Zero Boil Off System Testing

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Executive Summary

Objectives

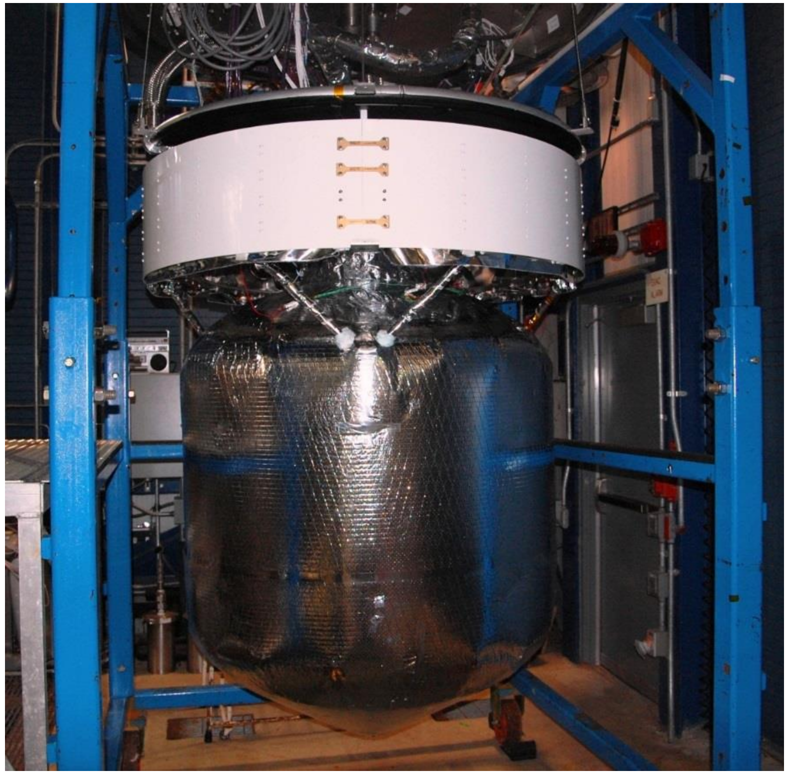
- Advance technology to enable spaceflight systems capable of storing LOX in space with zero boil-off
  - Task funded by Space Technology Mission Directorate
- Conduct ground demonstration with active thermal control technologies to demonstrate ability to achieve LOX ZBO. Tank and structures (conductive heat paths) should be representative of designs for flight loads.
  - Validate design of tube-on-tank distributed cooling network at 95.6K

Approach:

- Integrate a reverse turbo-Brayton cycle cryocooler with a propellant tank to achieve zero-boil off LN2 storage (LOX surrogate) with low thermal and flow loss.
- Demonstrate ability to control tank pressure using active cooling system.

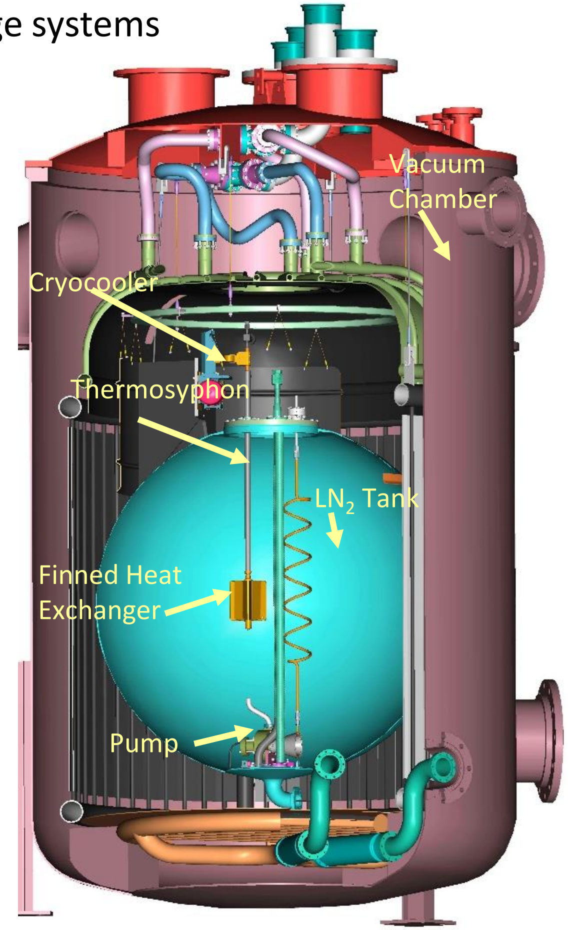
Results:

- An extensible and low-loss integrated design of distributed active cooling has been proven.
  - No loss propellant storage has been demonstrated with less than 4K thermal gradient, from top to bottom
  - Robust ability to control tank pressure demonstrated



Active Cooling Background/Definitions

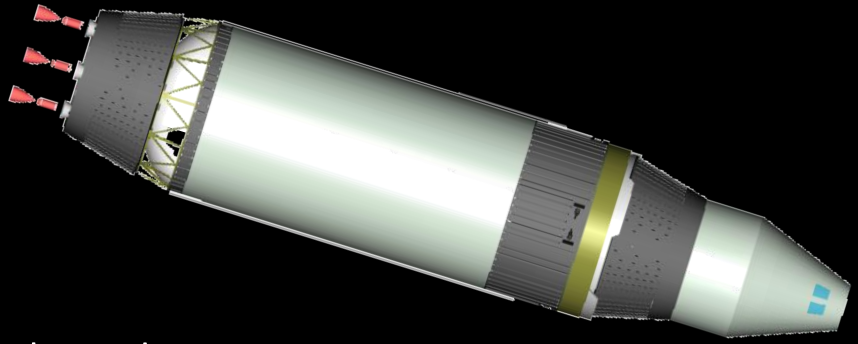
- NASA's future mission architecture's cryogenic propellant based stages will require long duration in-space storage of LH_2 and LO_2
- Propellant losses due to solar insolation and planetary albedo for these long duration missions must be minimized to insure mission cost effectiveness and success
  - Analysis has shown that use of a cryocooler to "actively" cool the LO2/LH2 storage systems becomes the mass efficient approach for missions longer than a few weeks
- Following a NASA depot study, focus has been on Cryogenic Boil-Off Reduction System to cool large tank surface areas
  - 2007 study by Glenn and Ames
  - Bench testing at Ames
  - 2009 system test at Ball
  - 2011 trade study at Glenn
- Boil-off reduction is accomplished by distributed or *broad area cooling (BAC)*
  - A transport gas (typically neon or helium) is cooled by the cryocooler and then circulated through a tubing loop covering the outer surface area of the propellant tank
  - The transport gas efficiently distributes the cooling capacity of the cryocooler throughout the surface of propellant tank storage system

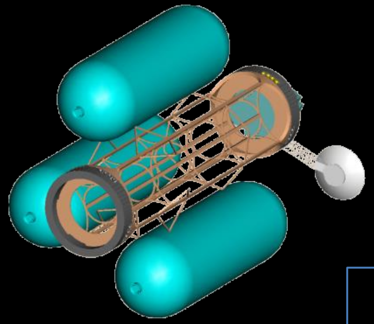


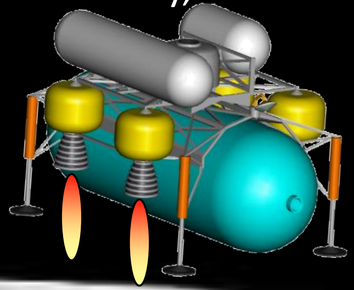
Advanced ZBO Demonstration, 2003

Objectives

- Three main objectives:
  - Demonstrate robust ZBO
    - Use the cryocooler to control tank pressure
    - Operate cryocooler over extended period of time
    - Use cryocooler to reduce tank pressure
    - Find if homogenous pressurization model can be accurately used
  - Eliminate boil-off at low fill levels
    - Condition will occur for in-space propellant depots and for multi-burn upper stages
    - Low fill level cryogenic tanks exacerbates tank stratification
  - Validate Scaling Study
    - D. Plachta, M. G. (2014). *Cryogenic Boil-Off Reduction System Scaling Study.* Elsevier, www.elsevier.com/locate/cryogenics.
    - Predicts ZBO inclusion reduces mass for loiter periods > week, when compared to MLI only, as used for cryogenic propellant storage







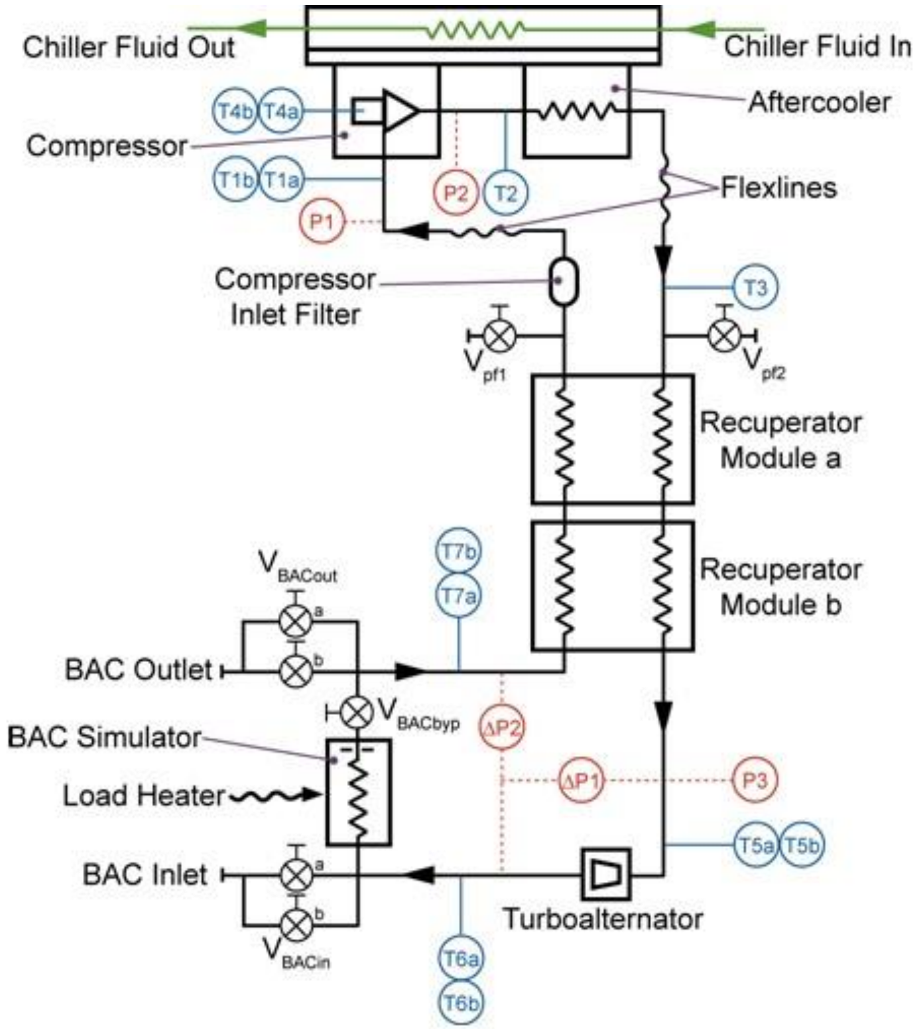
Facility and Hardware

- NASA GRC's SMiRF
  - Low Earth Orbit thermal environment
    - Cryoshroud use to create 220 K background temperature
    - Diffusion pumps create average hard vacuum of 1x 10^{-6} torr
  - LN_2 as LOX surrogate
    - Assumed LOX propulsion requirement at 25 psi, 95.6 K
    - Pressurized LN_2 to 82 psi, 95.6 K
- Test article assembled to vacuum chamber lid
  - Ring supported from lid
    - Cryocooler, radiator, and tank supported from ring
  - Tank diameter 1.2 m, volume 1.2 m^3
  - Tank struts 0.38 m long, wall thickness 0.8 mm (.032")
  - Radiator aluminum panel 4 mm thick, loop heat pipe design

Instrumentation

Location	Count	SD/TC	Notes – Purpose
Diode Rake	8	8/0	Liquid temperature and liquid level indication. Key sensors at 96.9, 87.2, and 28.4 % full.
Tank Wall	13	12/1	Exterior tank temperatures at top, bottom, and between cooling loops.
BAC System	28	21/7	Measure BAC system temperatures (cooling tubes, manifolds, and thermal strap)
Penetrations	16	6/10	Two at warm and two at cold end of vent, fill/drain, and cap probe. Used for heat leak calc's
Struts	26	2/24	Two at warm and two at cold ends. Heat leak calculations.
Radiator	25	0/25	Map radiator performance.
MLI	11	0/11	Determine MLI temperature profile.
Supports/cabling	12	0/12	Used to find misc. heat leak through wire bundles & suspension hardware.
Cryoshroud	18	0/18	Boundary temperature definition and control.
Tank Pressure	2	NA	Measure and control tank pressure. Range of sensors were 0-50 and 0-100 psia.
Boil-off Flow	4	NA	Mass flowmeters used to measure boil-off rates
Tank/Strut Heaters	14	NA	Warm up tank, warm liquid, and set warm boundary temperature on struts

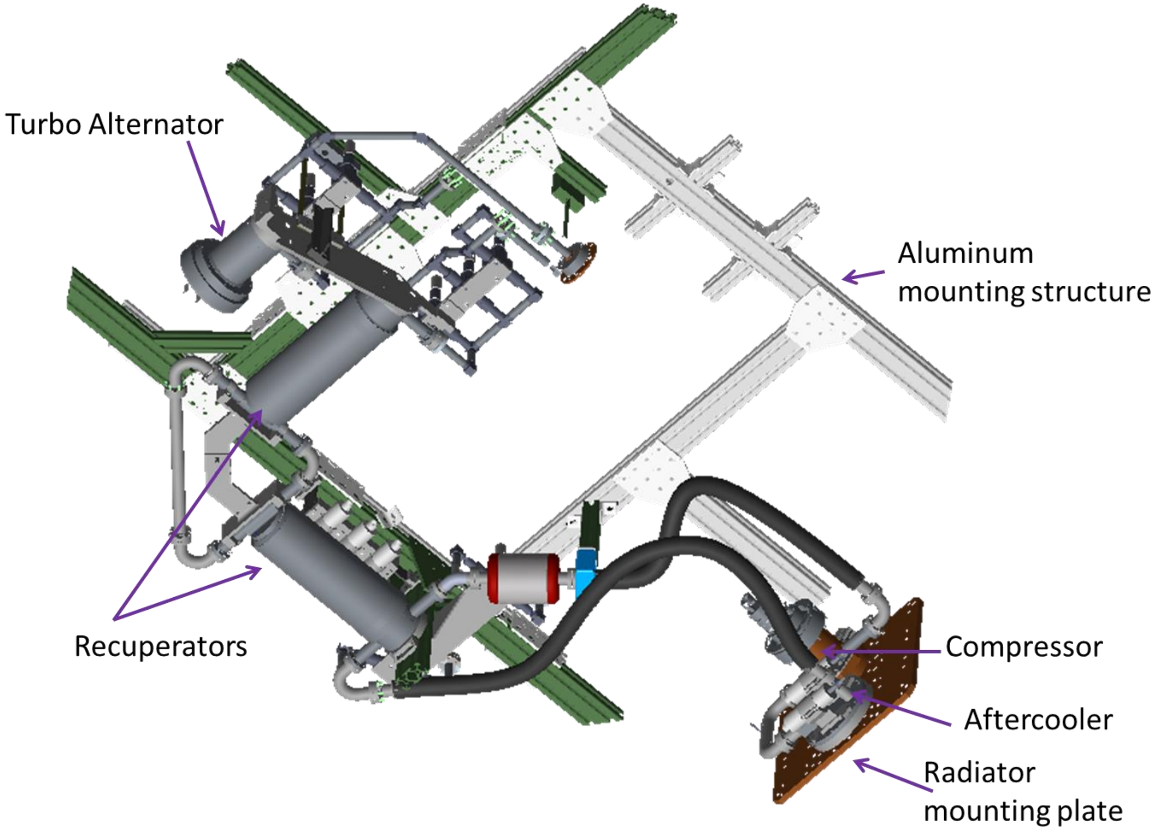
Cryocooler Instrumentation:



Cryocooler and MLI

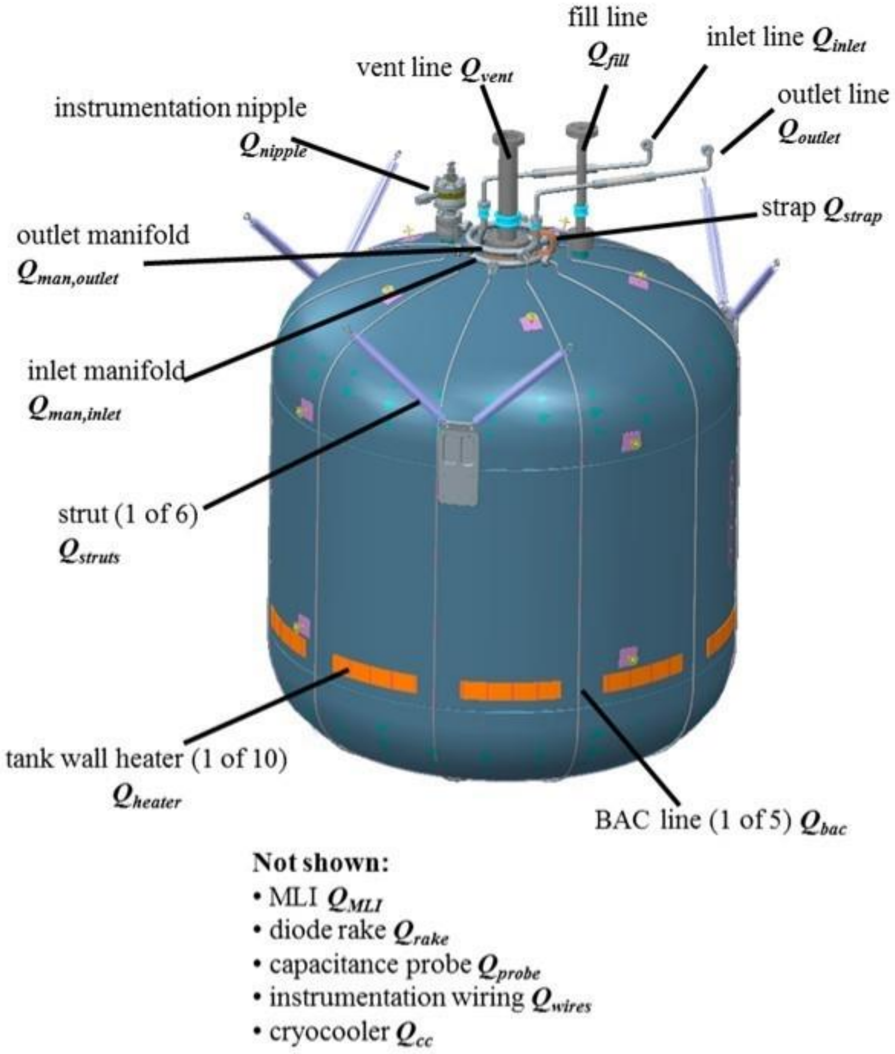
- Cryocooler: Creare reverse turbo Brayton cycle
  - Flight like design, based on the NICMOS cryocooler flown on Hubble
  - Integrated circulator for distributed cooling of neon at 2 g/sec, 2 atm
  - Capacity 15 W at 77 K

- Tank MLI
  - 75 layers of double aluminized Mylar
    - Traditional MLI design, 2 blankets 38 layers each
    - Seems butted and stich taped every 5th layer
  - 2 sheets of Dacron netting between Mylar layers
  - 1% perforations in outer 2-mil cloth reinforced Mylar
  - Layer density 24 layers/cm



Broad Area Cooling System

- Tube-on-tank design
  - ¼” tubes spot welded every foot
  - Tubes epoxied down length
  - Supply and return manifolds used at tank top to feed cooling loops
    - 5 loops run down tank wall
    - Spacing every 36 degrees around tank
    - No trim valves or orifices used
  - 4.2 m line length on tank
    - Cryocooler supply and return hoses 1 m long
    - 0.25 psi pressure drop



Test Plan

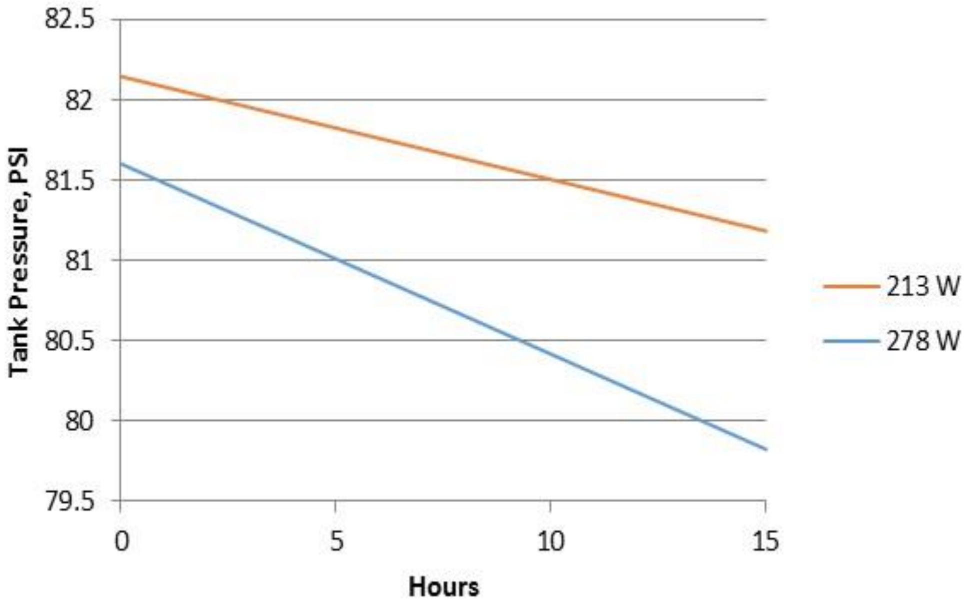
	Fill Level	Type	Purpose
Test 1	95%	Passive boil-off	Find tank heat leak
Test 2	95%	Passive Pressurization	Find tank pressure rise rate
Test 3	95%	ZBO	Achieve ZBO; collect data
Test 4	95%	ZBO high power	Find robustness of ZBO system
Test 5	95%	ZBO low power	More data to map pressurization rate with cooler power
Test 6	95%	ZBO destratification	Find tank pressure rise rate with tank heat added while at ZBO
Test 7	95%	ZBO high power 2	More data to map pressurization rate with cooler power
Test 8	25%	ZBO	Achieve ZBO; collect data
Test 9	25%	ZBO high power	More data to map pressurization rate with cooler power
Test 10	95%	Passive boil-off with cryoshroud set to 300K	Additional MLI data point for tank applied system

Component Results

- Broad Area Cooling
  - Dropped temperature gradient between tank top to tank bottom
    - Test 1—Passive—gradient was 10.2 K
    - Test 3 gradient was 3.8 K
  - Tube-to-tank thermal gradient was 0.5 K
    - More than expected, but heat exchanger effectiveness was 0.9
    - Loss caused ~ 0.5 W increase in cryocooler input power
  - Tube-to-tube gradient was insignificant
    - No noticeable change in 5 BAC tube temperatures
  - *Structural and thermal optimization of tube-on-tank configuration is required for flight*
- Cryocooler
  - Thermally, the cryocooler performed same as bench test
  - % of Carnot ranged from 10.6 for Test 3 and 12 for Test 4.
  - High power settings dropped tank pressure
    - Tank pressure changes were akin to a battery for storing cryocooler power
  - *Integration and control remain a challenge*
    - *Control of power setting and pressure feedback loop required*
- Parasitics
  - No design or model before test; average loss was 4.2 W
  - Poor performing Mylar tape on return manifold
    - Improved insulation projected to reduce parasitic to ~1.2 to 1.5 W
  - *Flight configuration needed to design and model parasitic loss realistically*

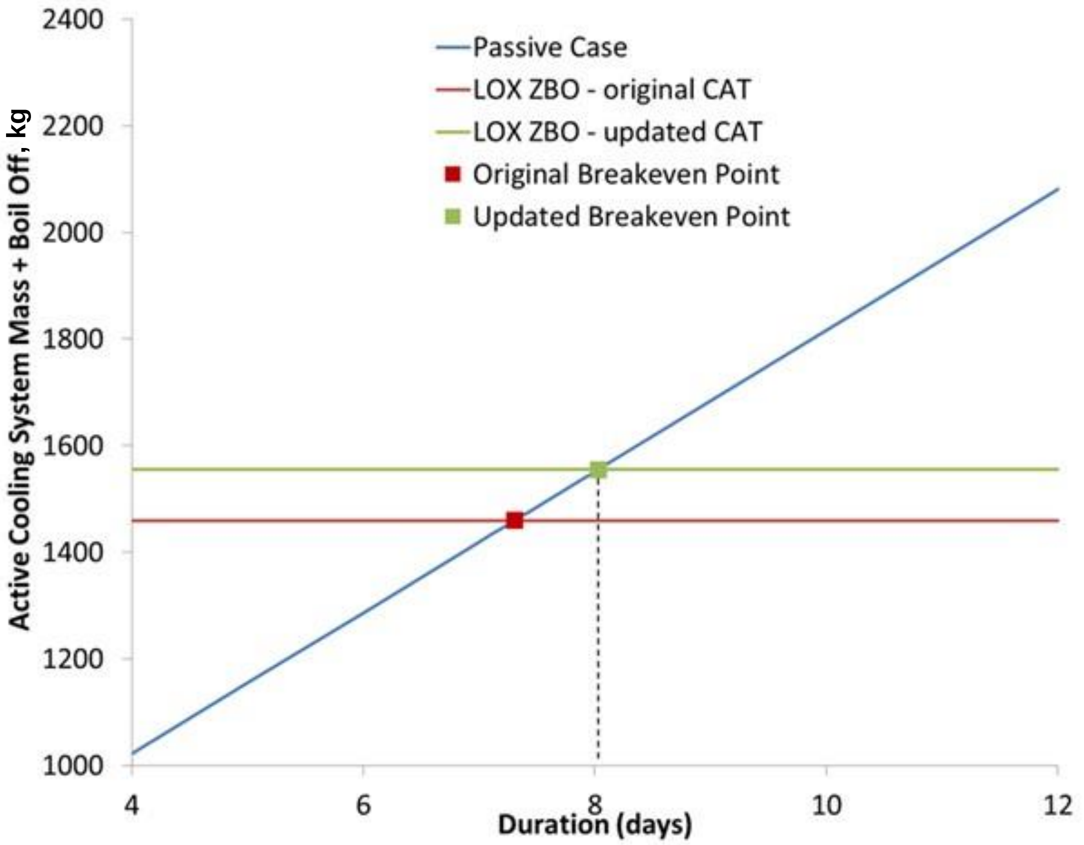
Revisiting Test Objectives

- Objective 1: Demonstrate robust ZBO
  - Cryocooler temperature setting used to control tank pressure to within +/- 0.1 psi
  - Cryocooler operated over 19 day period
    - Cryo stored without venting
  - High power settings used successfully to reduce tank pressure
    - Tank pressure dropped at rate consistent with uniform temperature pressurization model
  - Tank pressurization rate dropped 88% with active cooling
    - Test 2 tank pressure increased 36.2 kPa (4.6 W heat)
    - Test 6 tank pressure increased 1.3 kPa (2.6 W heat added to ZBO tank via heaters)
      - » dP/dt/W of tank heat leak dropped 88%
- Objective 2: ZBO at low fill level
  - High degree of stratification at low fill level did not affect cryocooler operation
    - Tank top temperature increased from 98.7 to 98.9 K
      - » Much lower than Test 1, 105.2 K
    - Cryocooler input power slightly increased (0.6%) from full tank ZBO power level to achieve ZBO



Revisiting Test Objectives

- Objective 3: Validation of Scaling Study (Cryogenics, D. Plachta, 2014)
  - In study, in-space loiter time break even point determined
    - Break even point is duration when Passive mass, MLI + boil-off, equals Active mass, MLI + cryocooler + radiator + solar array
      - » For LOX with 7.5 m tank, 186 m^3, 318 tank heat loiter period *break even point was 7.3 days*
  - Many assumptions in study
    - Test data used to update Cryogenic Analysis Tool (CAT)
      - » Most significant update was for parasitic loss
    - Dry mass increased 6.5%
      - » *Shifted break even point from 7.3 to 8 days*
  - *Test data confirms and validates predictions of scaling study*



Summary

- First of its kind demonstration of robust tank pressure control using cryocooler system
  - No venting, no mixing
- Tank stratification was cut dramatically
  - Unvented/unmixed tank pressurization rate was cut, per Watt heat leak, by 88%
  - Homogenous tank pressurization model validated
  - Tank lid to tank bottom temperature gradient dropped from 10.2 to 3.8 K
    - Tank mixer not required when active cooling system is operational
- Full ability of cryocooler system demonstrated
  - Tank pressure controlled to +/- 0.1 psi
  - Cryocooler decrease tank pressure at controlled rates at different levels of excess capacity
    - High power cryocooler operation to drop tank pressure could eliminate or reduce in-space battery requirement
- Test has validated Scaling Study, predicting large mass savings for applying ZBO to cryo upper stages
- Test series advance technology readiness level
- Test has reduced risk for future flight projects