Modeling of Cryogenic Multilayer Insulation from Launch through Achieving Steady State

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Presented By

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Background

- NASA desires to build long duration storage of cryogenic propellants for various in-space uses
  - Upper stages
  - Depots
  - Tugs
  - Requires the use of Multilayer Insulation (MLI)
- MLI Heat loads on orbit have been studied and modeled comprehensively for 50 years
- MLI Heat loads during pad hold and ascent have been somewhat neglected
  - Transient nature of physics is intimidating
  - Some test data exists
  - Modeling?
- Modeling required for complete end to end mission thermal modeling capability

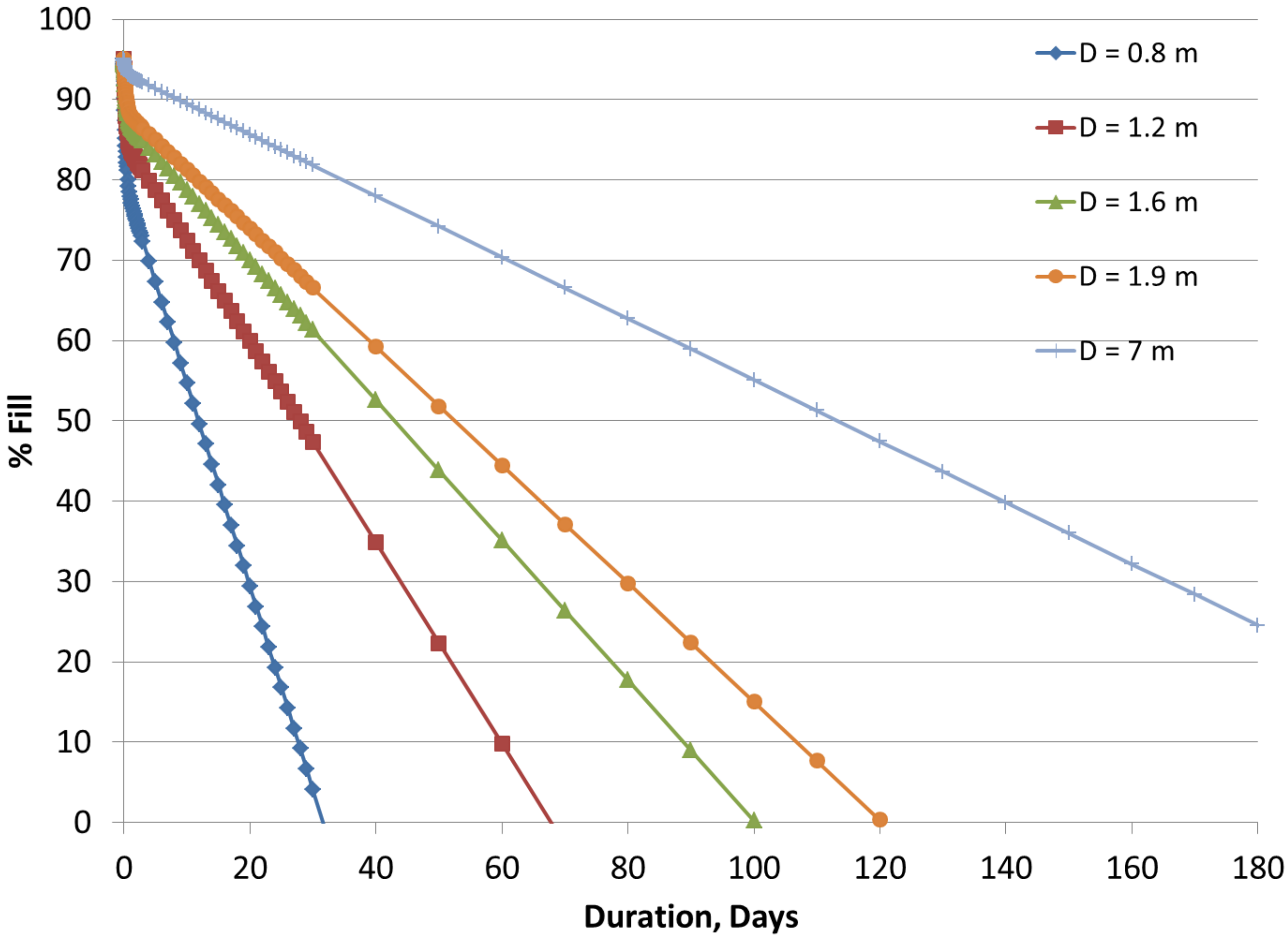
Goal

- Develop software package to:
  - Predict tank internal pressure and bulk temperature values as a function of time starting at launch until reach steady state on orbit
  - Use tank independent architecture
  - To the best of ability utilize existing data sets
- Compare software package to actual data sets produced after package complete

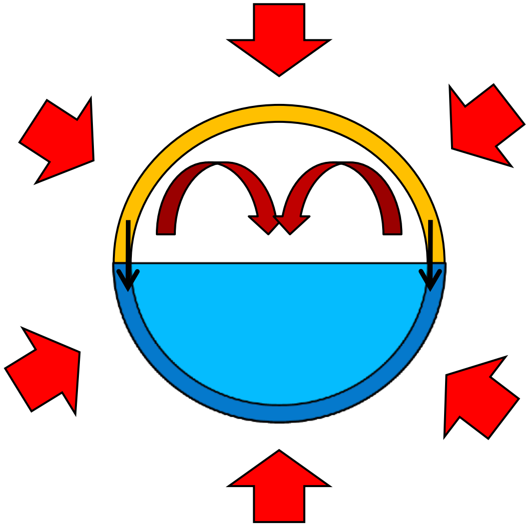
Important Variables and Questions

- Tank altitude versus time
  - Pressure versus altitude
  - Delta pressure across fairing
- MLI thermal performance versus pressure
  - If know thermal performance versus time for one system does that apply across the board? How much different?
- Outgassing within MLI
  - How does this change thermal performance vs. pressure & time?
  - How does a substrate such as Spray On Foam Insulation (SOFI) affect pressure within the blanket?
- Thermal mass of various components
  - Insulation components (MLI & SOFI)
  - Tank wall (based off of initial temperature gradients)
- Distribution of heat within the tank
  - All to the liquid?
  - Convection off of the ullage wall?

Simple, First Order Model



Modeling Approach – Fluid & Energy Model



- Multinode fluids model
  - Lumped liquid node
  - Lumped ullage node
  - Massless liquid/vapor interface node
    - Enables mass transfer between states
    - Allows non-saturated conditions
- Solve using:
  - Conservation of mass
  - First law of thermodynamics
  - Second law of thermodynamics
  - Must include work done by liquid/ullage on each other due to pressurization
  - This implies that the bulk ullage and liquid masses are not at equilibrium
- Energy distribution
  - All energy must first go through a wall node
  - Energy entering the wetted surface area goes straight to the liquid
  - Energy entering the dry surface area is conducted down along the wall to the L/V interface
    - Thus the dry ullage wall must have a temperature that is higher than the bulk liquid
  - The ullage gains energy by convecting off of the wall
  - The ullage gains mass and rejects energy by convecting on the liquid surface

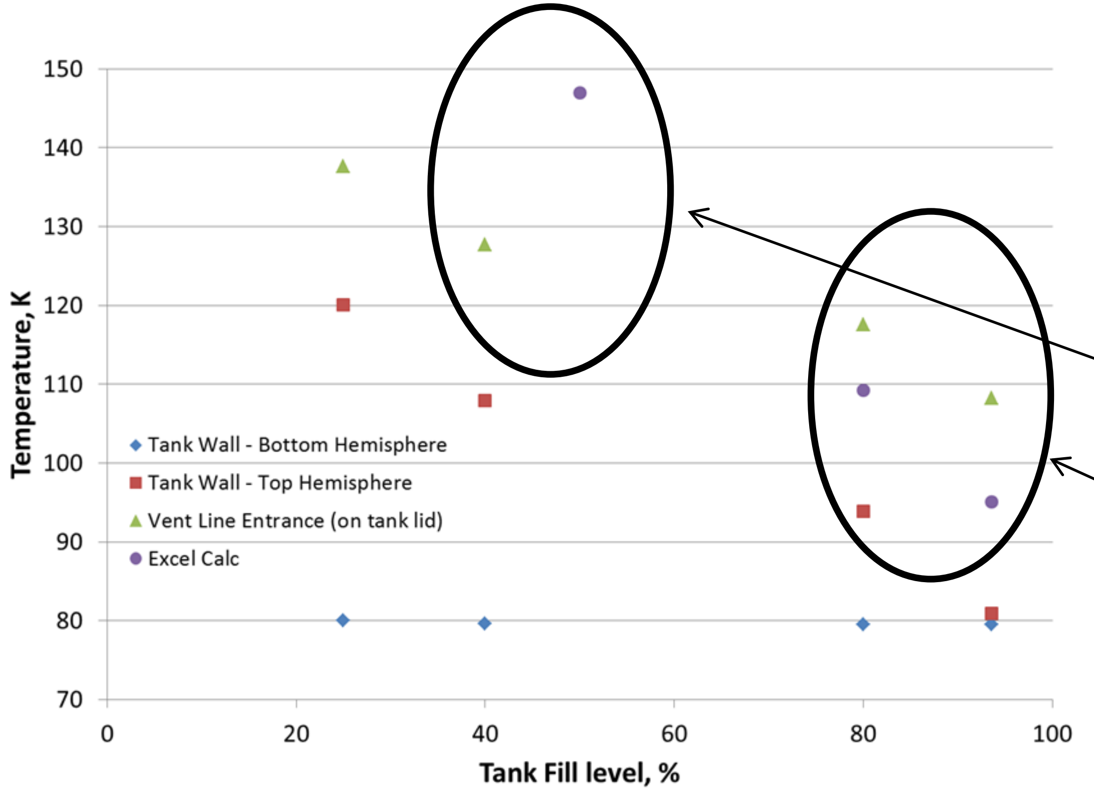
CRYOTE Testing vs Fill Level (Steady State)

Sphere:

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(kr^2\frac{\partial T}{\partial r}\right)+\frac{1}{r^2\sin^2\theta}\frac{\partial}{\partial\varphi}\left(k\frac{\partial T}{\partial\varphi}\right)+\frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left(k\sin\theta\frac{\partial T}{\partial\theta}\right)+\dot{q}=\rho c_p\frac{dT}{dt}$$

$$T-T_0=\frac{\dot{q}r^2}{k}\ln(\sin\theta)-\frac{\dot{q}r^2}{k}\ln(\csc\theta-\cot\theta)-\frac{\dot{q}r^2}{k}\ln(\sin\theta_0)+\frac{\dot{q}r^2}{k}\ln(\csc\theta_0-\cot\theta_0)$$

Θ_0 is a function of initial fill level



Note:
θ = 0 is the top of the tank
θ = π/2 is the equator

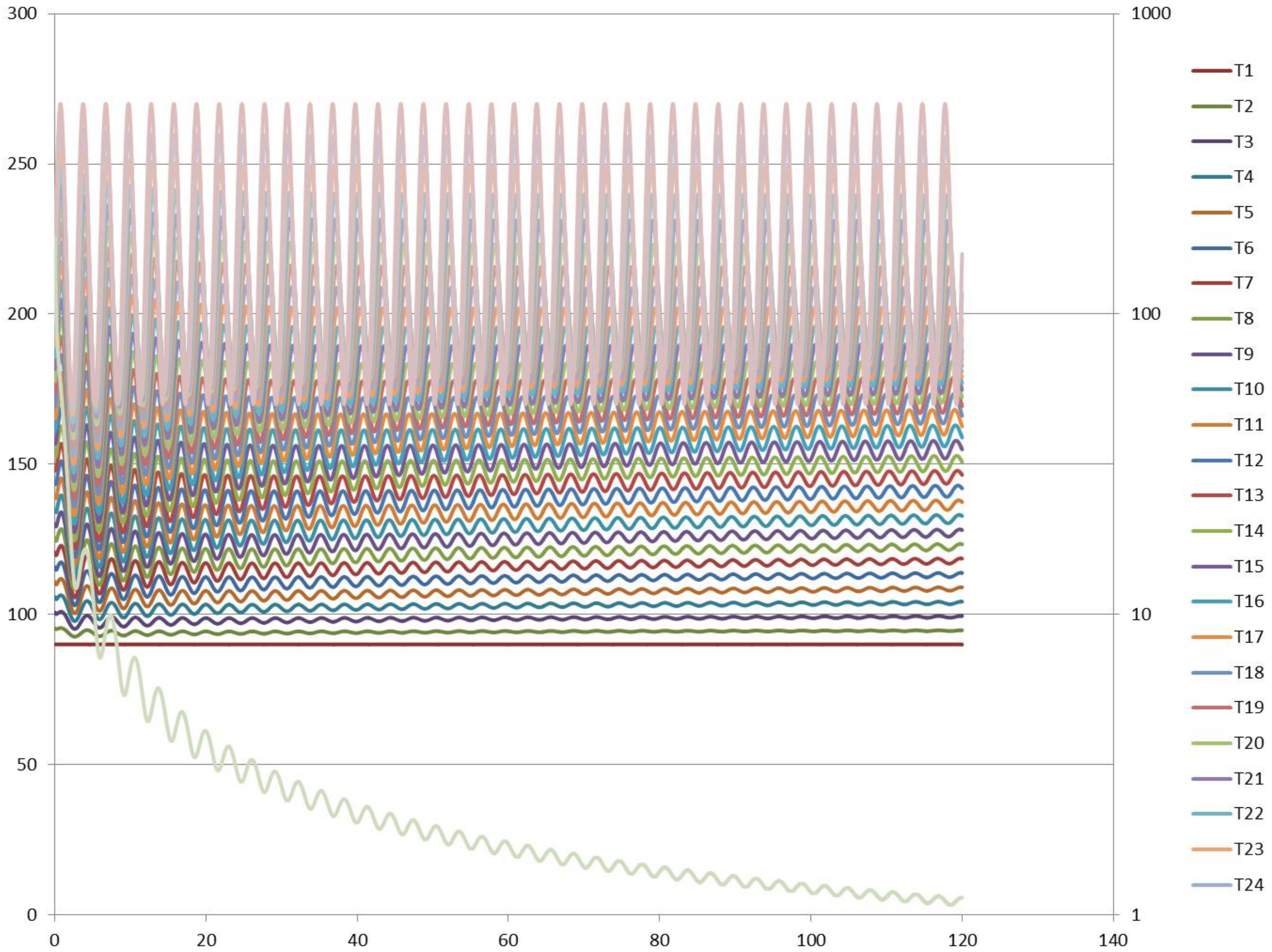
Convection Dominates

Conduction only works

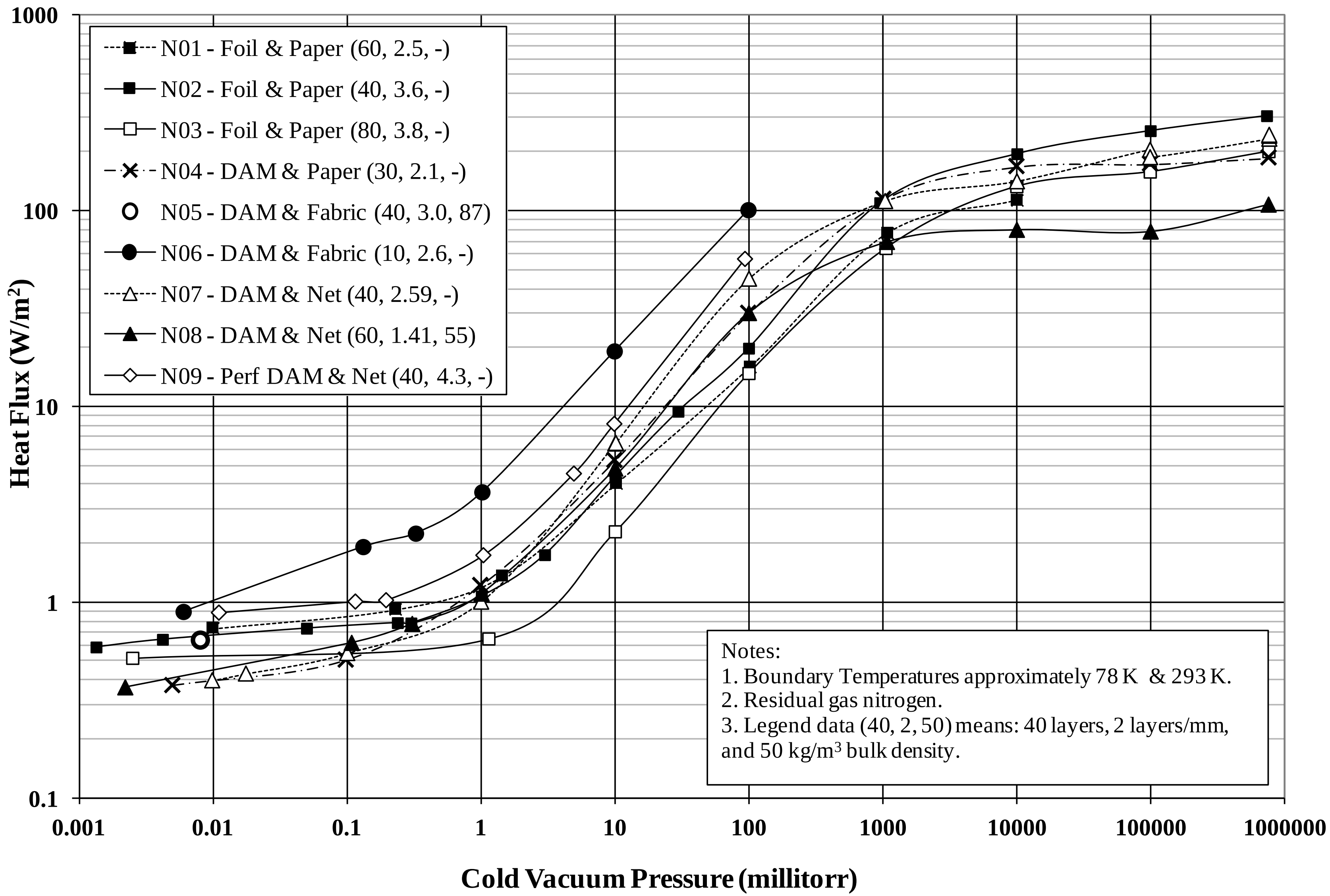
Modeling Approach – MLI Pressure

- External pressure boundary condition
  - Can model pressure at every time step in between every layer
    - Requires time step on order of 0.001 s to fully capture physics (and not blow up the model)
    - Requires modeling the temperature of every layer at every time step, time steps on the order of 0.1 s to fully capture physics
    - Requires some knowledge of the outgassing of the foam/MLI system
    - No data exists to anchor a model, thus you are always right?
  - Can assume that the MLI during rapid pumpdown performs either similar to steady state curve or similar to previous testing at same pressure
    - Get pressure from altitude (standard atmpspheric model)
    - Altitude from time dependent functions for various launch vehicles
  - Can assume that heat load is directly time dependent based on previous testing (i.e. don't care what pressure boundary condition as a function of time is)
- What about thermal mass of MLI and foam?
  - Required to solve conservation of energy in the first approach
    - For 1 inch thickness, is roughly 10 kJ/m^2 for foam
    - Similar for MLI
  - Can hand wave it away in other methods
  - Must account for thermal mass of tank

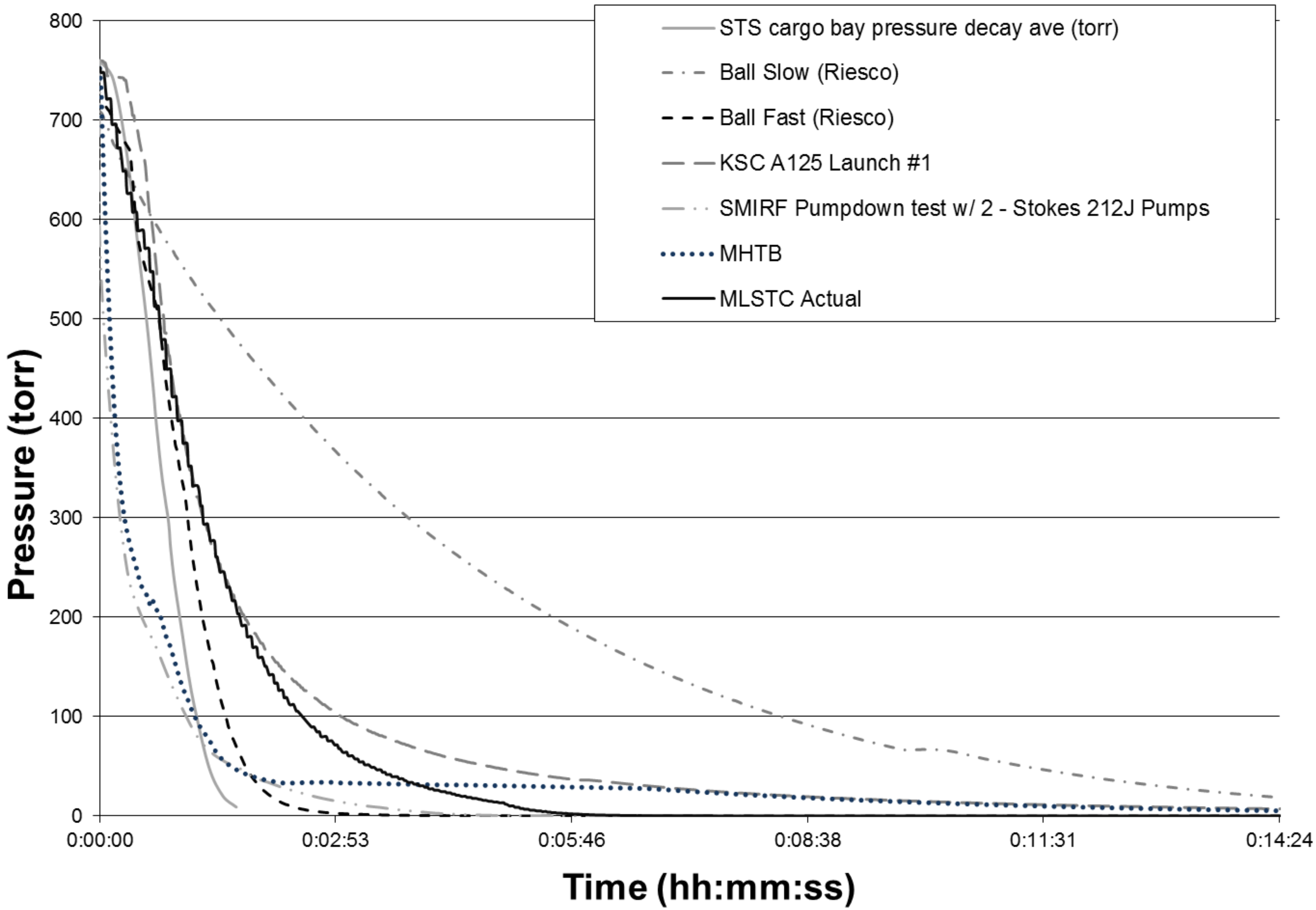
Transient Temperature/Pressure



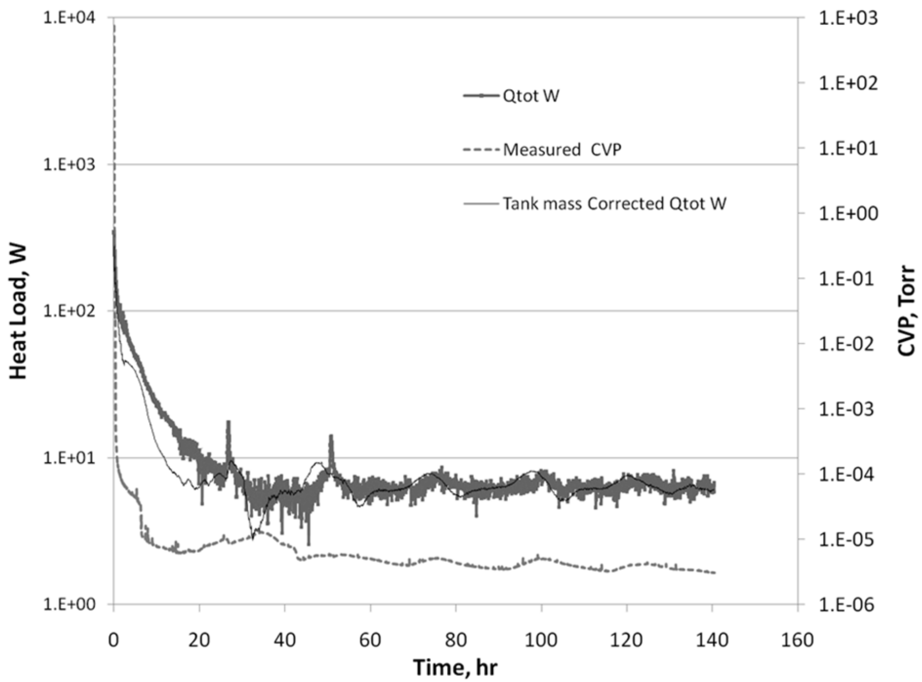
Multilayer Insulation Performance – Steady State



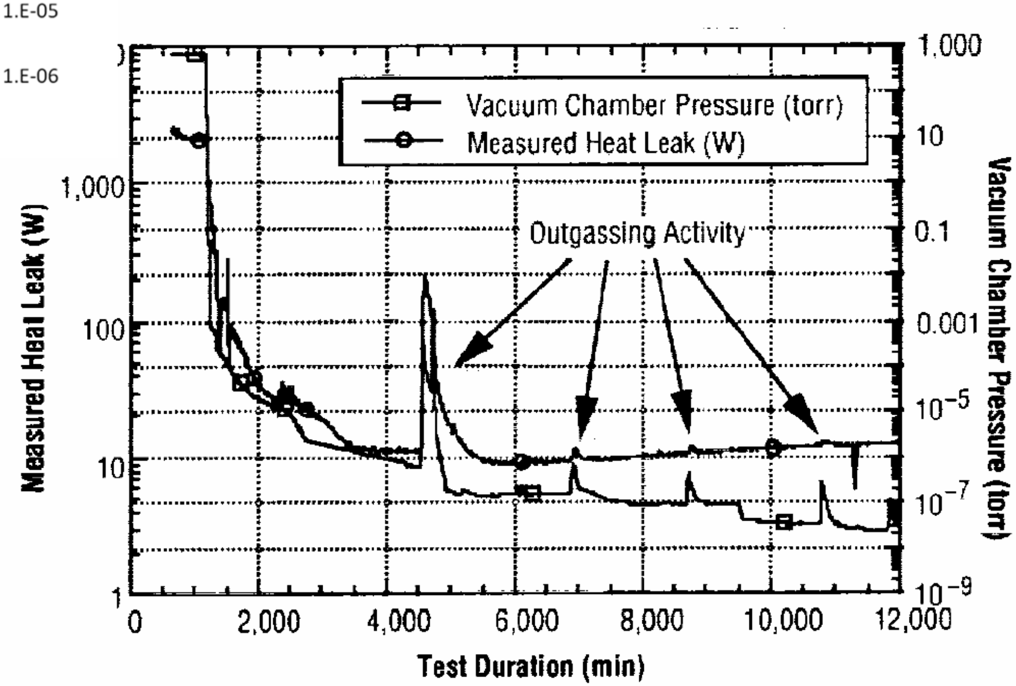
"Rapid" Depressurization



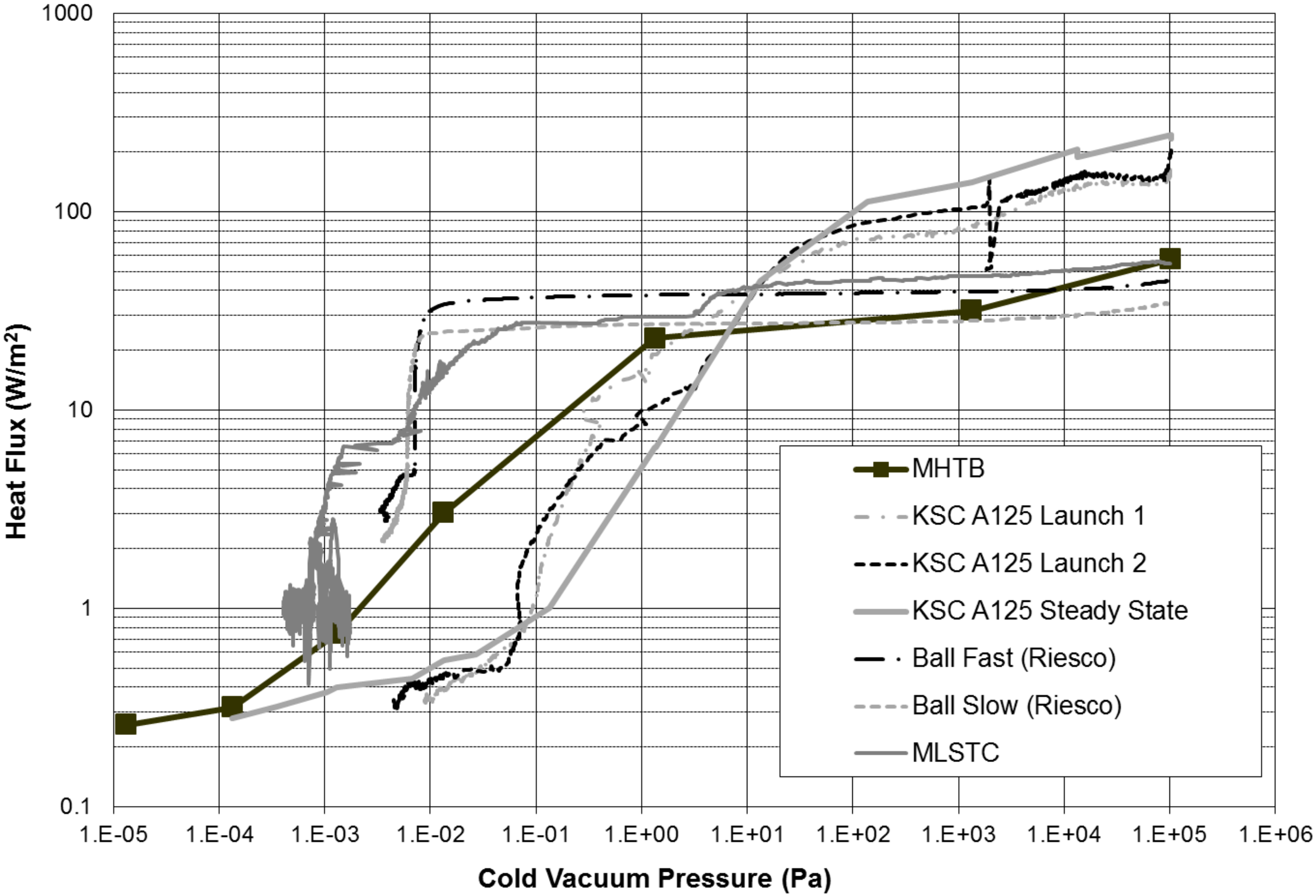
Heat Load vs. Time



- MLSTC on left
- MHTB below



MLI Performance – Pump Down



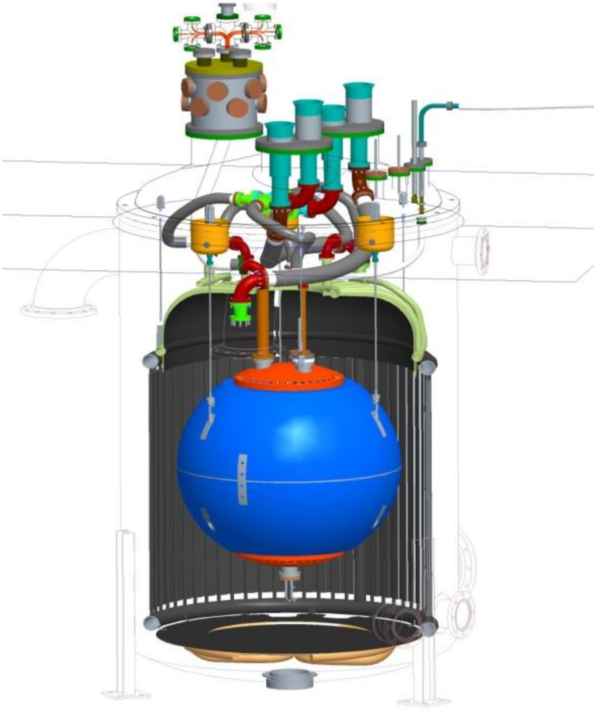
Input Variables

- Working Fluid: Oxygen, Hydrogen, Nitrogen, Methane
- Tank Shape: Geometry, Diameter, Cylindrical Length, Dome ratio, tank thickness, tank material (aluminum or stainless), vent diameter
- Insulation Definition: Foam Thickness, MLI layers & Density (up to three sections of different densities)
- Fluid Properties: Initial Liquid Temperature & Pressure (assume start saturated and rest of pressure is helium)
- Simulation Scenario:
  - Pad Hold time (and ambient temperature)
  - Initial fill level
  - Type: Boil-off vs. pressure-rise
  - Ascent Model (Ball (slow), SMiRF (med), STS (Fast))
  - How to determine tank ullage area mass (user input or calc using fill level & tank thickness)
  - Penetration heat load

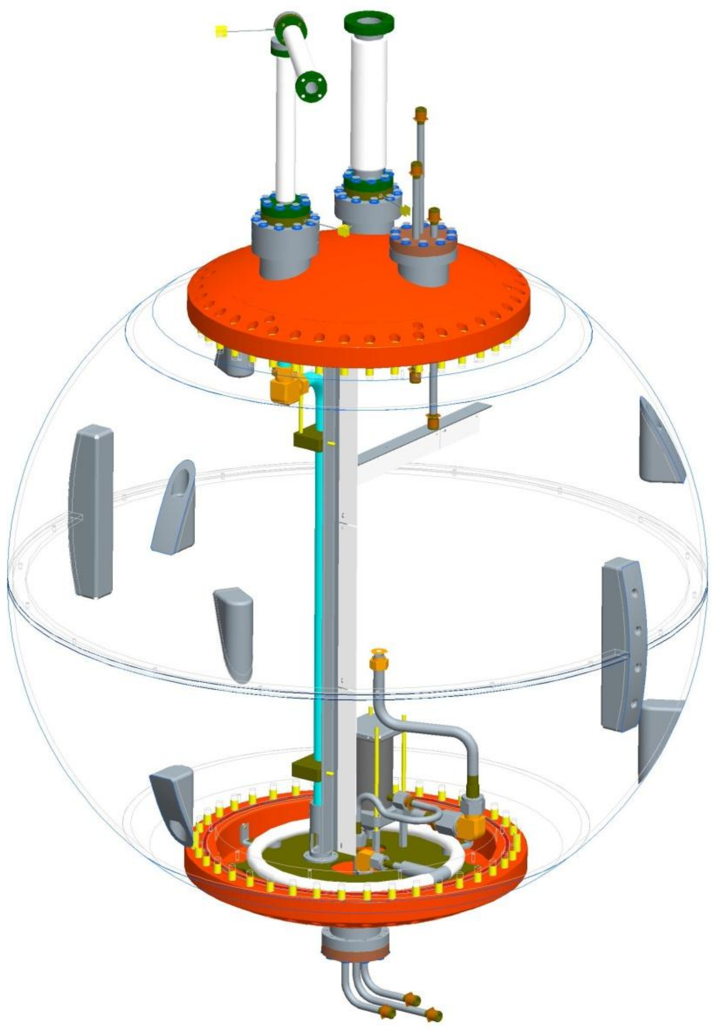
Application - MLSTC

- Methane Lunar Surface Thermal Control Test
- Glenn Research Center, SMiRF, 2010

- Use liquid methane to simulate full life cycle of Altair (Lunar Lander) ascent engine liquid methane tanks

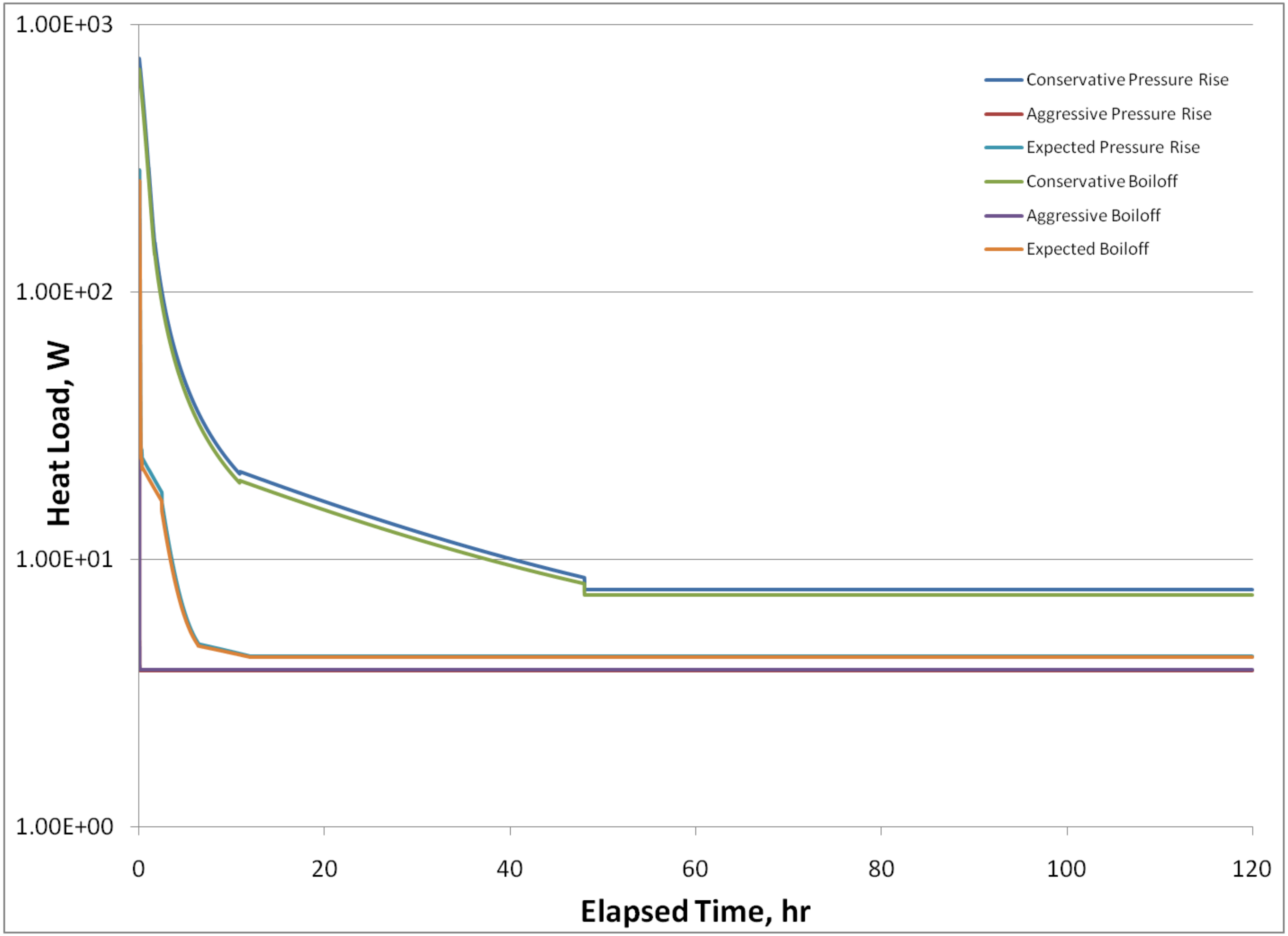


MLSTC Test Article Configuration

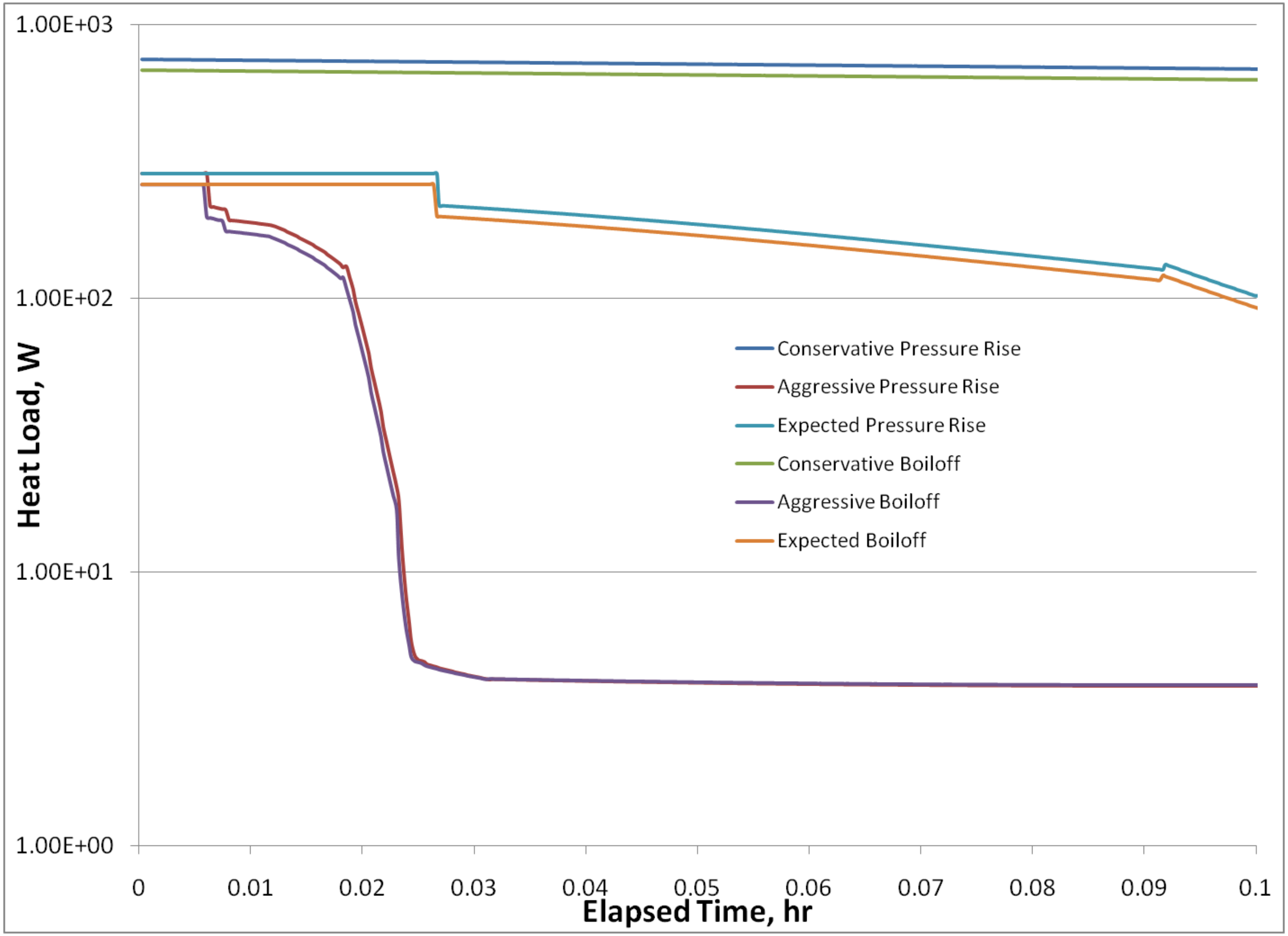


- Dia. (Volume): 4 ft (30.9 ft^3)
- Surface area 50.4 ft2
- Rated Pressure: 337 psig
- Rated temperature: -320 F to +100 F
- Material: Type 304 Stainless Steel
- Weight: 1,300 Lbs. empty
- ASME rated pressure vessel
- Submersible pump for fluid mixing
- Sparger bubbler bar for increasing methane temperature
- 2-axis instrument rake for liquid & gas temperatures
- Top ports for vent line (including sensor wires), fill line, and GHe pressurant
- Bottom port for gaseous methane bubbler and pump wired

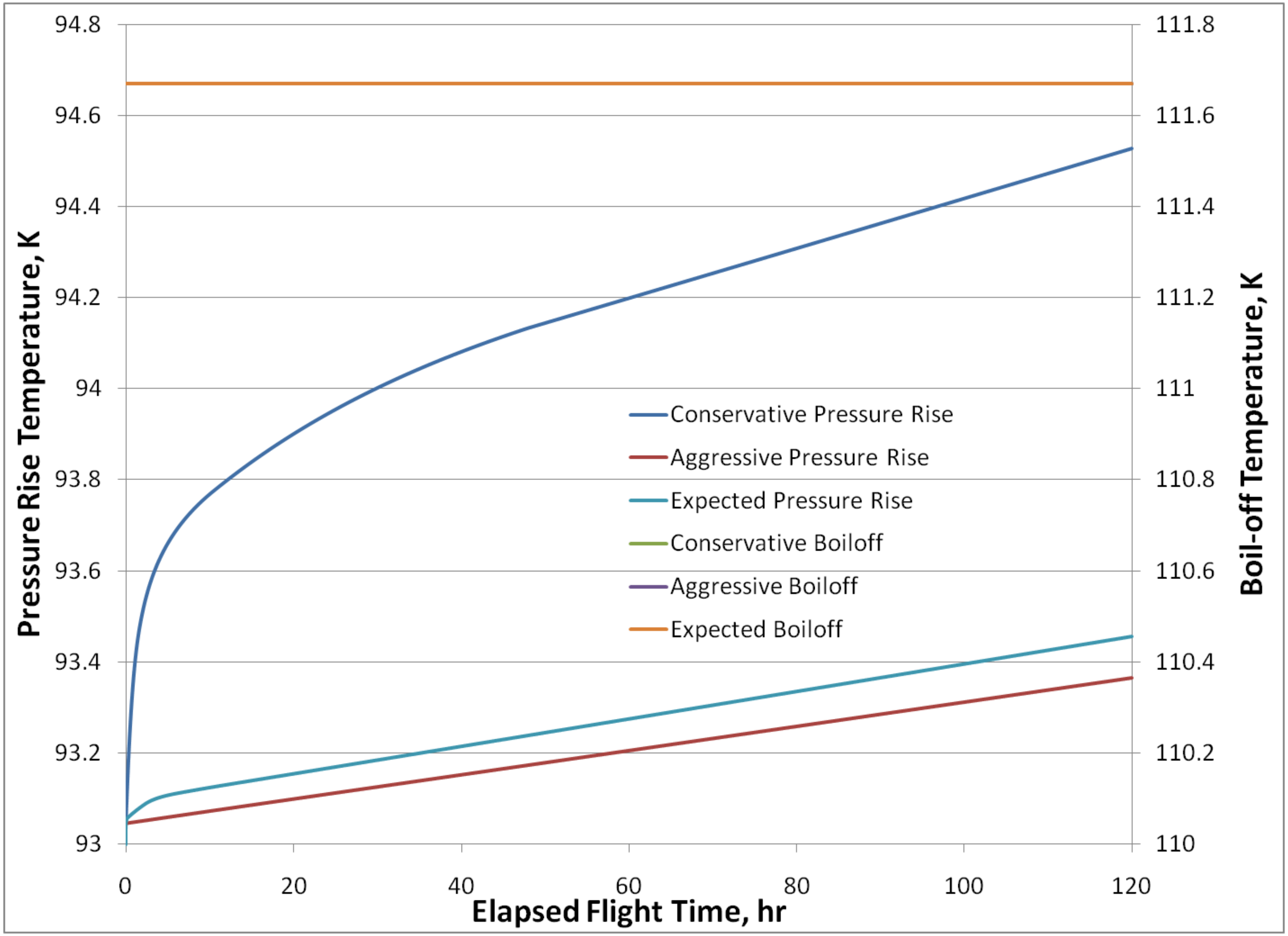
Pre-Test Predictions



Pre-Test Predictions - Zoom



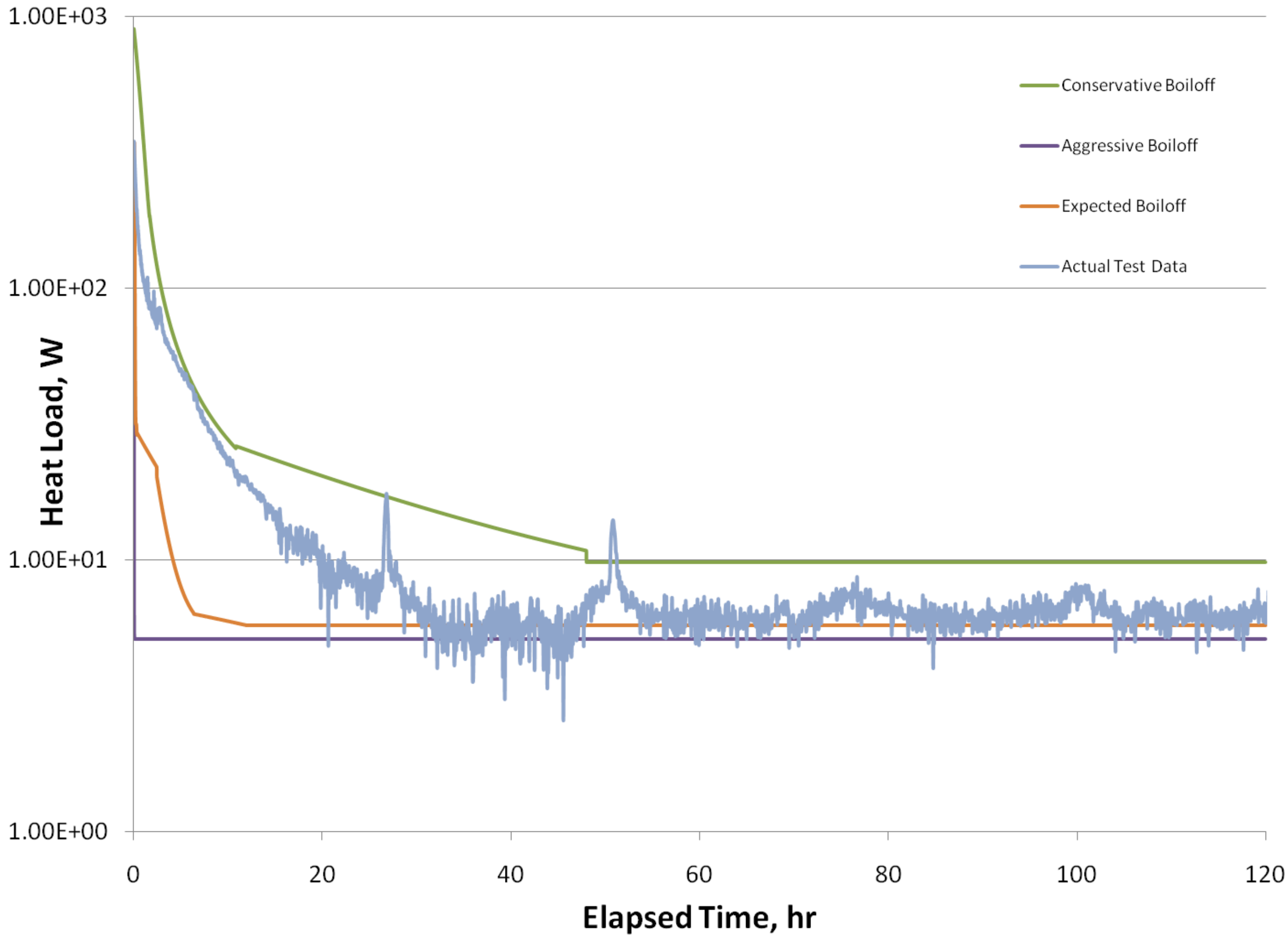
Pre-Test Predictions



Ascent Boil-off Test

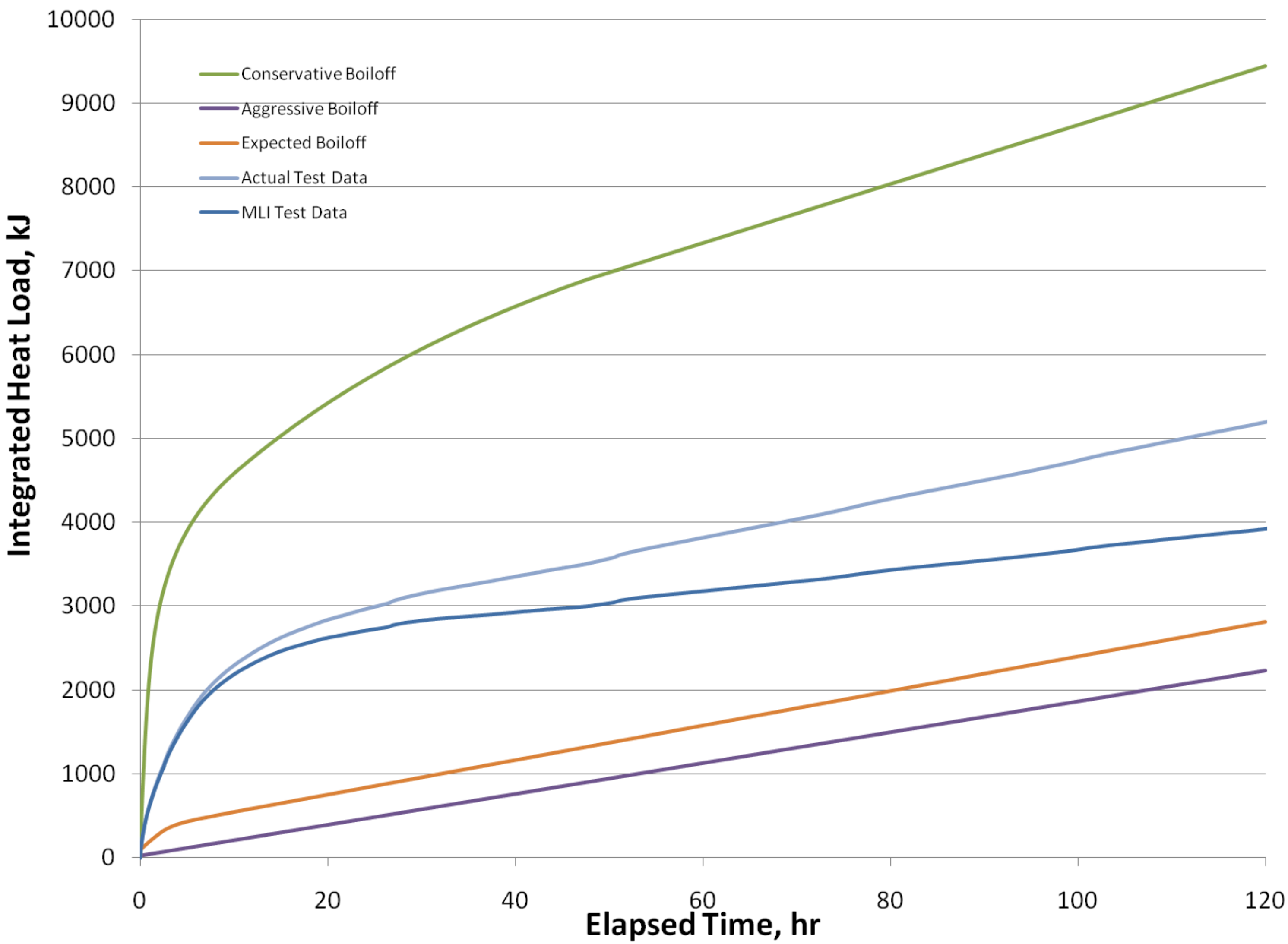
- Tank topped off, brought to steady state at ambient pressure (~5 hrs)
- Turn on vacuum pumps
  - Only open 1 for first ~60 seconds
  - Open second after 60 seconds
- Heat flow approaches steady state after ~30 hours
- Temperature take ~120 hours (5 days) to meet steady state criteria
- Steady state heat load of 6.51 W (WBT of 306 K)
  - Penetrations heat load = 2.94 W
  - MLI heat load = 3.57 W (LSF = 4.5)
- Noticed large water background as within vacuum chamber (after 24 was predominate gas in system).

- Total Integrated heat load: 5700 kJ (914 kJ/m^2)
- MLI Integrated heat load: 4200 kJ (674 kJ/m^2)
  - Assume penetration heat load of 3 W (actually probably varies a bit)
- Excess Q caused by depressurization 2407 kJ (387 kJ/m^2)



Note: Predictions scaled based on surface area.

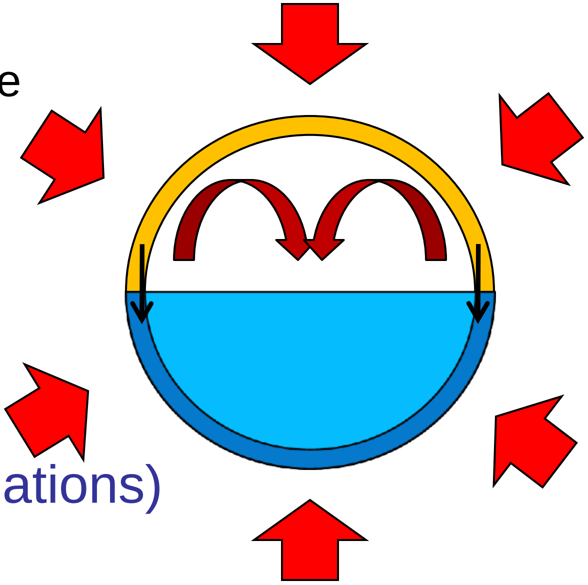
Pre-Test Predictions



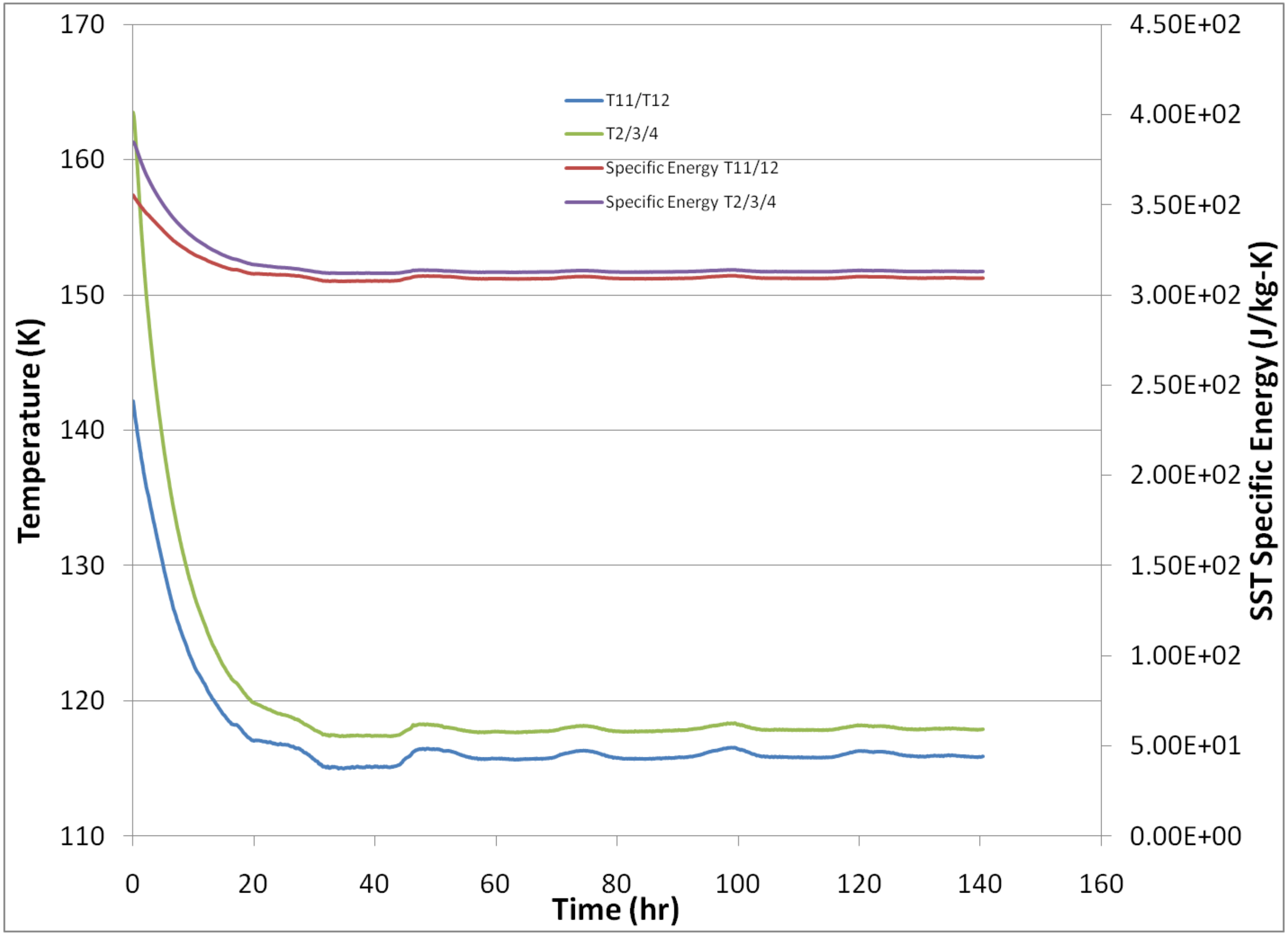
Note: Predictions scaled based on surface area.

Tank Energy

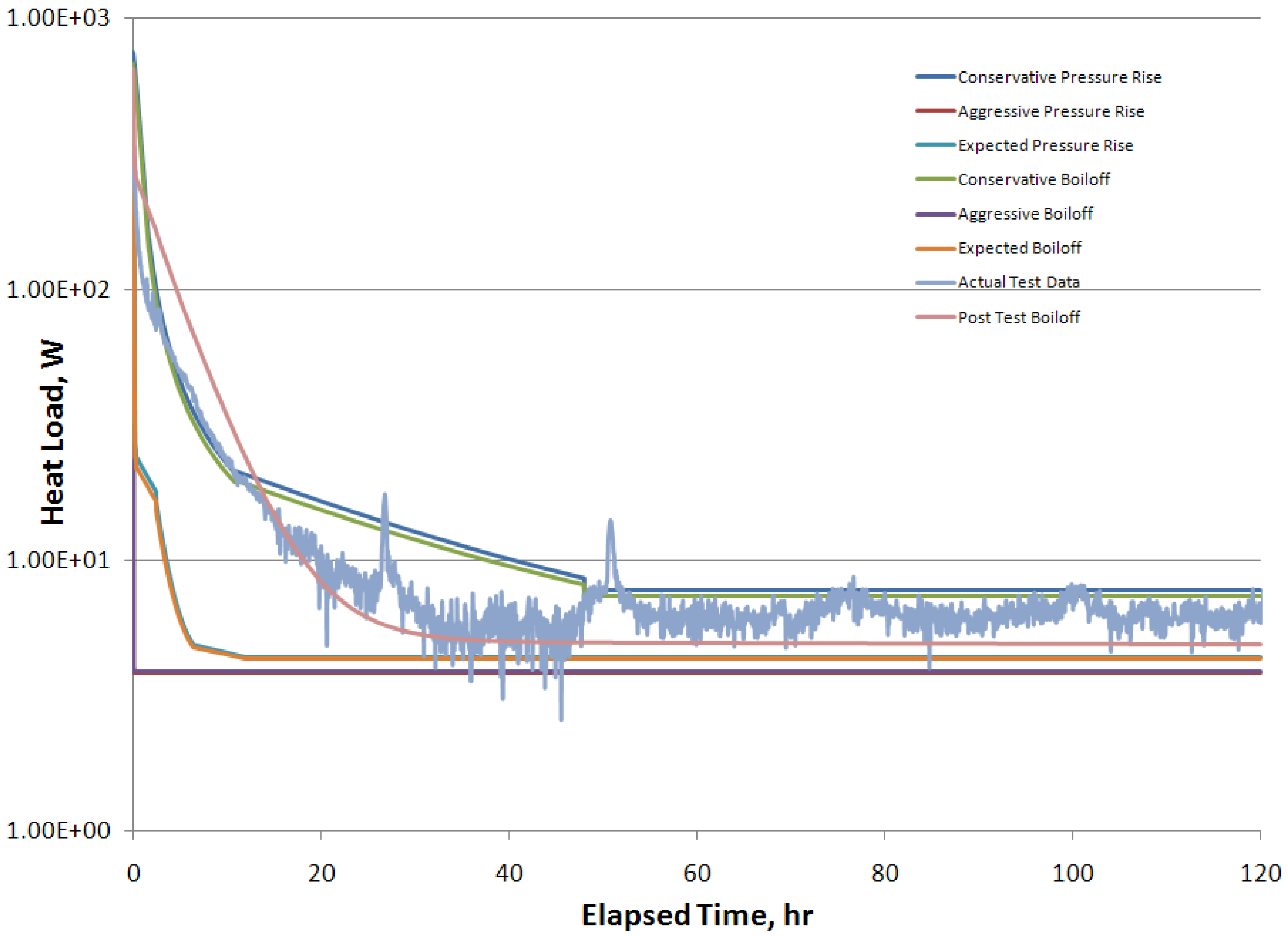
- During the ascent, temperature of the tank (T11 & T12) around the flange drop from 140 K to 115 K
  - Steady state is balanced between thermal resistance through insulation and gas insulation in ullage
  - T2, T3, & T4 (top of tank) drop from 163 K to 117 K
- Energy is rejected into liquid
- Increases boil-off during pumpdown
- Liquid level starts at 92.3 % full
  - 165.6 kg of tank mass (made of SS 316)
- Integrate $c_p dT$ from start to finish (use NIST equations)
  - 8740 J/kg (CryoComp gives 8550 dH for SS304)
- Product give energy input into liquid from tank
  - 1447 kJ (if assume T11/12 profile)
- Previous chart:
  - Total 2402 kJ Assumed Launch Load
  - Remove Tank Energy input gives 956 kJ (60% reduction)
  - Results in 154 kJ/m^2 MLI heat load over steady state
  - 3.6 Equivalent days



Tank Temperatures



Final Result



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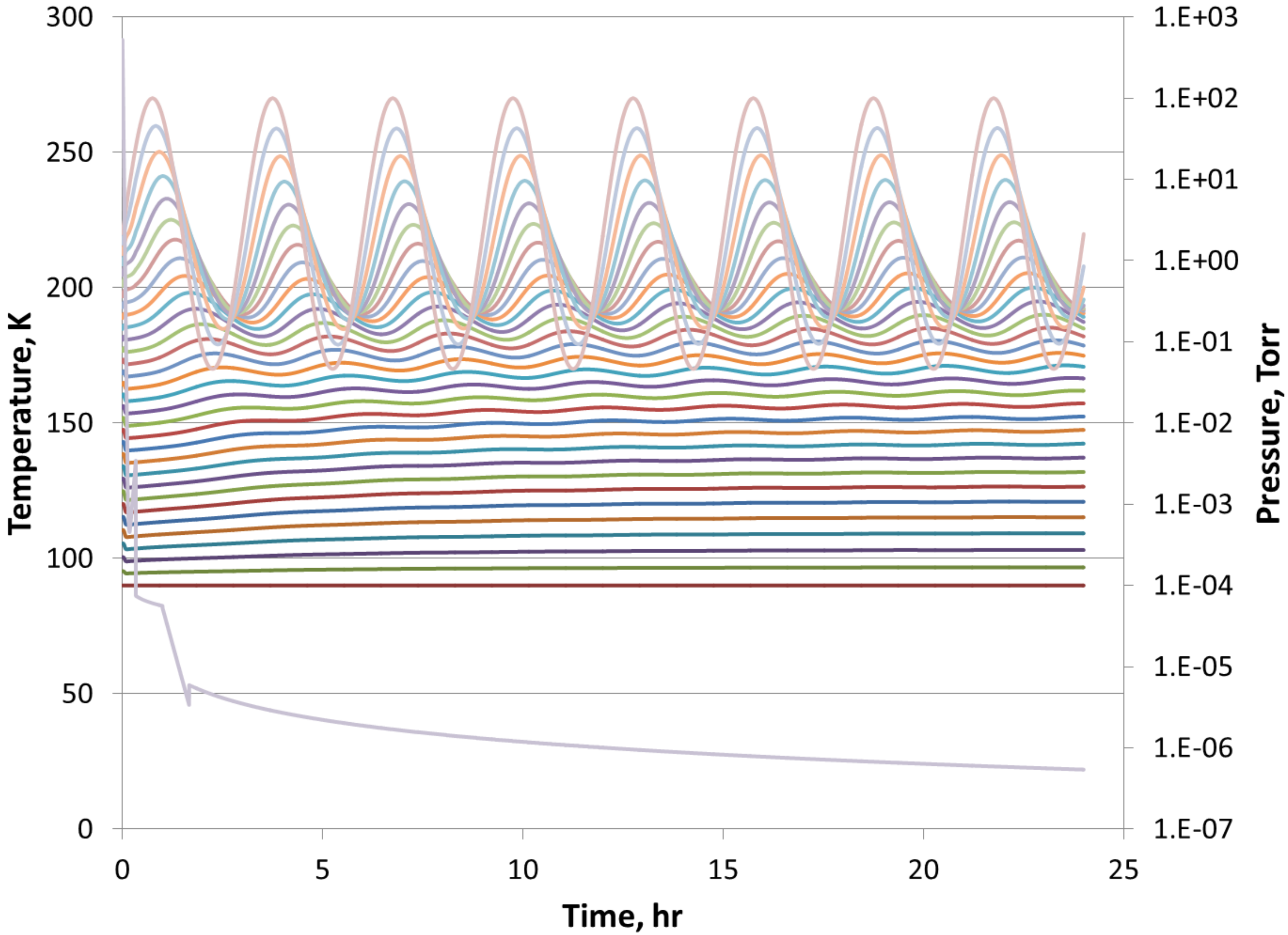
Questions



300
250
200
150
100
50
0
0
5
10
15
20
25
Time, hr
Temperature, K
1.E+03
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1.E+00
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1.E-04
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Pressure, Torr