Cryogenic Boil-Off Reduction System Testing

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Introduction

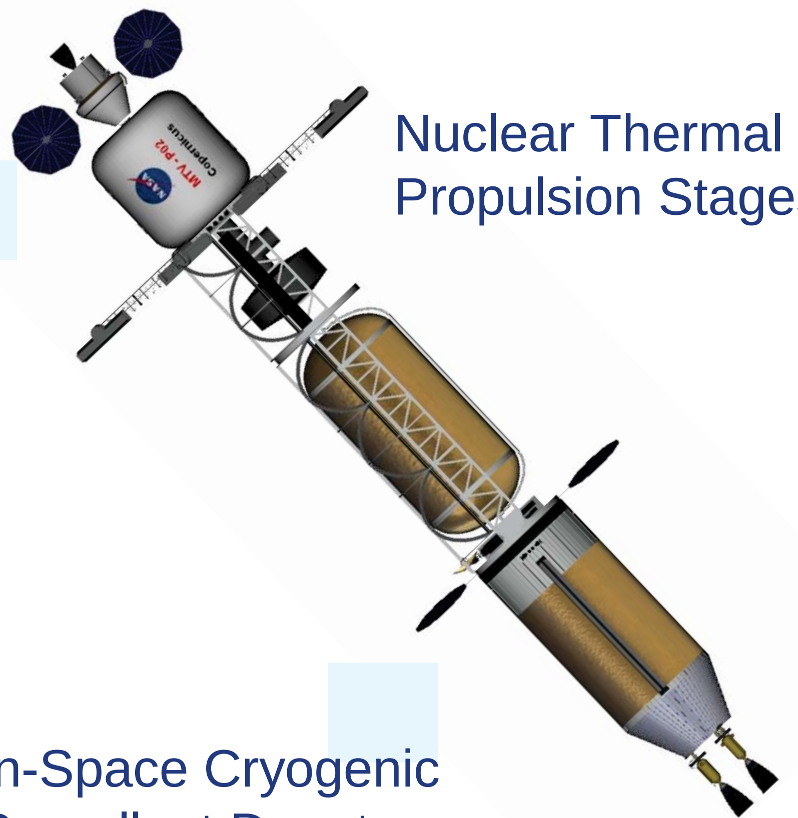
- Liquid hydrogen ($LH_{2)}$ and oxygen (LO_2) are highly efficient propellants
  - Upper stages utilizing LH_2 and LO_2 are competitive in mission architecture studies for upper stages and depots
  - Low LH_2 and LO_2 boiling points, however, mean they boil-off propellant in low Earth orbit
    - Extra propellant must be tanked and launched from Earth
- Reducing boil-off requires good insulation
  - Multi-layer Insulation (MLI) used
- For long duration missions, however, active refrigeration of propellant tanks is being considered

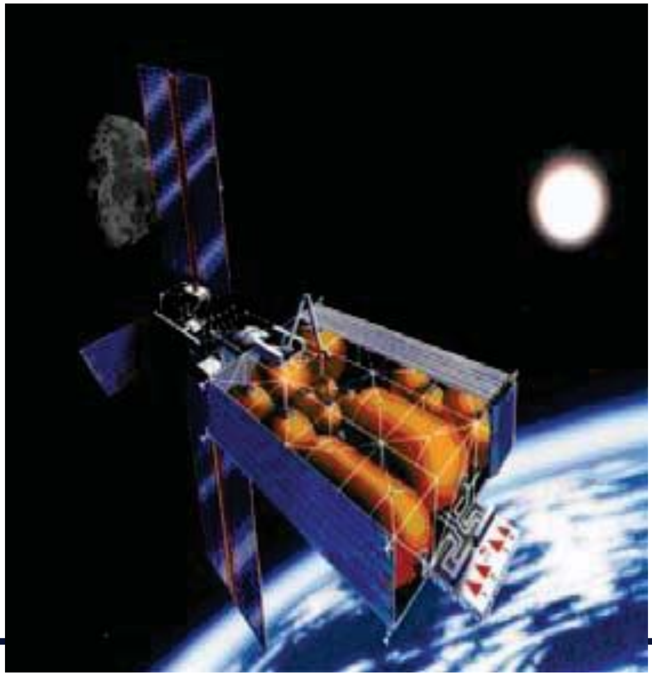
Potential NASA Uses for Boil-Off Reduction System

NASA is Developing capabilities to take exploration crews beyond low Earth orbit (LEO)

Cryogenic Propulsion Stages

Nuclear Thermal Propulsion Stages





In-Space Cryogenic Propellant Depots

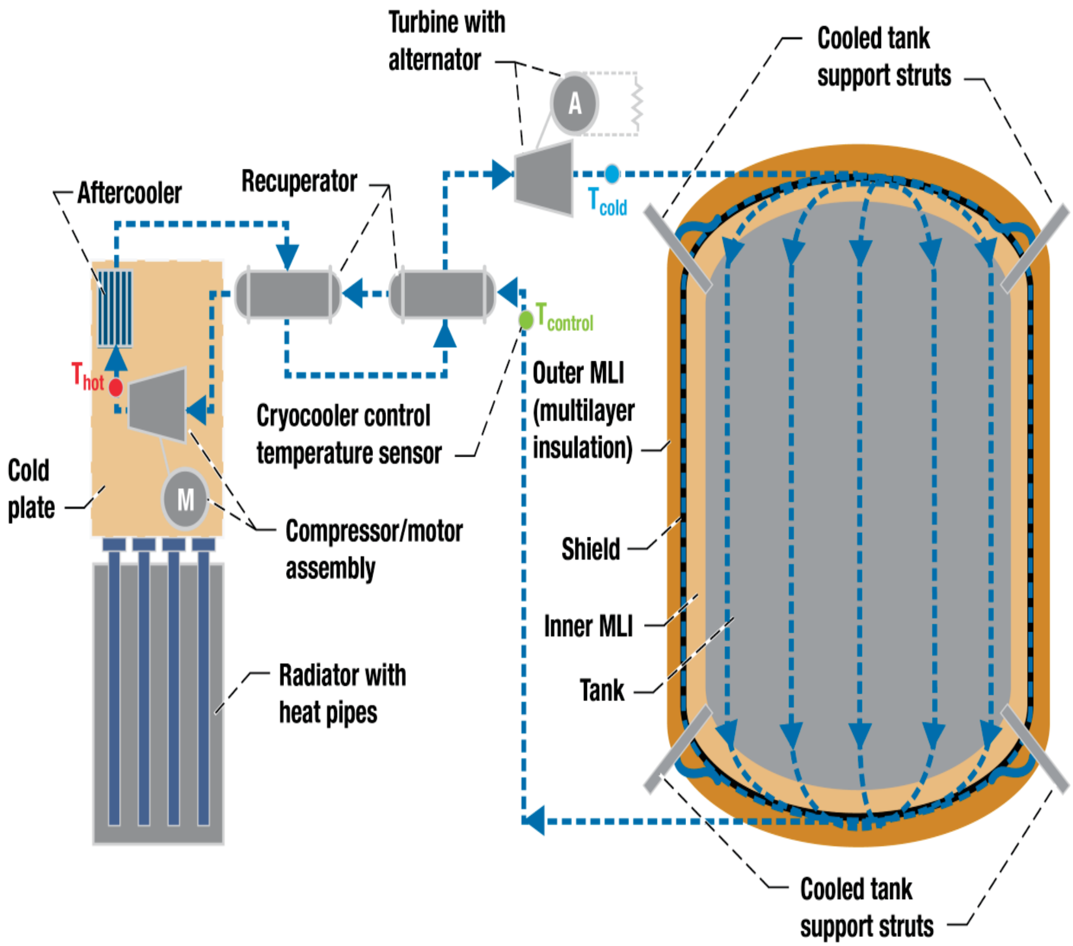
Needs and Goals

- Need:
  - Enable long-term cryogen storage for future exploration missions beyond Earth's orbit
  - Validate cryogenic boil-off reduction system (CBRS) scaling study that predicts this system reduces mass after just several weeks loiter in low Earth orbit
- Goal:
  – Efficiently reduce or eliminate tank boil-off
    - Determine integrated system performance
    - Validate system model

Assembled test article being lowered into SMiRF vacuum chamber at NASA Glenn Research Center.

Cryogenic Boil-Off Reduction System

- Uses a cryocooler to transfer heat from propellant tank to reduce or eliminate cryogen boil-off
  - Primary application is LH_2 and LO_2 storage
- Incorporating existing 90 K cryocoolers that can substantially reduce propellant boil-off
  - Similar to a vapor cooled shield, but coupled with a cryocooler
  - Cool struts and plumbing in addition to insulation system
- Lack of large scale 20 K class cryocoolers limits current availability to achieve zero boil-off with liquid hydrogen



LH_2 tank show with integrated reduced boil-off system

CBRS Background/Definitions

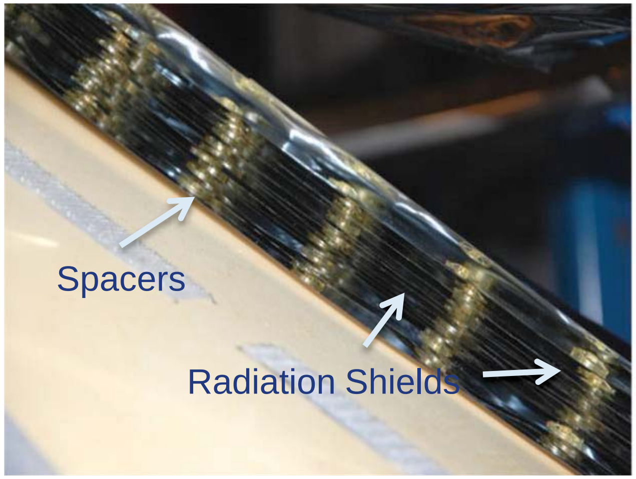
- NASA has been developing two approaches
  - For LH2 *Reduced Boil Off* (RBO) propellant storage applications,
    - *A tube-on-shield* approach is used where a tubing loop is attached to a aluminum sheet embedded in the propellant tank Multi-Layer Insulation (MLI)
    - Integrates existing flight-type warmer temperature cryocoolers (e. g. 90K) to intercept some of the heat before it reaches the tank
  - For LH2 *Zero Boil Off* (ZBO) propellant storage applications,
    - A *tube-on-tank* approach is used with the tubing loop attached directly to the outer tank wall of the propellant tank.
    - Unfortunately, at this time there are no flight-type cryocoolers available that remove heat at 20K with sufficient heat removal capacity to be useful for LH2 *Zero Boil Off* (ZBO) propellant storage applications
  - For LO2 ZBO *tube-on-tank* approach integrating existing flight-type warmer temperature cryocoolers can be used

Tube on Shield RBO test

Tube on Tank ZBO test

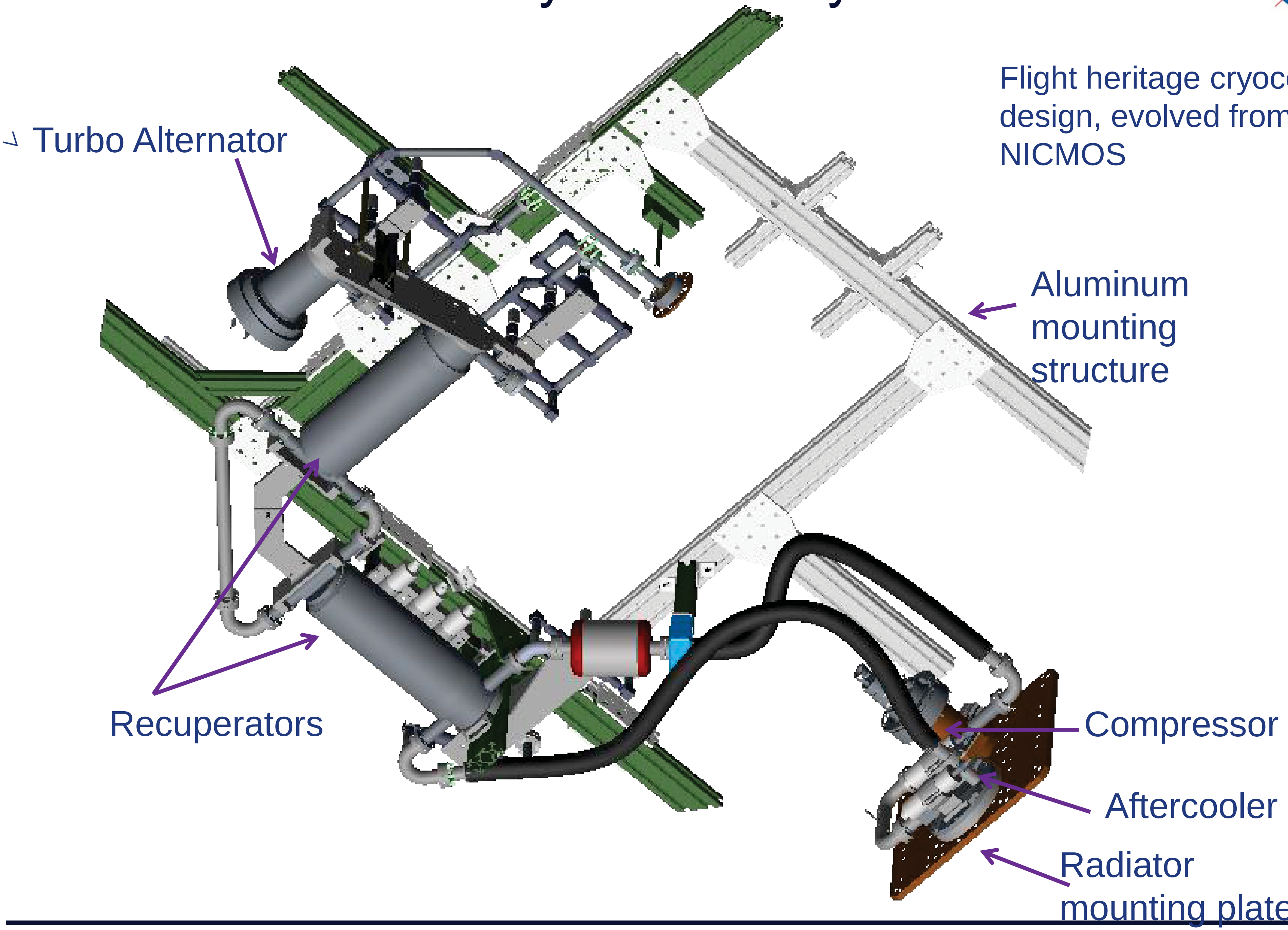
Key Technology Developments

- Demonstrate the low loss integration of a reverse turbo-Brayton cycle cryocooler with a propellant tank to reduce and eliminate boil-off
  - Demonstrate ability to control tank pressure using active cooling system.
- Determine the tank applied self-supporting multi-layer insulation (SS-MLI) performance
  - Uses polymer spacers to maintain layer separation
  - Can reduce heat leak through the insulation system
- Its advantages over conventional MLI include:
  - Improved thermal performance per layer
  - Estimated lower fabrication and installation cost
  - More predictable and repeatable performance



RTBC Cryocooler Layout

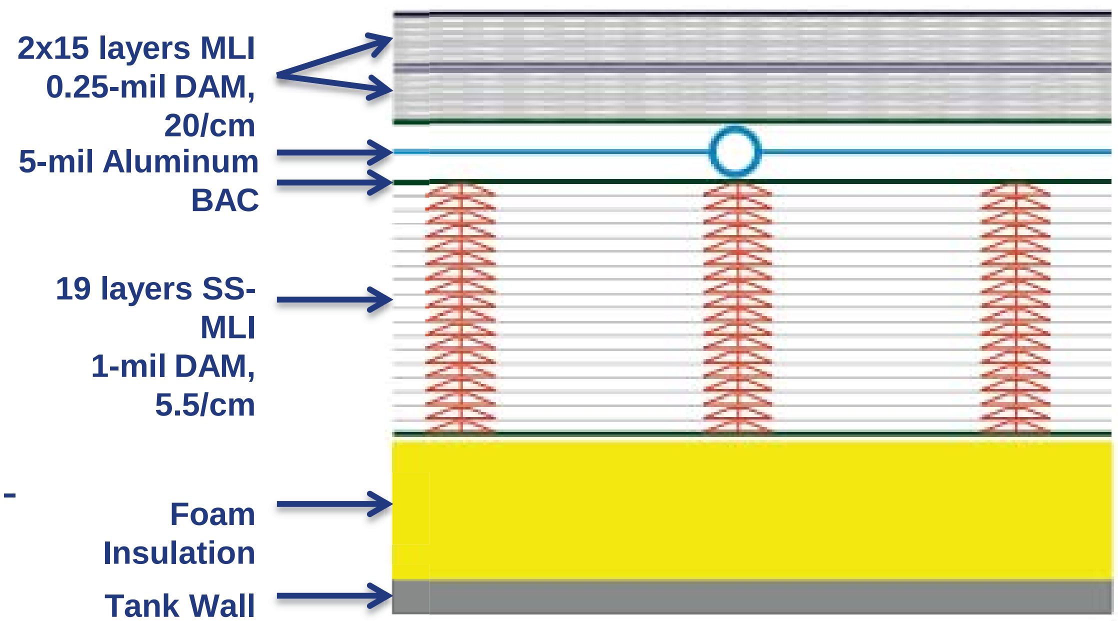
Flight heritage cryocooler design, evolved from NICMOS



Test Program

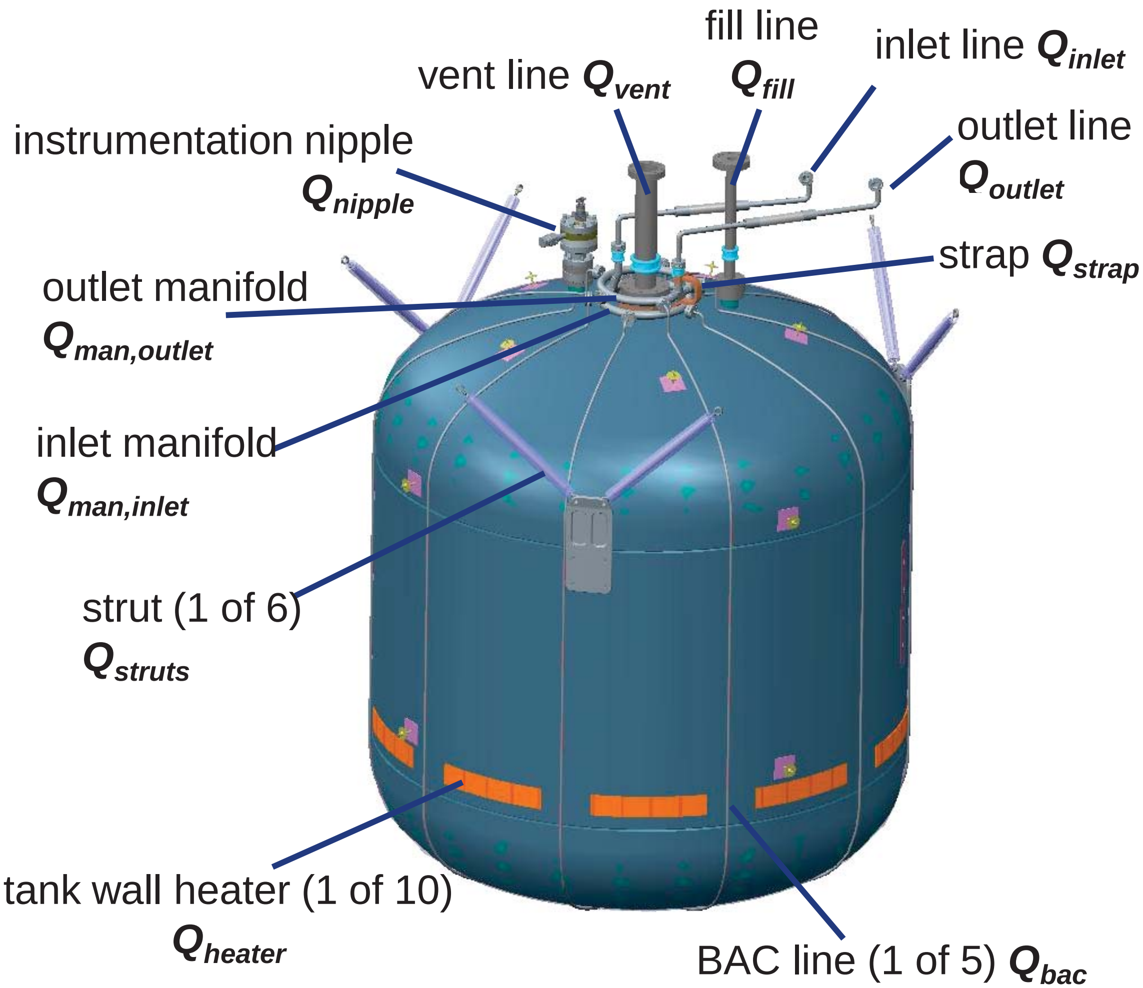
- Tests conducted at NASA Glenn SMiRF in vacuum chamber with cryoshroud providing LEO temperature.
- Three test series, all with 1.2 m dia 1.4m^3 tank, with same reverse turbo-Brayton cycle cryocooler and heat pipe radiator

- Test Series 1
  - LH_2 test with 60 layers of traditional MLI used
  - Cooled shield located after 30 layers of MLI
- Test Series 2
  - LH_2 test with 30 layers of traditional MLI over shield
  - Inner MLI was 18 layers of SS-MLI
- Test Series 3
  - ZBO tube-on-tank test with 75 layers of traditional MLI



Cross-sectional view of Test Series 2 insulation

Key Components and Heat Paths



Not shown:

- MLI Q_{MLI}
- diode rake Q_{rake}
- capacitance probe Q_{probe}
- instrumentation wiring Q_{wires}
- cryocooler Q_{cc}

- penetration heat leak

$$Q_{pen} = Q_{vent} + Q_{fill} + Q_{struts} + Q_{nipple}$$

- instrumentation heat leak

$$Q_{instr} = Q_{rake} + Q_{wires} + Q_{probe}$$

- total heat load on tank (tank thermal balance)

$$Q_{tank} = Q_{MLI} + Q_{pen} + Q_{instr} + Q_{heater} - Q_{bac}$$

- total heat load on cryocooler (cryocooler thermal balance)

$$Q_{cc} = Q_{bac} + Q_{strap} + Q_{par}$$

- parasitic heat load on cooling loop

$$Q_{par} = Q_{inlet} + Q_{man,inlet} + Q_{man,outlet} + Q_{outlet}$$

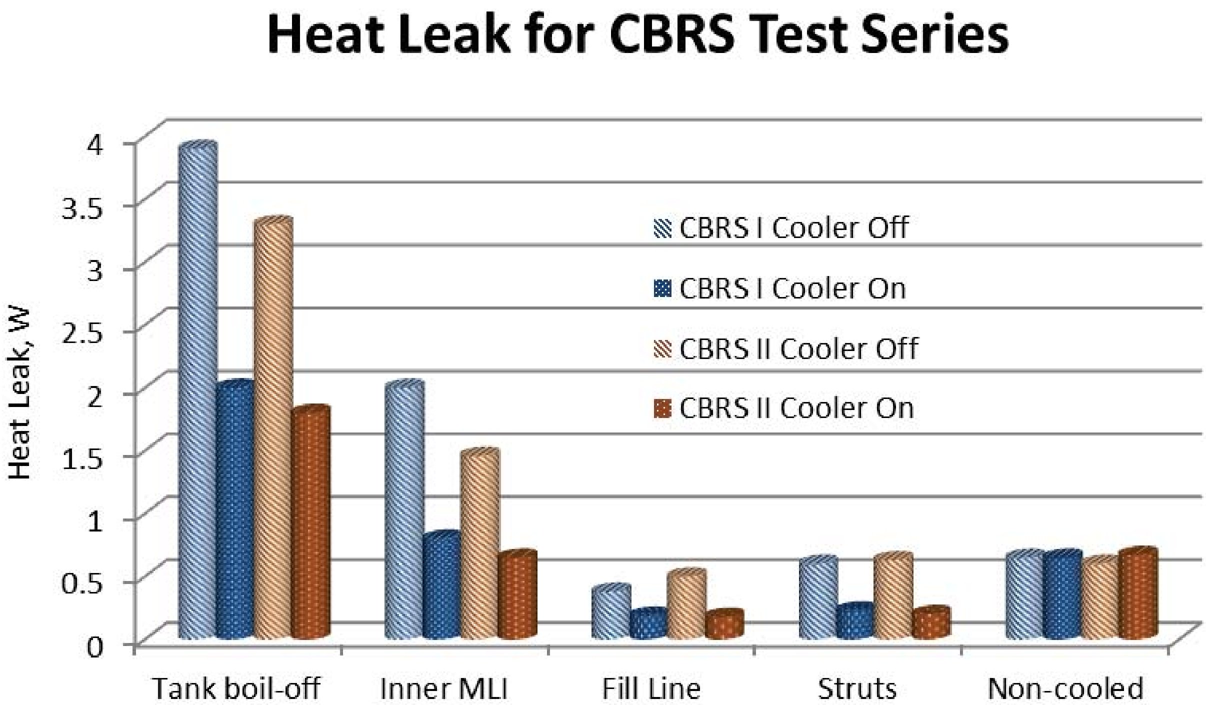
$$Q_{man} = Q_{man,inlet} + Q_{man,outlet}$$

Test Data

	CBRS I			CBRS II			ZBO	
	Cooler Off	Cooler On	Heat or *Boil-Off (%)* Reduction	Cooler Off	Cooler On	Heat or *Boil-Off (%)* Reduction	Cooler Off	Cooler On
BO*	3.87	2.03	48%	3.32	1.83	45%	4.3	0
MLI	2.04	0.79	61%	1.46	0.65	55%	2.62	2.62
Vent	0.09	0.11	-22%	0.046	0.11	-139%	0.14	1.43
Fill	0.38	0.19	50%	0.5	0.18	64%	0.49	0.51
Struts	0.604	0.23	62%	0.63	0.2	68%	0.38	0.40
Capacitance Probe	0.21	0.21	0%	0.21	0.22	-5%	0.006	0.006
Penetration Integration	0.34	0.34	0%	0.17	0.17	0%	0	0
Standoffs	0.12	0.05	58%	0	0	0%	0	0
Instrumentaion	0.1	0.1	0%	0.17	0.17	0%	0.07	0.06
Instr. port				0.13	0.13	0%		
non-cooled heat	0.65	0.65	0%	0.596	0.67	-12%		
Cooled items	*3.114*	*1.32*	*58%*	*2.59*	*1.03*	*60%*		
				3.186	*1.7*			
*Thermal acoustic oscillation heat removed								
Q lift		13.2			10.7			8.5
Q BAC		5.84			5.23			4.52
Qstruts		1.21			2.09			0.48
Q parasitic		6.17			3.34			4.2
Q compressor		245			223			145

Summary of Results

- First of its kind demonstration of flight heritage reverse turbo-Brayton cycle cryocooler integrated with broad area cooled shield to reduce boil-off of a LH2 storage tank
- Cooling loop flow and BAC shield thermal losses were lower than expected
- Boil-off % reduction was less than expected (48% measured vs. 60% predicted for test 1)
  - Where cooling was used, tank heat leak was reduced by 60%
  - Model configuration differed slightly from as-built test



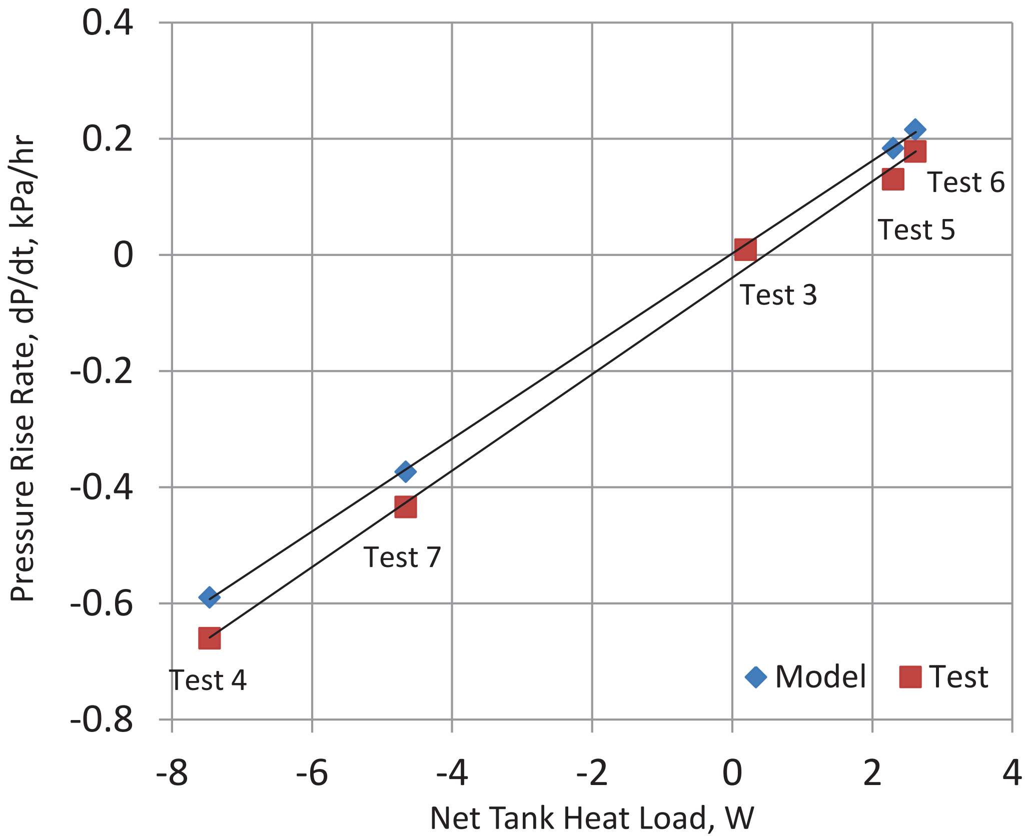
- Inner MLI heat leak was reduced with SS-MLI, but still higher than expected
  - Low warm (90K) temp boundary conditions of both inner MLI concepts had higher than expected heat
  - Models do not work over this temperature range
  - Very little MLI data exists at these temps
  - Improved models require additional data
- Experienced Thermo-Acoustic Oscillations in hydrogen tank

Test Series 2- SS-MLI Performance

- SS-MLI reduced tank heat
  - Passive MLI heat was 1.46 W, reduced by 28% from Test I
  - Active MLI heat was 0.65 W
    - Improvement of 18% from RBO I
    - Both values were improvements over traditional MLI
- SS-MLI adequately supported the BAC shield
  - No movement or shifting of BAC noticed
  - Velcro supports were held intact on shield and tank foam

Test Series 3--Robust ZBO Demonstrated

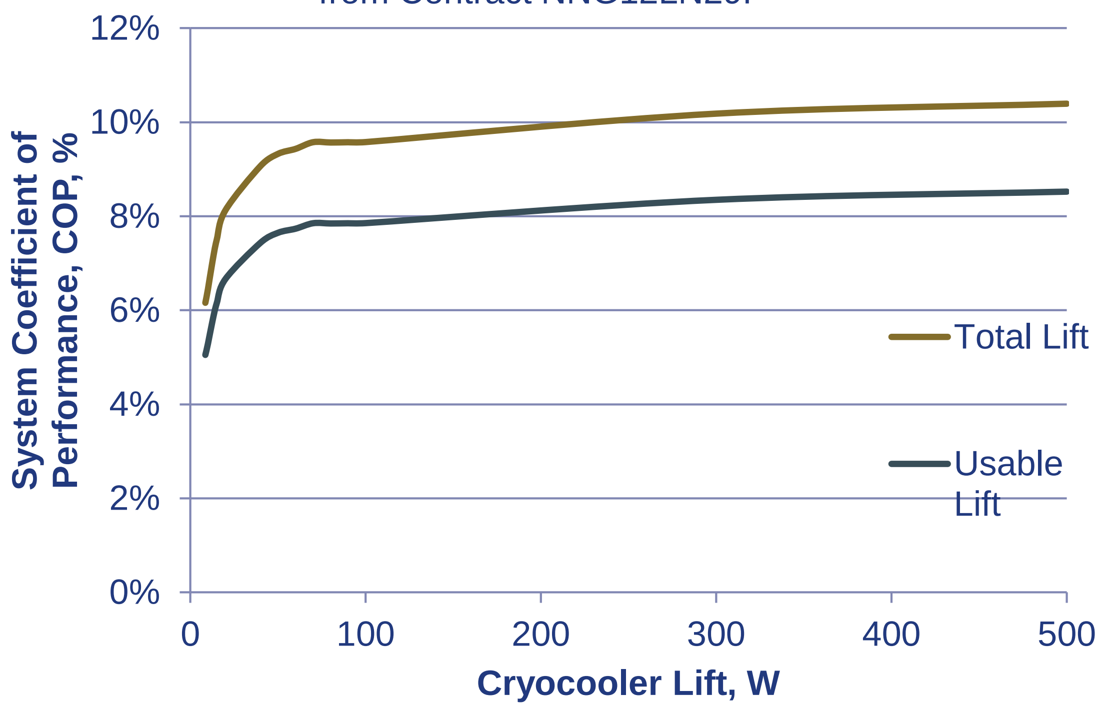
- ZBO was easily achieved
- Robust tank pressure control using cryocooler system also demonstrated
- Testing established the pressurization rates vs net heat load into or out of the tank
  - With Cryocooler power increased 33% over that for ZBO, tank pressure dropped 1.4 psi over 22 hr period
- Model correlations show active system pressurization rates compare well with that of an isothermal system
- Tube-on-Tank system effectively prevented thermal stratifications within the tank while:
  - Being external to tank
  - Introducing minimal parasitic heat loads to *tank* with cooler off



LOX ZBO System Scalability

Use of test data to help size propellant storage cryocoolers

- Goal: Find system Coefficient of Performance (COP) for tank applied broad area cooling systems
  - With improved insulation on cryocooler to BAC supply lines and on the manifold, Q parastic (Q par) =1.5 W
    - This represents an 18% parasitic loss for active cooling of propellant tanks
      - 1.5 W/8.5W lift is 18% of cryocooler lift
    - *Assume parasitic loss of 18% for integration of cryocoolers into propellant tanks*
  - The system coefficient of performance is defined as:
    - $COP_{sys} = Q_{useful} / P_{comp}$
    - Find COP_{sys} for variety of LOX ZBO tank heat leaks by combining test data, CAT analysis, and that from Contract NNG12LN29P

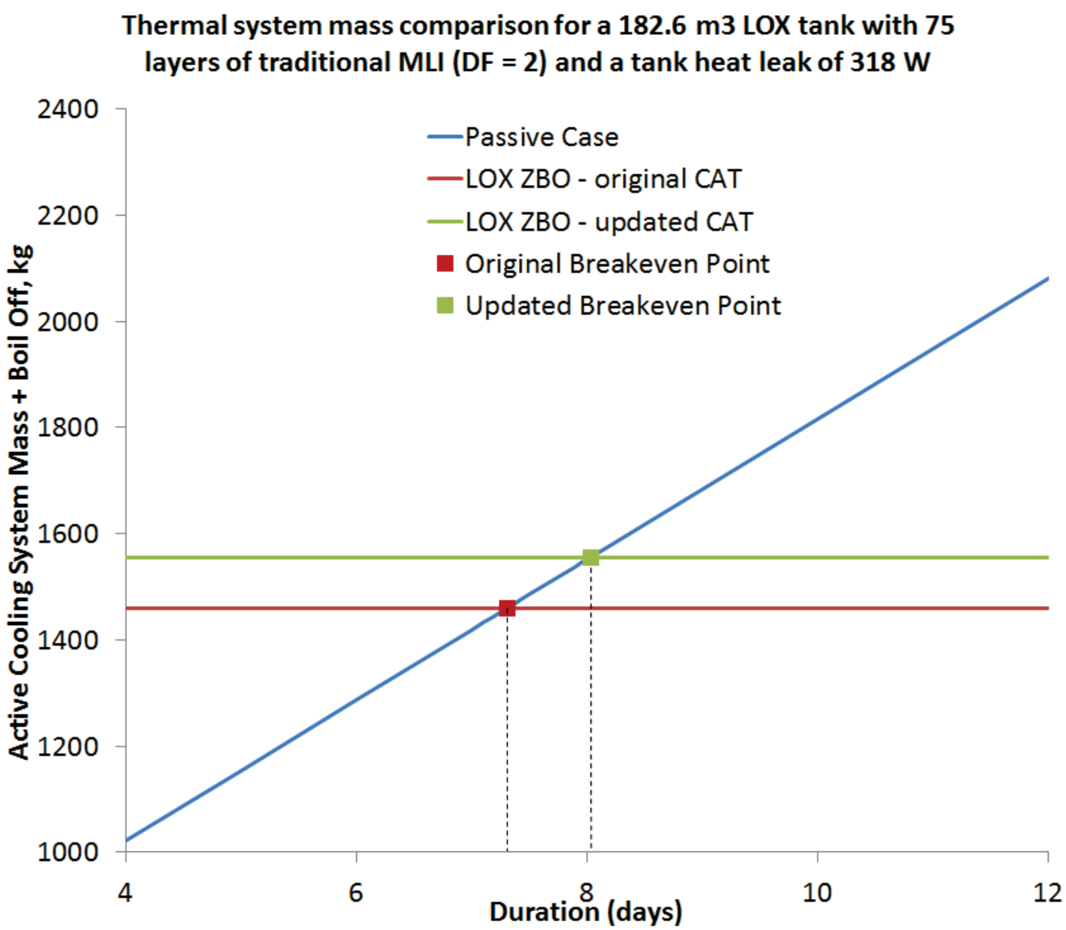


Tank Heat Leak				
	8.5 W	100 W	300 W	500 W
Q par	1.5	18	54	90
Q useful	7	82	246	410
P comp	145	1046	2946	4810
COP system	4.8%	7.8%	8.4%	8.5%

Scalability

Updates based on cryocooler system data generated from LO_2 ZBO and LH_2 RBO testing have been integrated into NASA's Cryogenic Analysis Tool

- Revisions from RBO testing were incorporated in tool and scaling study results last year
  - Updates were done on the radiator-cryocooler interface plate, cooling strap, cryocooler parasitics, and MLI below 90K
  - Impact: a slight increase in active cooling system mass is noted and shown in the figure, which moves the mission duration break even point for including LO_2 ZBO less than a day*



*Note, this is a simplified analysis and a more detailed analysis would be required to assist in the decision to include a LO2 ZBO system in a future mission.

Ref.: Plachta, D, Guzik, M., *Cryogenic Boil-Off Reduction System Scaling Study*, Cryogenics Volume 60, pages 62–67, 2014.

Conclusions

- Cryocooler and cryocooler integration hardware have been tested in first large surface area thermal test in simulated low-Earth orbit environment
  - Reverse turbo-Brayton cycle cryocooler performance was outstanding
    - Integrated circulation system had minimal losses
  - End-to-end system test was successful
    - Component performances were as expected except inner MLI
      - Reasons are not clear, however--
        - » Little development work has been done for low-temperature (20-90K) MLI
        - » MLI designs are straightforward and solutions are possible
- SS-MLI offers promise for space flight applications
- First successful test of distributed cooling system used to achieve ZBO
  - Controlled tank pressure using active cooling system.
  - Decreased tank pressure at controlled rate with cryocooler system operating at 33% excess capacity.
  - Testing indicates that internal tank mixer operation and its associated heat and risk may not be needed while operating ZBO systems
- ZBO Scaling Study effort was updated
  - Simplified approach for ZBO cryocooler sizing has been presented
  - Projected mass savings of RBO/ZBO has been confirmed

Questions?