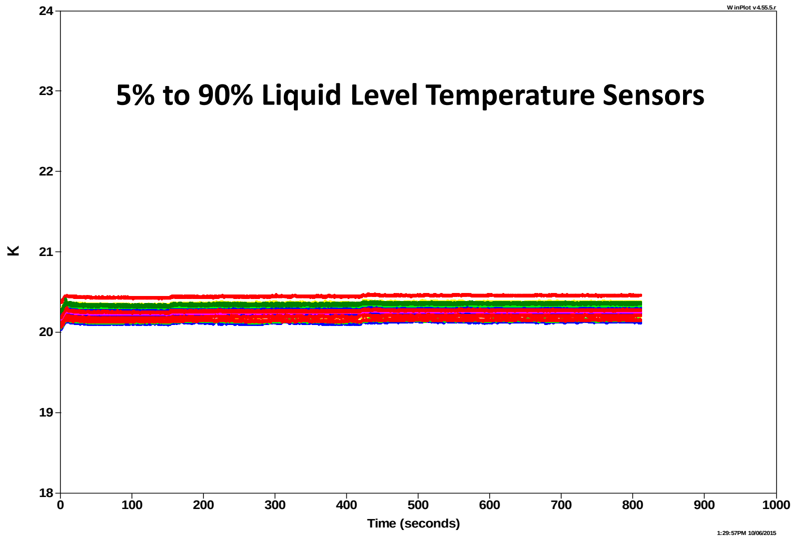
Pressurant Gas to Ullage – Ullage Temps



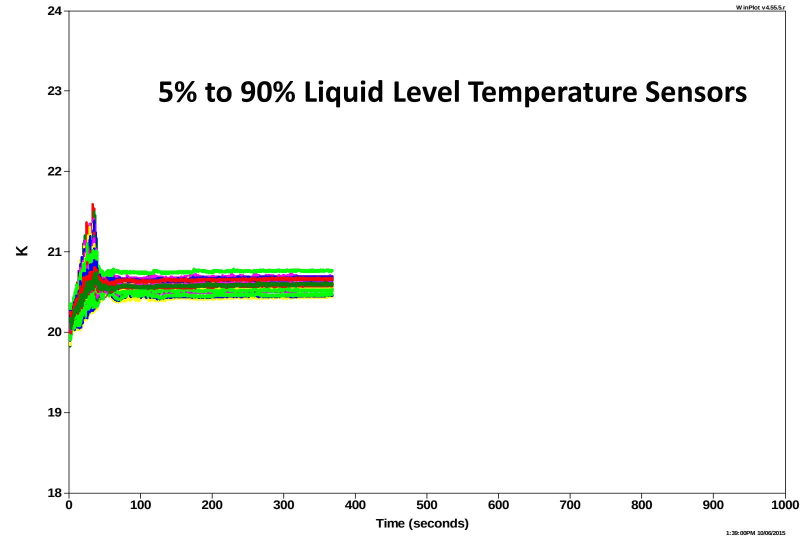
Sub-Surface Pressurization – Ullage Temps



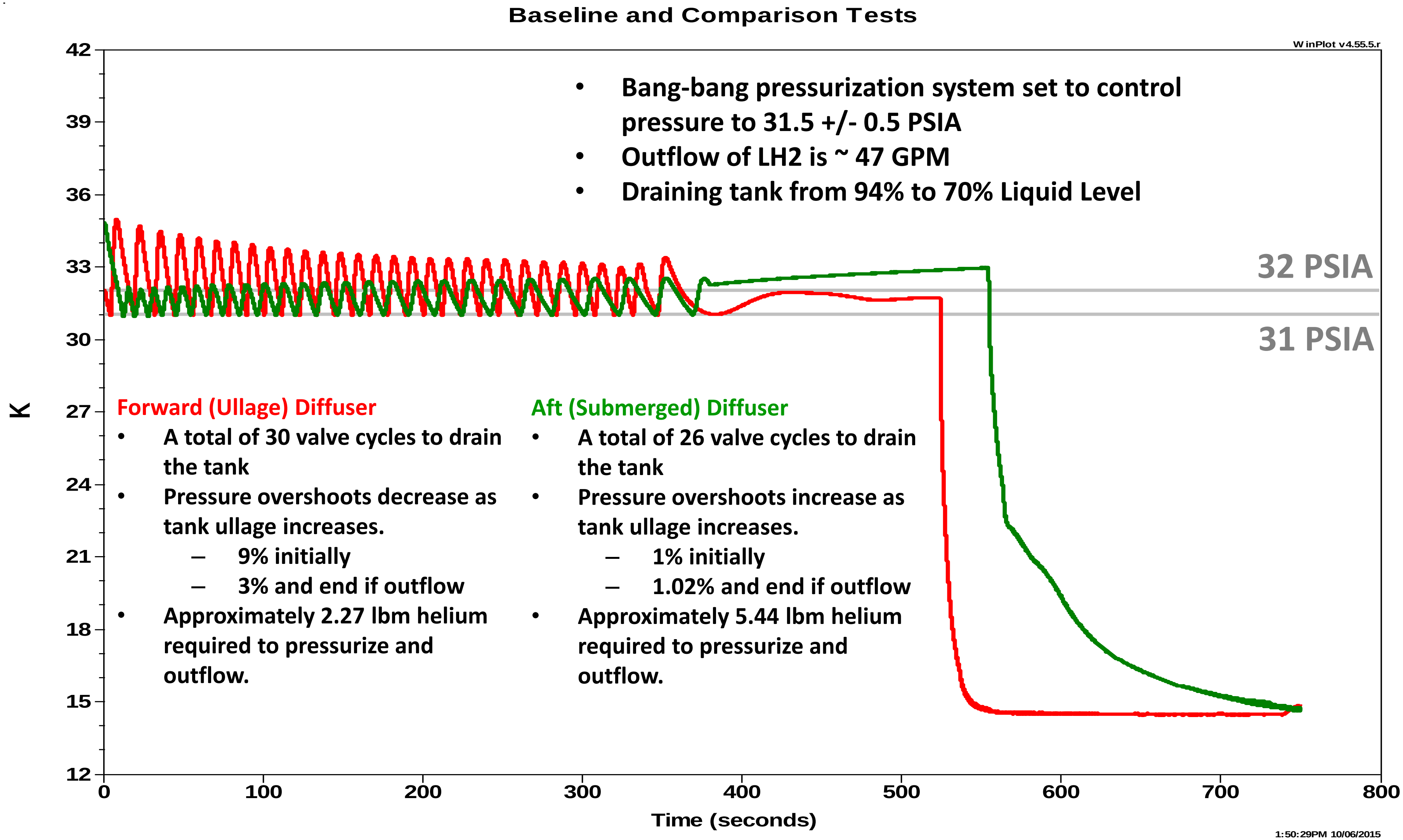
Pressurant Gas to Ullage – Liquid Temps



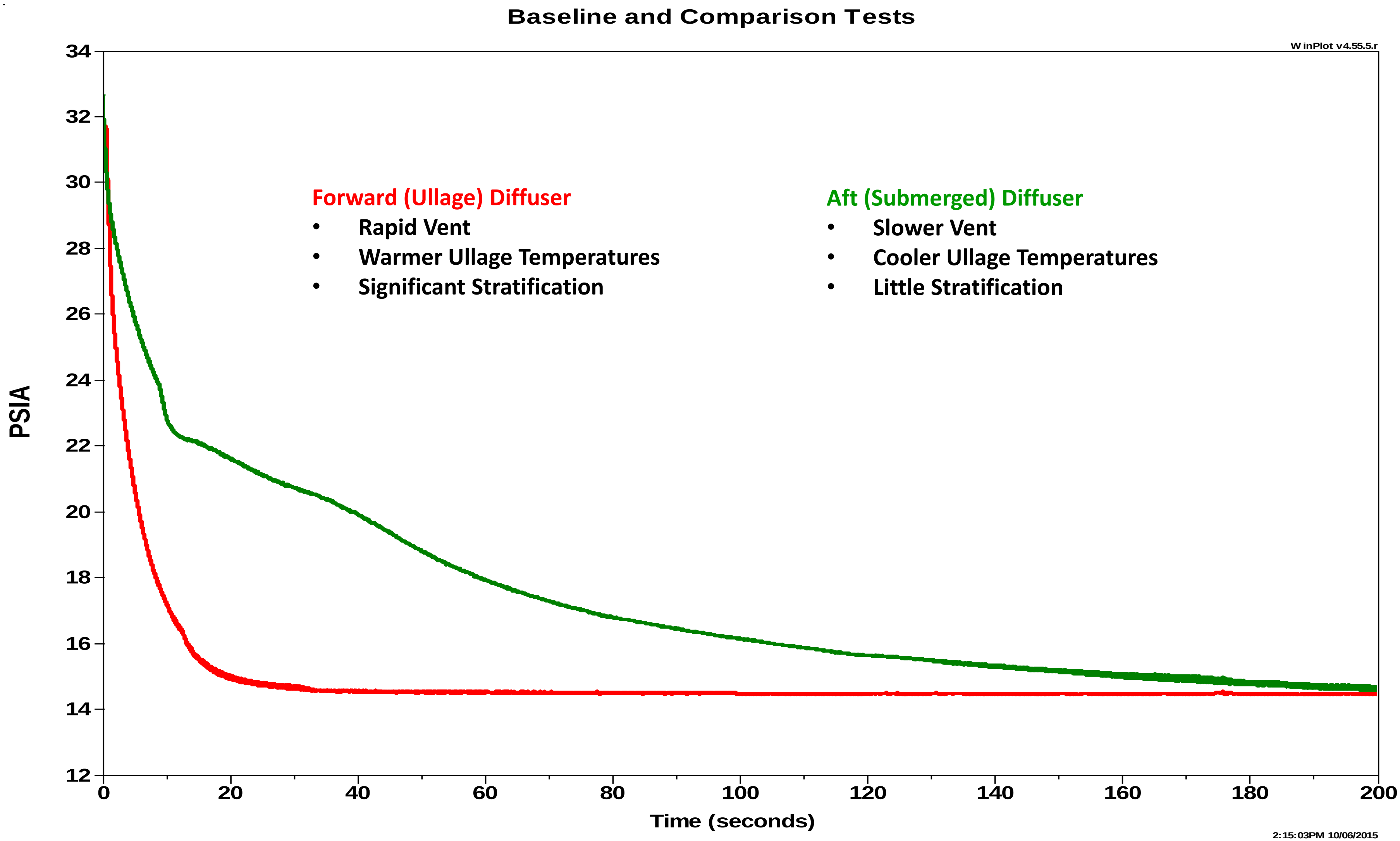
Sub-Surface Pressurization – Liquid Temps



Tank Ullage Pressure - Propellant Outflow
Liquid Hydrogen and Gaseous Helium

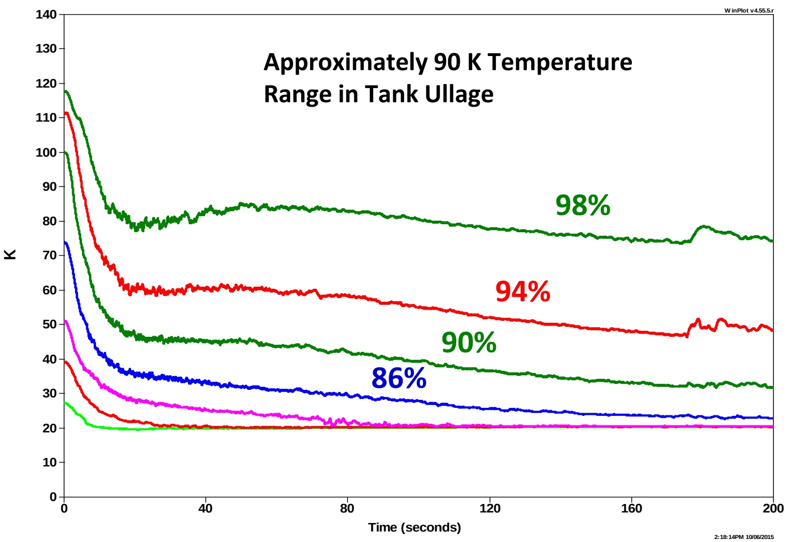


Tank Ullage Pressure - Tank Vent to Atmosphere
Liquid Hydrogen and Gaseous Helium

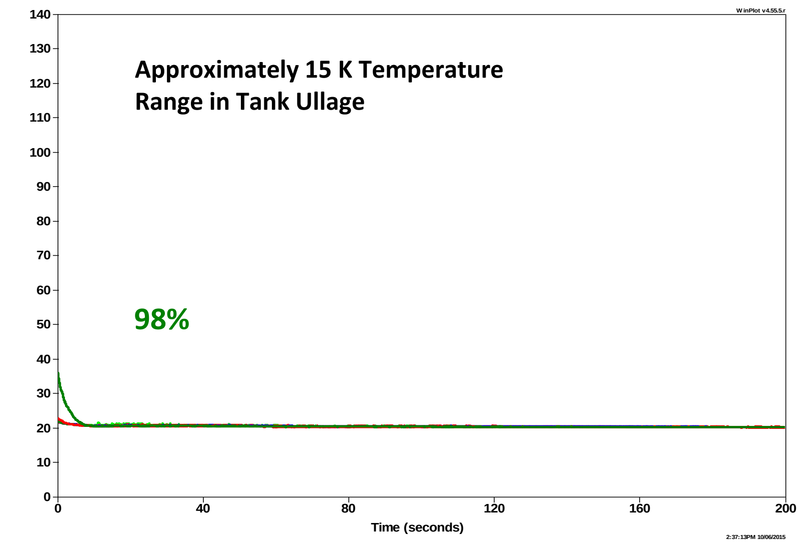


Tank Temperature - Tank Vent to Atmosphere
Liquid Hydrogen and Gaseous Helium

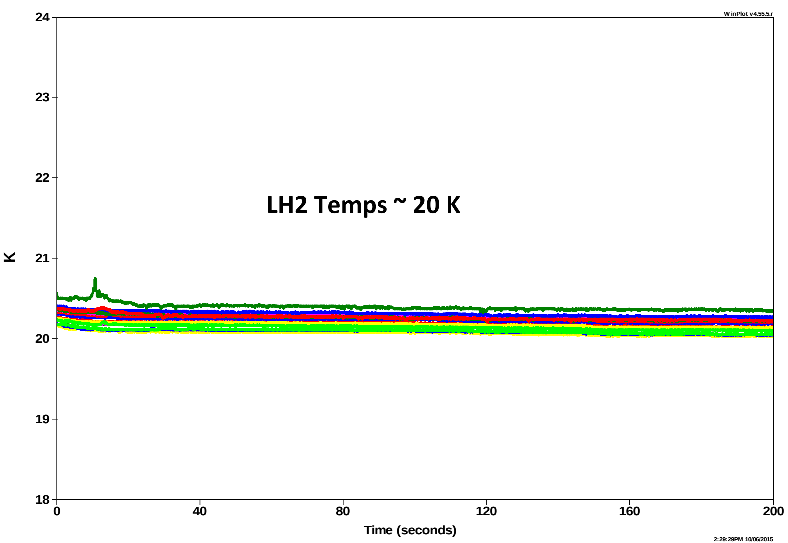
Pressurant Gas to Ullage – Ullage Temps



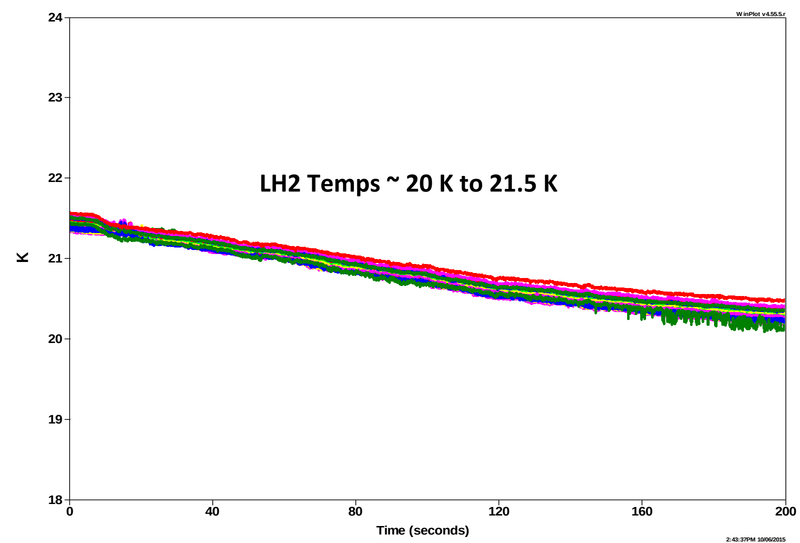
Sub-Surface Pressurization – Ullage Temps



Pressurant Gas to Ullage – Liquid Temps



Sub-Surface Pressurization – Liquid Temps



Summary

CONCLUSIONS

- The bang-bang pressurization tests with sub-surface pressurization were conducted successfully for both liquid nitrogen and liquid hydrogen using helium as a pressurant gas.
- The pressurization system was sized sufficiently and maintained tank ullage pressure during propellant outflow thanks to the modeling efforts of Andre Leclair (ER43).
- Sub-Surface Pressurization with a bang-bang Control System
  - Requires fewer pressurization cycles to prepress and maintain tank pressure.
  - Results in smaller overshoots when compared to applying pressurant gas directly to the tank ullage space.
  - Pressure is maintained without significant pressure slumps or overshoots
  - Little ullage gas stratification after tank vent when compared to applying pressurant gas directly to the tank ullage space.
- Sub-Surface Pressurization utilizing ambient helium as a pressurant gas appears to have a more significant adverse effects with liquid hydrogen than with liquid nitrogen.
  - Helium dissolves in hydrogen
  - Helium gas collapses further due to the lower temperature of liquid hydrogen.