Liquid Acquisition Strategies for Exploration Missions: Current Status 2010

David J. Chato
NASA Glenn Research
21000 Brookpark Rd., Cleveland, OH
Phone: (216)977-7488
e-mail David.J.Chato@nasa.gov

Abstract:

NASA is currently developing the propulsion system concepts for human exploration missions to the lunar surface. The propulsion concepts being investigated are considering the use of cryogenic propellants for the low gravity portion of the mission, that is, the lunar transit, lunar orbit insertion, lunar descent and the rendezvous in lunar orbit with a service module after ascent from the lunar surface. These propulsion concepts will require the vapor free delivery of the cryogenic propellants stored in the propulsion tanks to the exploration vehicles main propulsion system (MPS) engines and reaction control system (RCS) engines. Propellant management devices (PMD's) such as screen channel capillary liquid acquisition devices (LAD's), vanes and sponges currently are used for earth storable propellants in the Space Shuttle Orbiter OMS and RCS applications and spacecraft propulsion applications but only very limited propellant management capability exists for cryogenic propellants. NASA has begun a technology program to develop LAD cryogenic fluid management (CFM) technology through a government in-house ground test program of accurately measuring the bubble point delta-pressure for typical screen samples using LO2, LN2, LH2 and LCH4 as test fluids at various fluid temperatures and pressures. This presentation will document the CFM project's progress to date in concept designs, as well ground testing results.

Liquid Acquisition Strategies for Exploration Missions: Current Status 2010

Presented at 24th Symposium on Gravity-Related Phenomena in Space Exploration Research and Technology

By

Dr. David J. Chato

NASA Glenn Research Center

Acknowledgements

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  - Facility and Operations personnel at GRC and MSFC test stands
  - Project Office personnel for funding and administrative support
  - Contracted research teams at Boeing Aerospace and Innovative Research Solutions
- Special thanks to Adam K. Martin for assistance with preparation of the slides on the MSFC research efforts

Cryogenic Fluid Management Liquid Supply Task Description

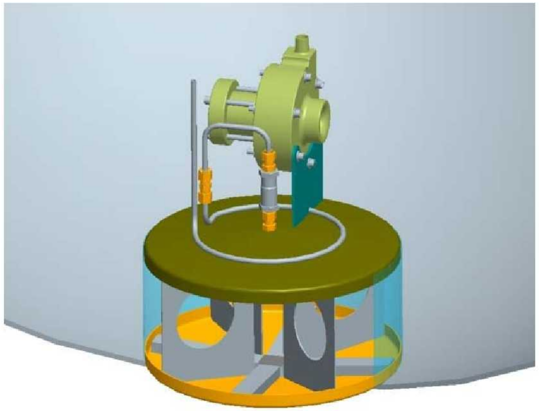
- **Objective:** Provide thermally efficient, delivery of a single phase fluid to the CFM Transfer System.
- **Approach:** Development and test of liquid acquisition devices, including settling and outflow, analysis of data on performance of screen channels, and Helium pressurization validation studies.
  - Current focus: Liquid Acquisition Devices:
    - Uses a capillary screen retention device called a Liquid Acquisition Device (LAD), to provide vapor-free liquids for on-orbit propulsion systems, at flow rates necessary for Main Engine Systems, RCS, and TVS.
  - Technology development:
    - Characterizing the LAD screen properties, minimizing the LAD mass properties and minimizing propellant tank residuals.

Liquid Acquisiton POC: Dr. David Chato, NASA GRC

Technology Development Testing

Low-g Propellant Management

- ***Liquid Acquisition***
  - Perform **analytical modeling** to predict screen channel performance
  - Conduct **bubble point testing**, including subcooled conditions, to determine temperature effects on bubble point for screen channel LADs
  - Conduct Helium pressurization tests to **assess bubble point predictions at elevated temperature** conditions for LO2.
  - Perform **computational fluid dynamic modeling and testing to quantify heat entrapment** within screen channels and start baskets and develop technical approaches to mitigating it
  - Conduct tests at representative flow conditions for main engine burns, reaction control burns, and TVS systems **to assess pressure drop across the screen channel LAD** and to determine the breakthrough pressure at those conditions



Screened Sump Conceptual Design for Lunar Lander Ascent Stage

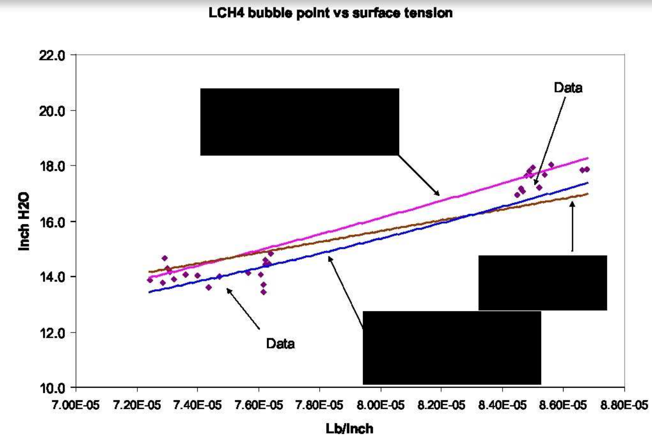
CFM Low-g Propellant Management Technologies
Liquid Acquisition Progress

Prior Year Accomplishments:

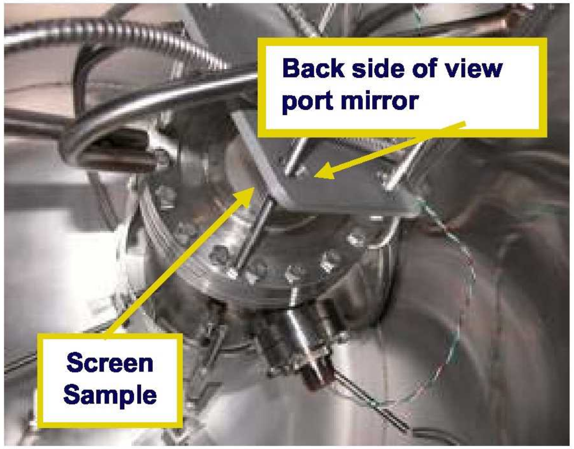
- Completed heat entrapment testing using water and LN2. Testing with both water and liquid nitrogen has demonstrated that heat may be entrapped inside screen channels and start baskets.
- Test series at GRC Creek Road Complex cryogenic test facility (CCL-7) to measure the bubble point (breakthrough) pressure for saturated and subcooled LCH4 were completed.
  - Two screen samples tested with both LN2 and LCH4.
- Presented technical paper, "Screen Channel Liquid Acquisition Device Testing Using Liquid Methane," at JANNAF
- Presented technical paper, "Bubble Point Measurements with Liquid Methane of a Screen Capillary Liquid Acquisition Device,"at the Cryogenic Engineering Conference

Significance:

- Partial demonstration of vapor free cryogenic propellant distribution: Obtained key design data (bubble point).
- Conceptual propellant management device design analyzed for LAT-2
- Qualitatively verified heat entrapment in LAD screens.



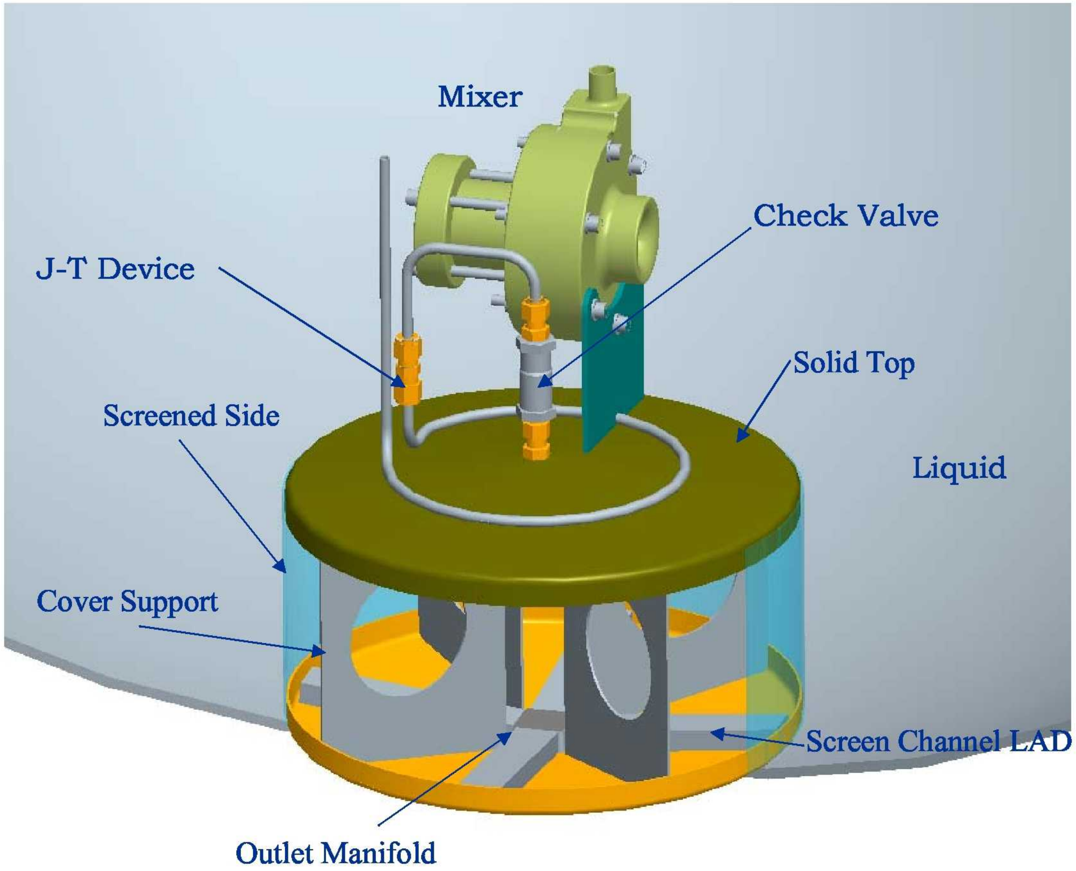
Test data resulting in analytical model



GRC Creek Road Complex cryogenic test facility (CCL-7) to measure the bubble point pressure for LCH4, determine pressure drop across fine mesh screens during flow

Target Design from Lunar Service Accent Module Study 2007

- Goals:
  - Provide common tankage for main engine and reaction control system oxygen/methane propellants
  - Provide Vapor Free Liquid To Main Engine During Engine Start Until Settling Is Achieved
  - Provide Vapor Free Liquid To Reaction Control System During Final Rendezvous And Docking
- Approach:
  - Screened Cylindrical Basket forms Sump to enclose required propellant quantity
  - Four Screen Channels Ensure Drainage Of The Sump Without Vapor Ingestion
  - Thermodynamic Vent System (TVS) Outlet draws from high point in sump (allows ground venting)
  - Top of Sump acts as TVS Heat exchanger



Alternate Designs from Lander PMD Trade Study Final Report

Objective:

Provide conceptual designs of cryogenic fluid propellant management devices (PMD) to support both Altair ascent propulsion and cryogenic reaction control system (RCS) for Altair descent propulsion.

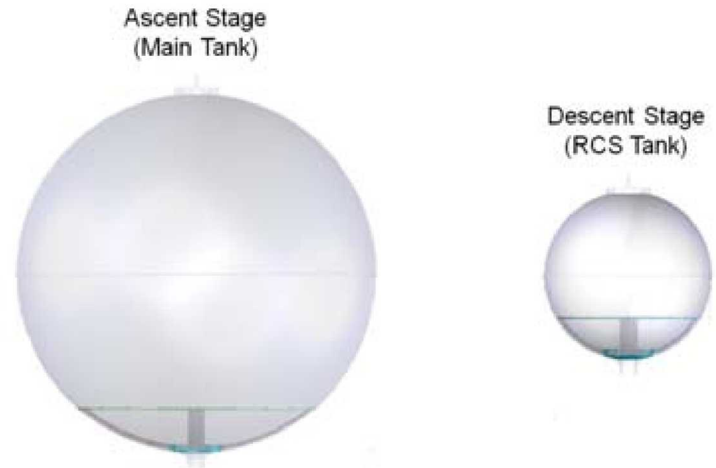
Key Accomplishment /Deliverable /Milestone:

- Four candidate PMD concepts evaluated against Altair Ascent Stage propulsion and Descent Stage Reaction Control System (RCS) requirements
- Two designs Studied in Detail:
  - –Screen channel system for Descent RCS
  - –Flexible Screened sump for Lunar Ascent
- Finding Documented in Final Report delivered 4/30/2009

Significance:

- Conventional Screen Channel LAD devised
- Innovative Flexible Screen sump PMD devised
- Both concepts satisfy all design requirements
- Due to the high tank pressures and high performance insulation required by the mission possible to treat LO2 and LCH4 as if they were equivalent to earth-storable propellants.

Study Performed by
Innovative Engineering Solutions,
San Diego, CA under contract from NASA



Ascent Stage and Descent Stage Tank Size comparisons

Alternate Descent Stage PMD Designs

CFD Bulk Liquid/LAD Interaction Final Report

Objective:

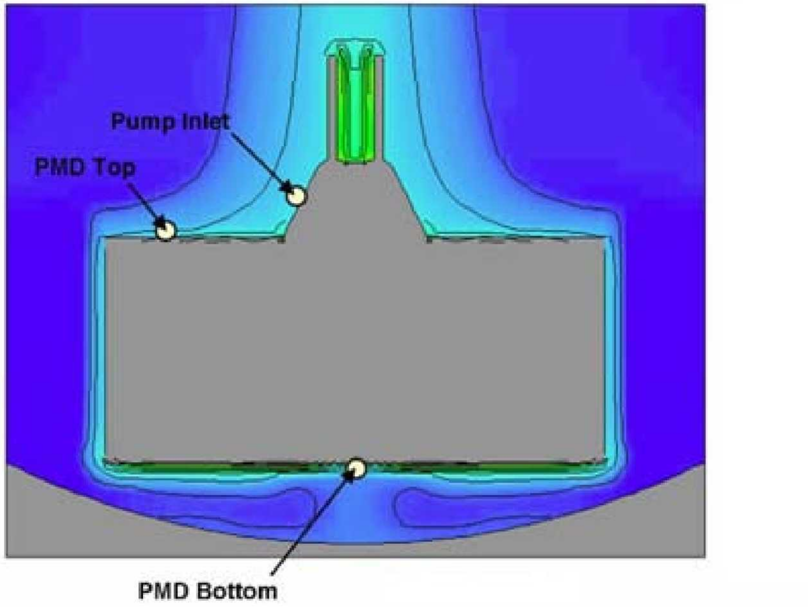
Evaluate pressure control strategies for the Altair ascent stage LCH_4 tank, and understand the interaction of the LAD with the bulk liquid

Key Accomplishment /Deliverable /Milestone:

- Final report submitted by Boeing on March 30, 2009
- Model for LCH_4 tank and TVS added to the FLOW-3D CFD code used in the PCDC study
- Report includes simulation results for the LCH_4 tank under a variety of conditions relevant to a lunar stay

Significance:

- Pressurization rates determined for a range of LAD heat leaks (0.15W – 15W)
- TVS flow rates and inlet temperatures needed for prompt pressure relief were determined. Lower bulk liquid temperatures at the inlet are not sufficient if the flow rate is too low.
- Slightly warmer liquid accumulates around the lad (especially below it). A tapered LAD might help in releasing this trapped heat



Temperature distribution around LAD

Study Performed by
Boeing Aerospace Corporation,
Huntington Beach, CA under contract from NASA

LAD Heat Entrapment Subscale Model Test Data Review*

PT: Cryogenic Fluid Management
PM: Mary Wadel
PI: Adam Martin (MSFC/ER24)

*This deliverable provides the status of all FY09 LAD / Heat Entrapment efforts, including **Thermal modeling of the LAD**, **Bulk Liquid CFD Modeling**, **Condensation Conditioning**, and **System Integration Testing,** results that were all reported out at the Subscale Model Test Data Review on 10/8/09.

Objective:

Determine whether heat entrapment in a Liquid Acquisition Device (LAD) in the Altair ascent-stage liquid methane tank during a lunar surface stay will be a problem.

Key Accomplishment / Deliverable / Milestone:

•Final report on FY09 work delivered Sept. 30, 2009 (Test Data Review held on Oct. 8th, 2009); report and briefing includes:

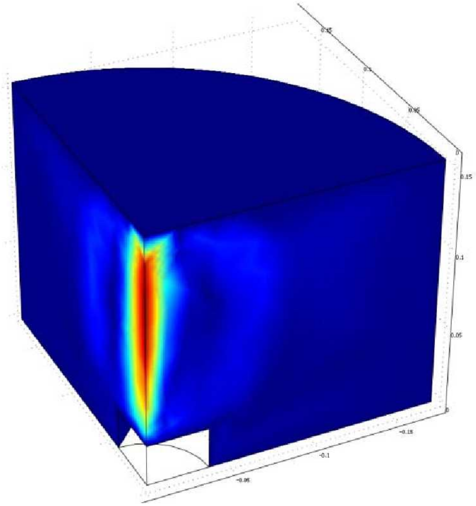
- •Results from a numerical CFD/thermal model of the LAD
- •Computational results from the Boeing LAD / Bulk Fluid interaction study
- •Results of screen wicking experiments
- •**Results of the sub-scale water test**

Significance:

•An empirical scaling, supported by theory and experiment, indicate that the LAD comes into thermal equilibrium with the bulk liquid in the tank on short timescales (a few hours), with temperature differences between the two of at most a few 10s of milli-Kelvin.

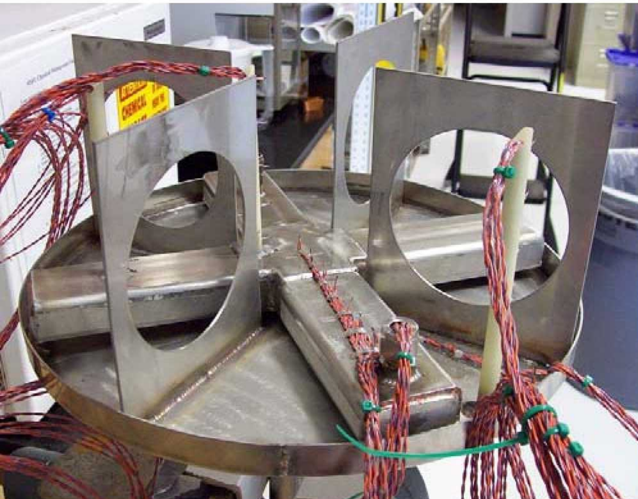
•Heat entrapment is not expected to be a concern for liquid methane on the lunar surface.

Flow velocity from natural convection in the LAD, calculated using COMSOL: P_h = 10 W, peak flow velocity (on axis) = 8 mm/s



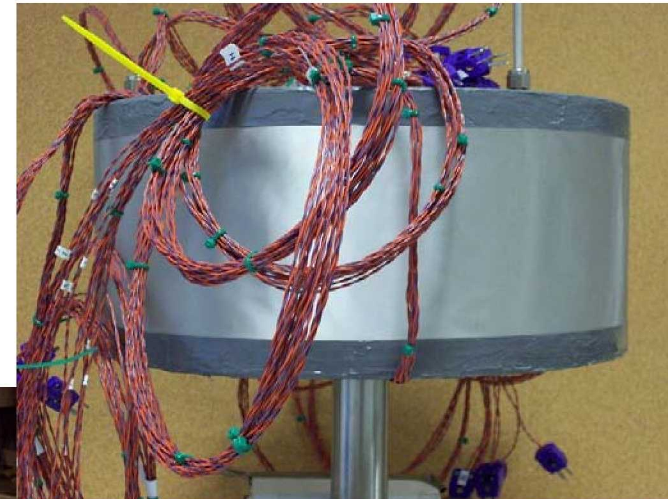
Sub-scale water test apparatus

Sub-scale Water Test Apparatus

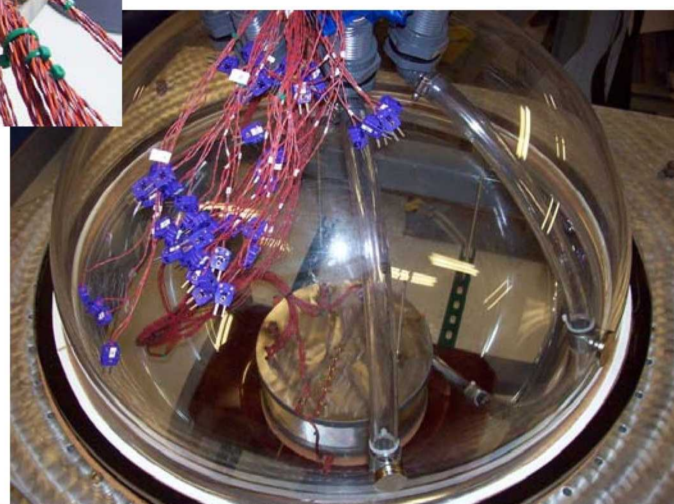


← LAD interior, partially assembled

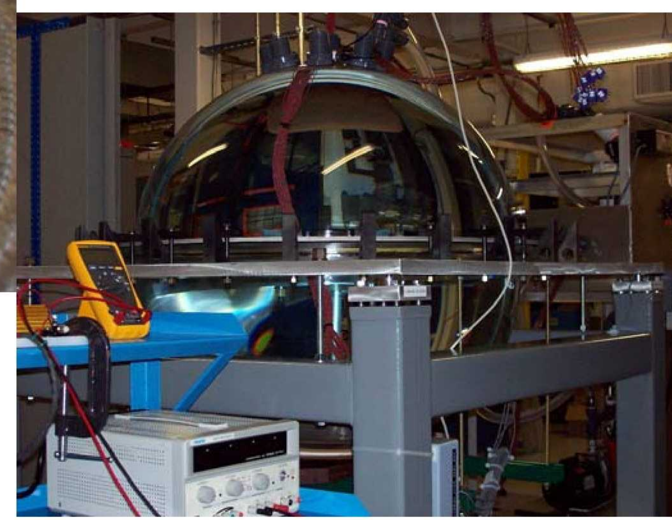
Finished LAD →



LAD Inside of Tank



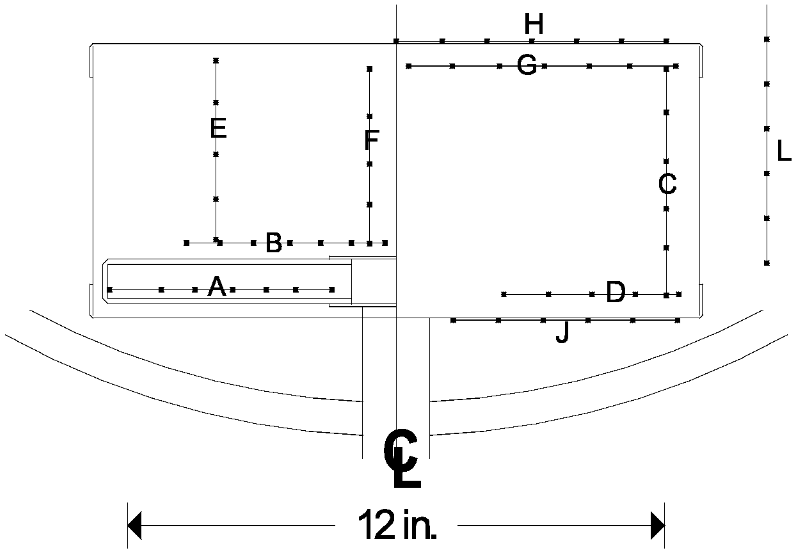
Filled Tank



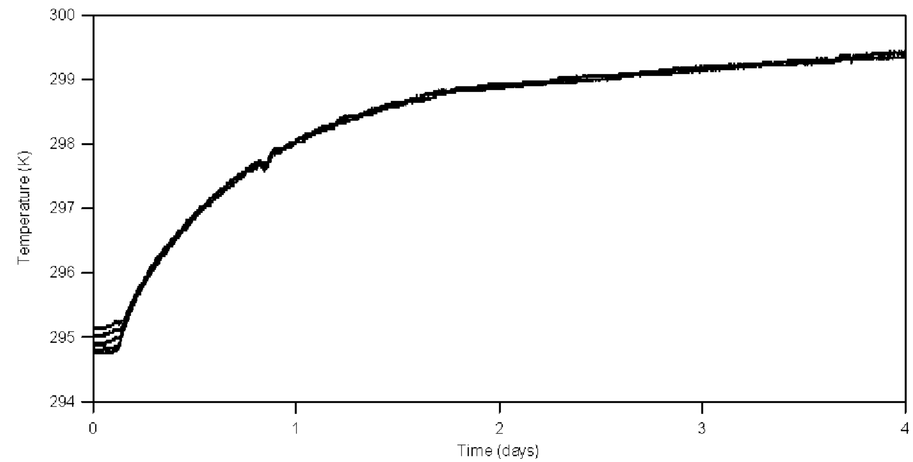
Heater Assembly

Sub-scale Water Test Results: P_{in} = 19.5 W

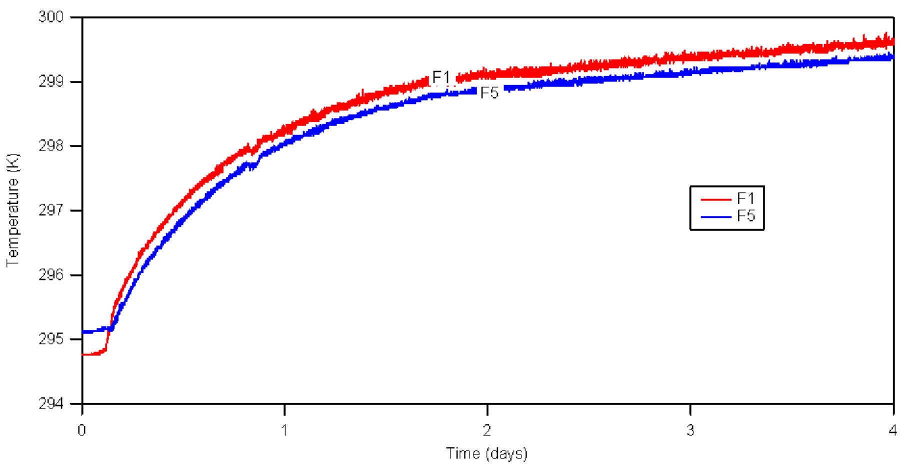
Key to TC probe arrays



Array E



Array F



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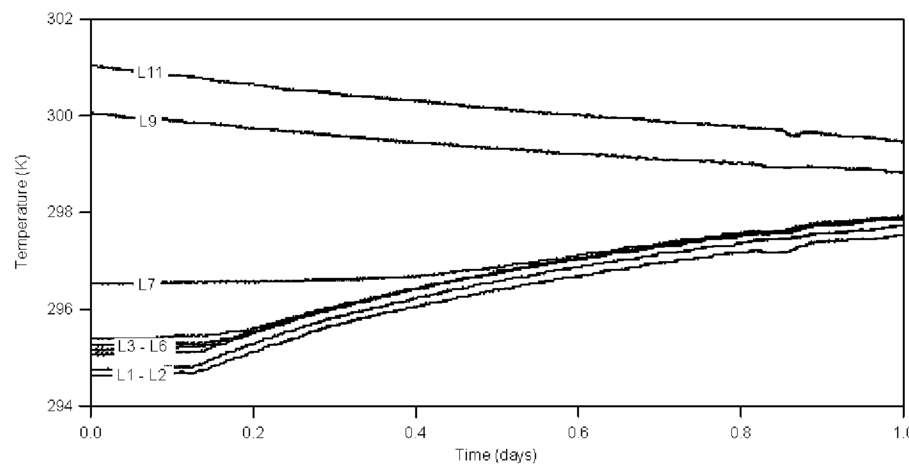
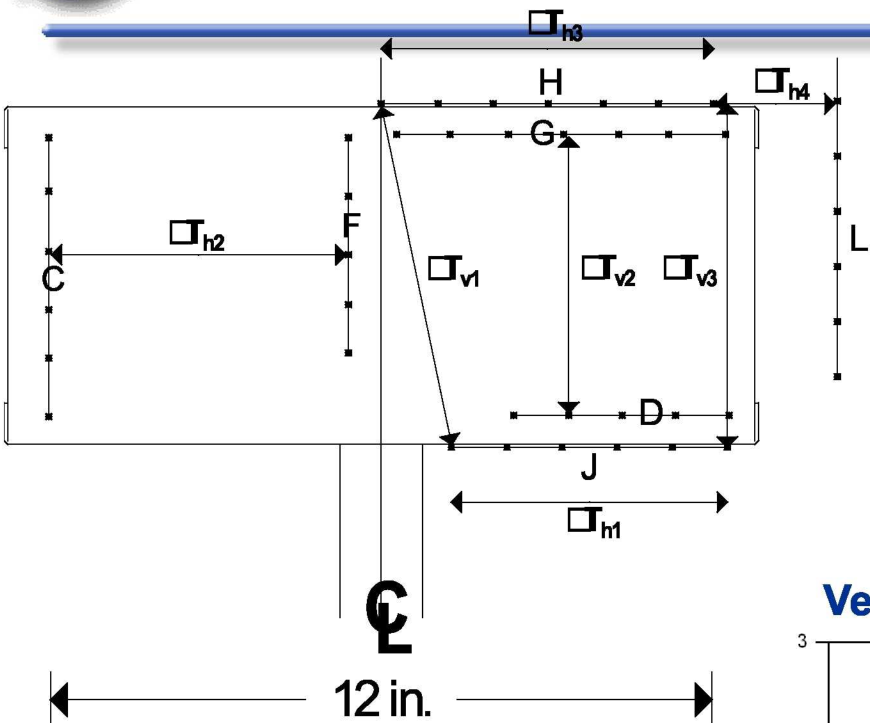
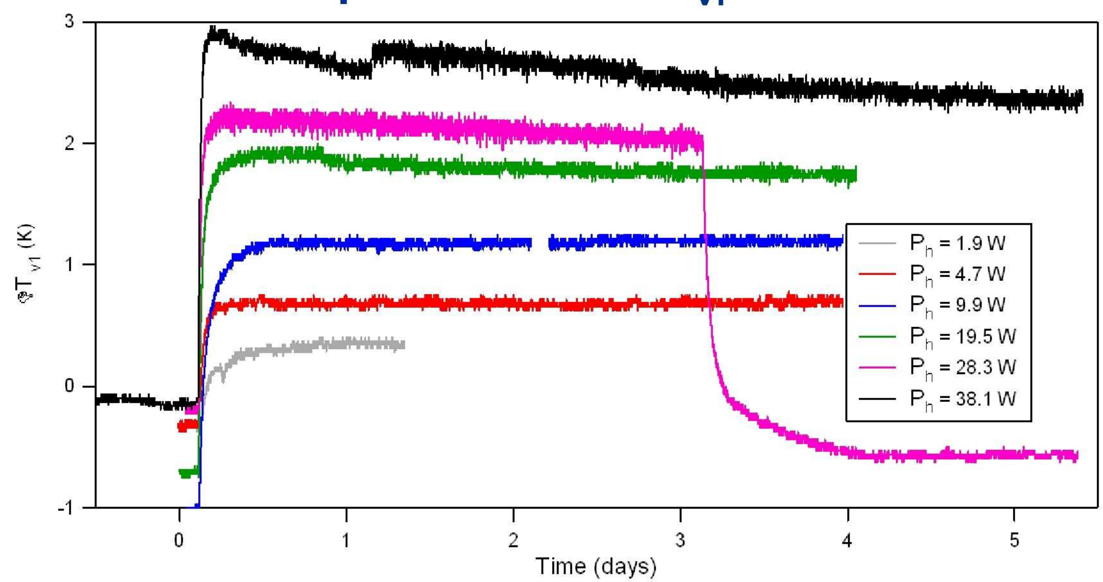


Sub-scale Water Test Results

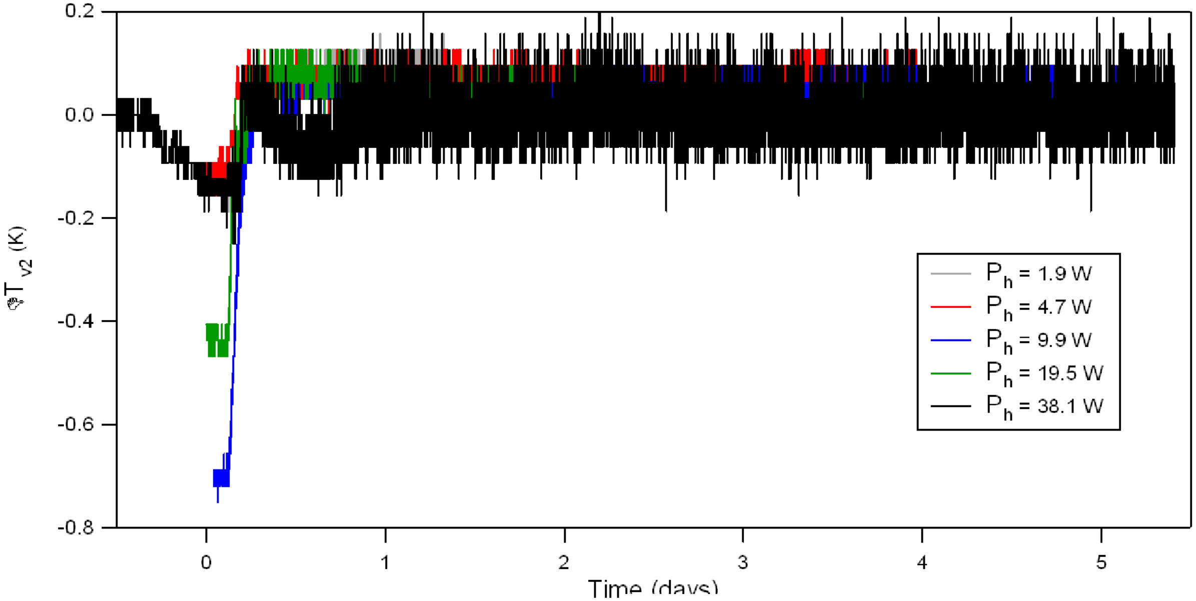


Key to Temperature Indices

Vertical Temperature Index ΔT_{v1}

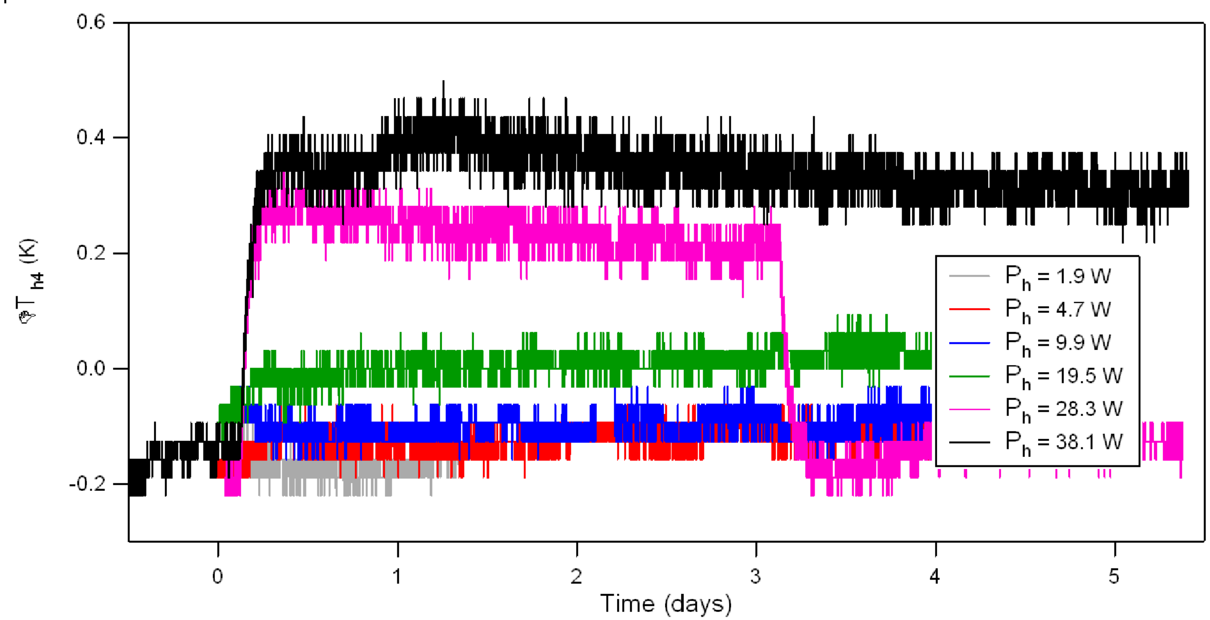


Sub-scale Water Test Results



– **Vertical Temperature Index ΔT_{v2}**

Horizontal Temperature Index ΔT_{h4} →



Empirical Scaling

Using an empirical scaling law for a sphere (with the same surface area as the LAD: R_{sphere} = 6.7") immersed in a liquid, the film heat transfer coefficient is given by:

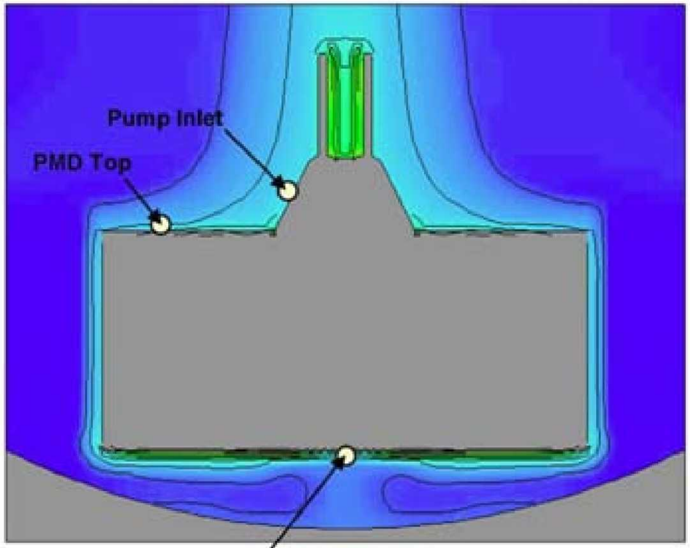
$$h_f = 3.58 \left(\frac{\kappa^3 g \beta C_P \rho^2}{\mu R} \right)^{1/4} (\Delta T)^{1/4}$$

In equilibrium, the heat extracted from the LAD equals the input heating power, P_{in} = P_{out}, and the relation above can be used to estimate the temperature drop, ΔT, between the LAD and the bulk liquid:

$$\Delta T = \left(\frac{P_h}{345\ W/K^{5/4}} \right)^{4/5}$$

The table at right compares measured (and computed) temperature drops with the estimates made from the empirical relation. Empirical estimate is typically ½ of measured (computed)

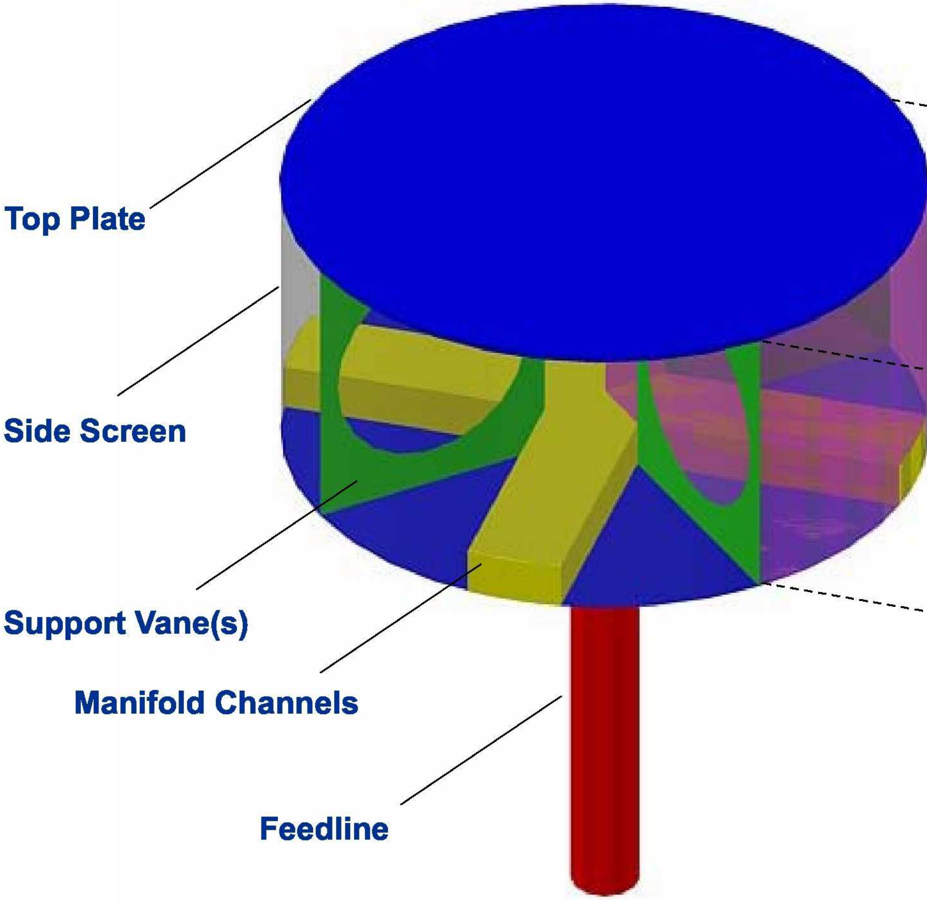
*Results from CFD calculations performed by G. Grayson of Boeing (figure, top right)

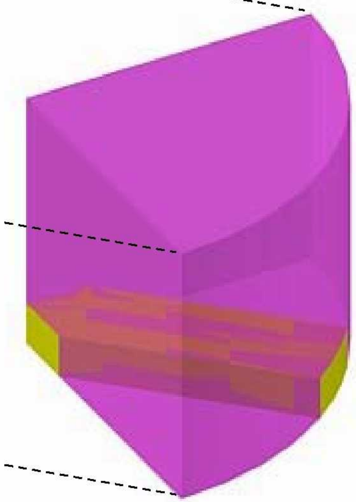


Case	P_h (W)	ΔT (K) Meas. / Comp.	ΔT (K) Empirical
H_20, Exp.	1.9	-0.18	0.02
H_20, Exp.	4.7	-0.15	0.03
H_20, Exp.	9.9	-0.1	0.06
H_20, Exp.	19.5	0.0	0.10
H_20, Exp.	28.3	0.25	0.14
H_20, Exp.	38.1	0.35	0.17
CH_4, Comp.*	0.66	0.02	0.009

LAD CFD Modeling using Comsol*

Start Basket Geometry

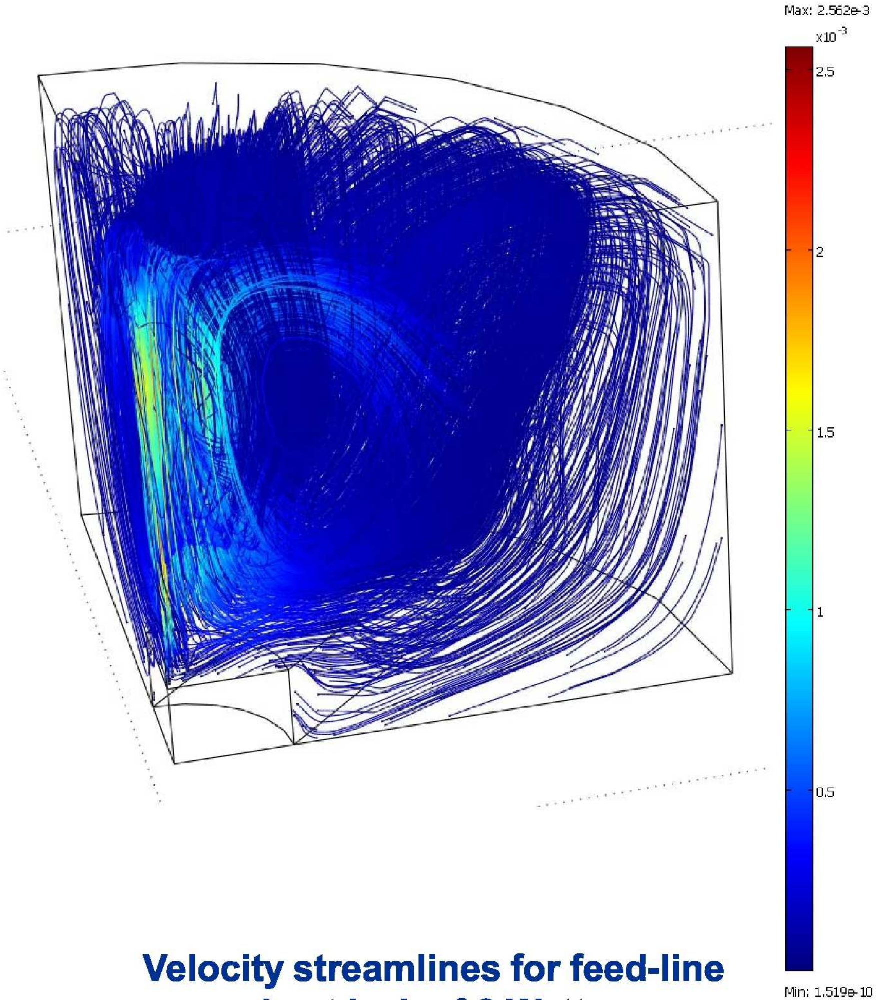




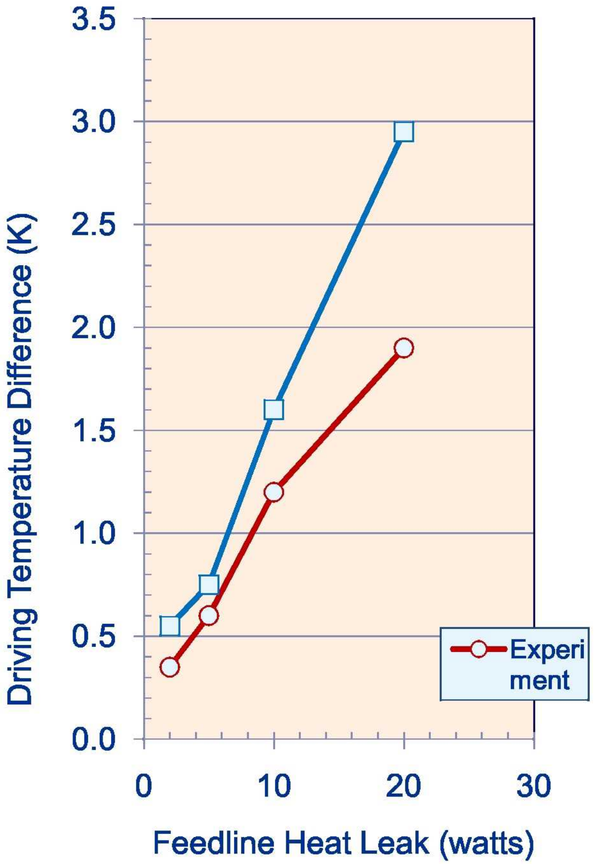
Model Geometry based upon Symmetry
(90^o Slice)

* Work done by Greg Schunk, MSFC / EV34

LAD CFD Modeling using Comsol



Velocity streamlines for feed-line heat leak of 2 Watts

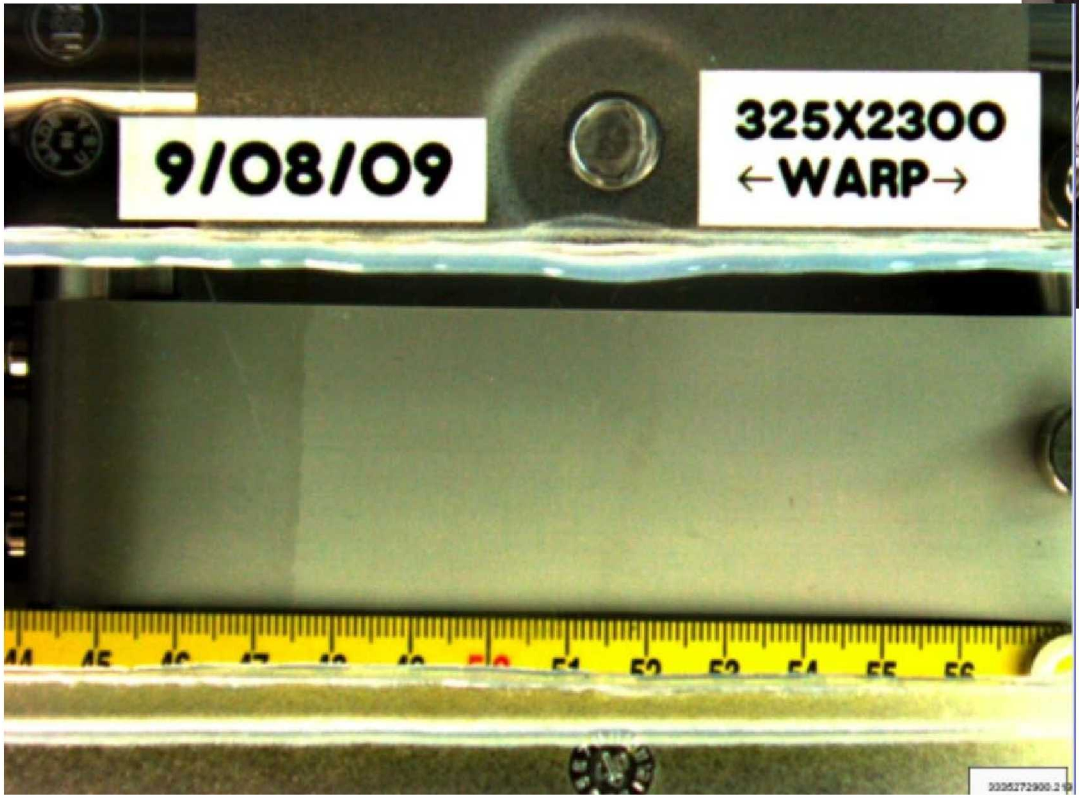


Temperature difference ΔT_{v1} as a function of heating power

Alcohol Wicking Tests: Horizontal*

Tests conducted to determine wicking behavior of fine-meshed wire cloths used for LADs. Horizontal wicking is equivalent to the zero-gravity condition.

Apparatus for horizontal alcohol wicking test →



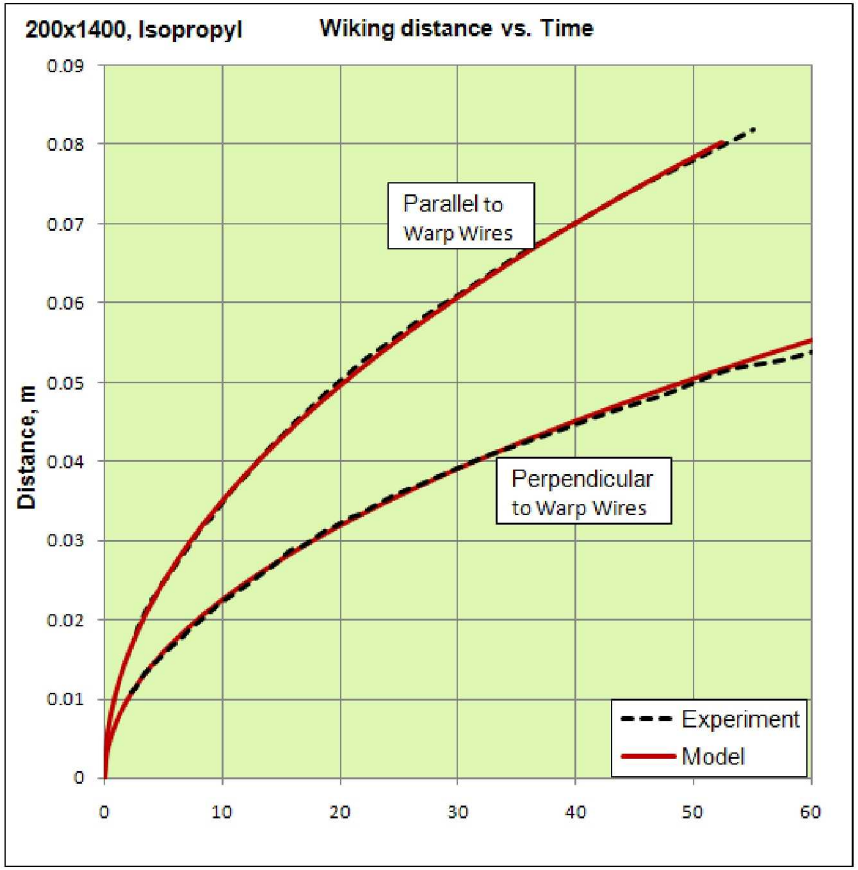
← Single frame from video showing alcohol wicking front (parallel to warp wires

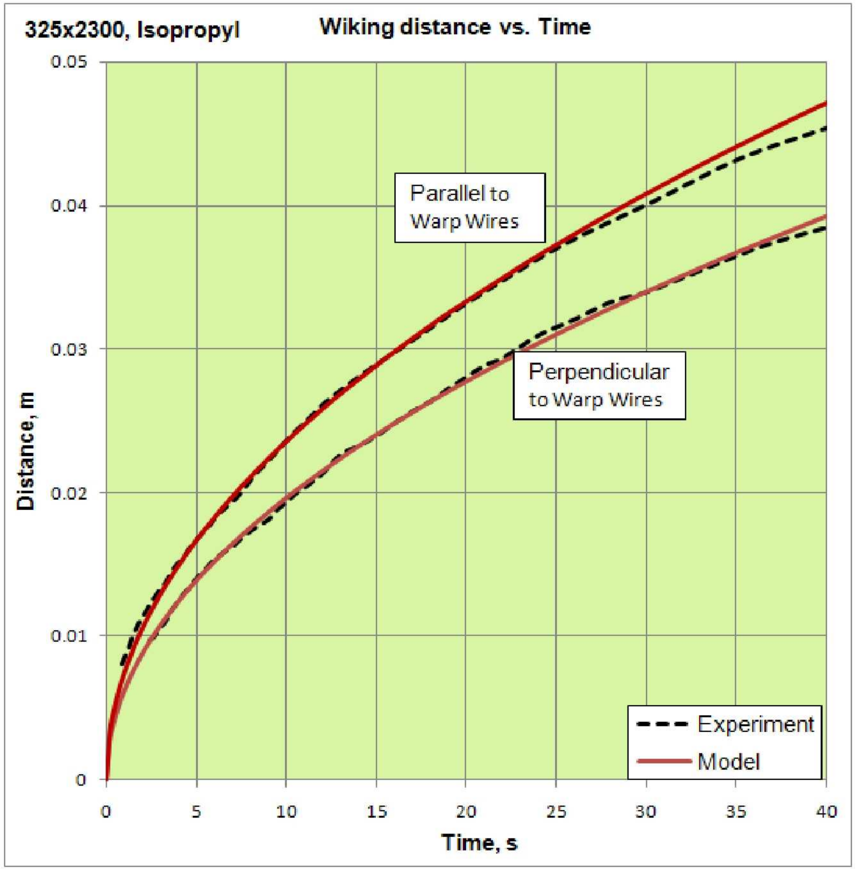
*** Richard Eskridge (MSFC/ER24)**
Leo Bolshinskiy (UAH)
David Wilkie (Qualis)

Alcohol Wicking Tests: Horizontal

Data from horizontal wicking tests using IPA, with fits to theoretical model:

$$l = \sqrt{K D_e t} \qquad K = \frac{\sigma \cos\Theta}{4\mu} \qquad D_e = \frac{D_h^2}{D_c}$$

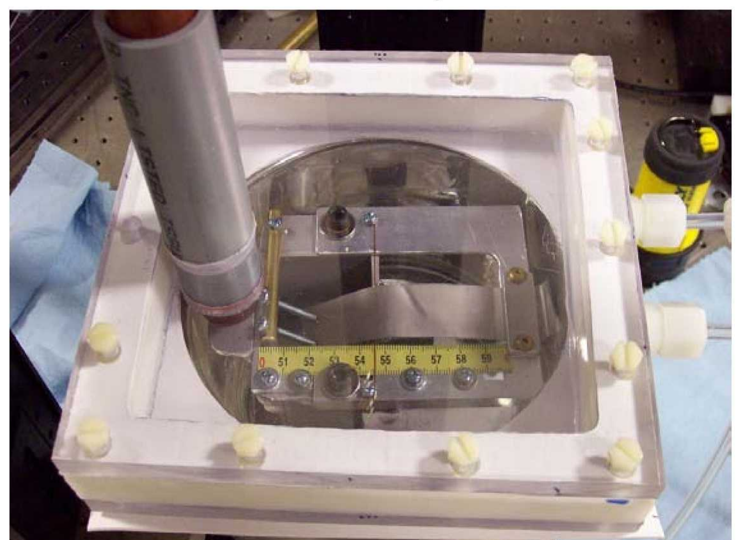


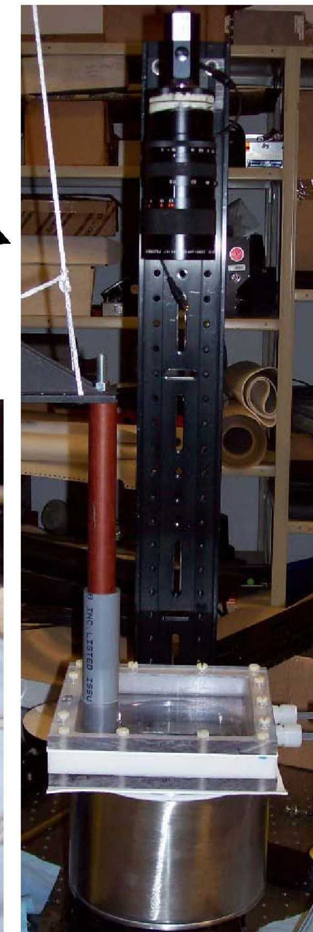


Future and Pending Work for FY10 at MSFC

- Horizontal wicking tests using LN_2 (in progress)
- Refinement of LAD CFD model
- Extension of Heat Entrapment analysis to the
- cases of:
  - LH_2, and
  - micro-gravity conditions
- Flow visualization measurements in sub-scale
- tank to provide better correlation with
- computational results

Apparatus for horizontal LN_2 wicking tests





LOX HIGH PRESSURE HELIUM BUBBLE POINT TEST

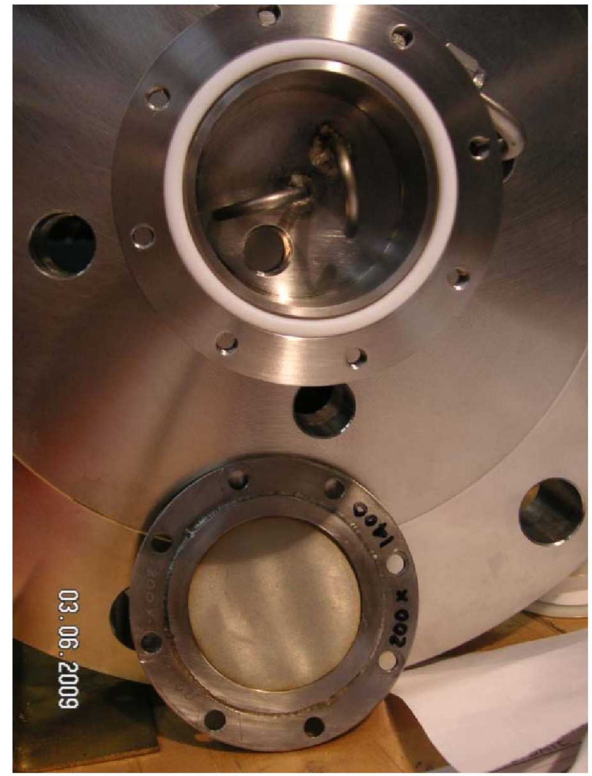
Test Objectives

- The purpose of this experimental program is to collect additional bubble point data for a screen channel LAD by performing bubble point tests using LOX to ascertain if the use of helium pressurant gas at pressures up to 250 psia , has any effect on the performance. There are three proposed objectives for this test effort:
  - Ascertain whether helium dissolution into liquid oxygen is significant to alter the relevant liquid oxygen properties, namely liquid oxygen surface tension.
  - Verify liquid oxygen surface tension at temperatures up to 220 deg R .
  - Continue the assessment of the effect of liquid viscosity on bubble point.

Description of Experiment

- The experiment will be conducted at GRC Creek Road Cryogenic Complex – Cryogenic Component Lab 7 (CCL-7). CCL-7 will be modified for LOX testing capabilities at higher pressure. New research hardware is being developed for this test program. Additional facility changes are necessary though to accommodate the high pressure testing including the following:
  - High pressure LAD test tank
  - High pressure supply system for the helium.
  - High pressure, high accuracy helium pressure controller to replace the existing Druck controller
  - High pressure piping for the new LAD test tank

LOX HIGH PRESSURE HELIUM BUBBLE POINT TEST HARDWARE



High Flow Rate LAD Test Objectives

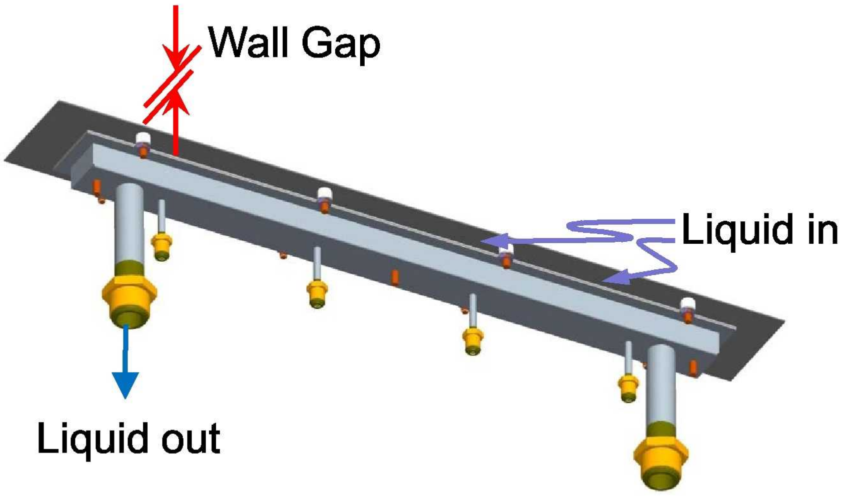
Objective: Provide Exploratory Benchmark Data For Representative Flow Conditions Of LOX Through A Prototypical LADs Channel.

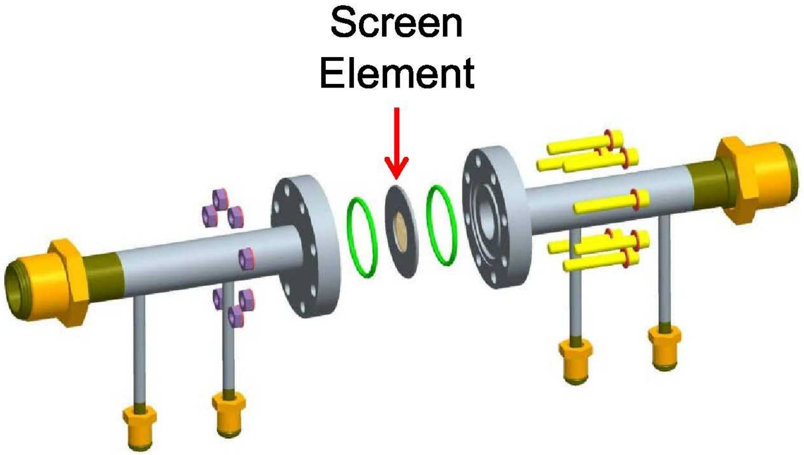
- Representative Flow Conditions Include Expected Flow Rate, Pressure And Temperature Of LOX As Specified Within LAT-2 Study That Are Within Capabilities Of SMiRF.
  - LAD as a Flow Restriction: System Pressure Drop
  - Bubble Breakthrough Aspect
- Data Will Be Used To Develop And Refine Predictive Models For LAD Design.
- These LAD Channels Will Later be Tested Using methanol For Detailed Flow Field Measurements.

Flow Restriction Tests

Flow into LAD Channel

- From 0.5 To 1.4 X LAT-2 Study Flow Rate
- Channel Geometry
  - 1 Inch High X 2 Inch Wide Channel
  - 19 Inch Long X 2 Inch Wide Screen Area
  - 3 Taps Used For Pressure Loss Measurements
- Cover Plate
  - One Channel With Covered Screened Area
  - One Channel Open To Bulk Liquid In Tank



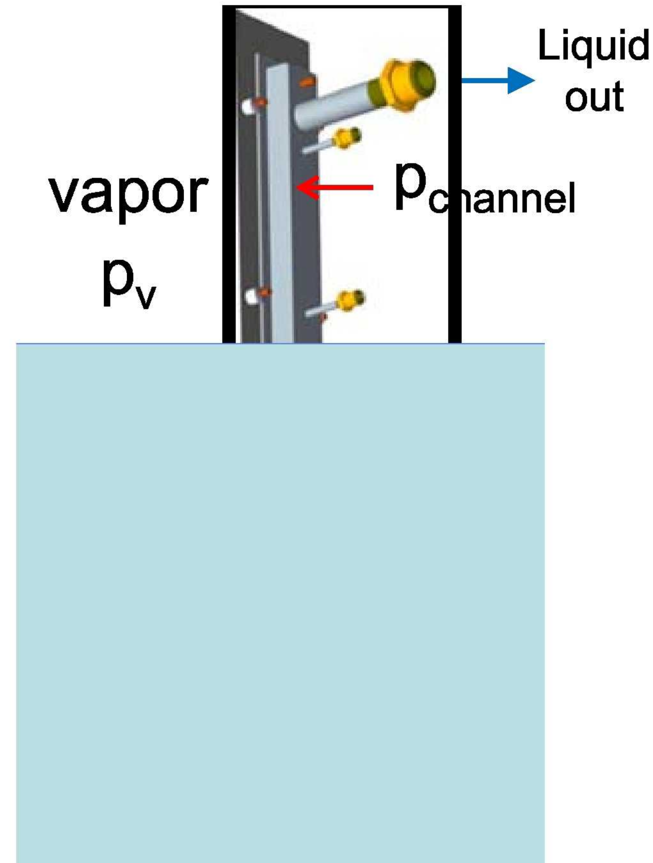


Flow Across Screen Only

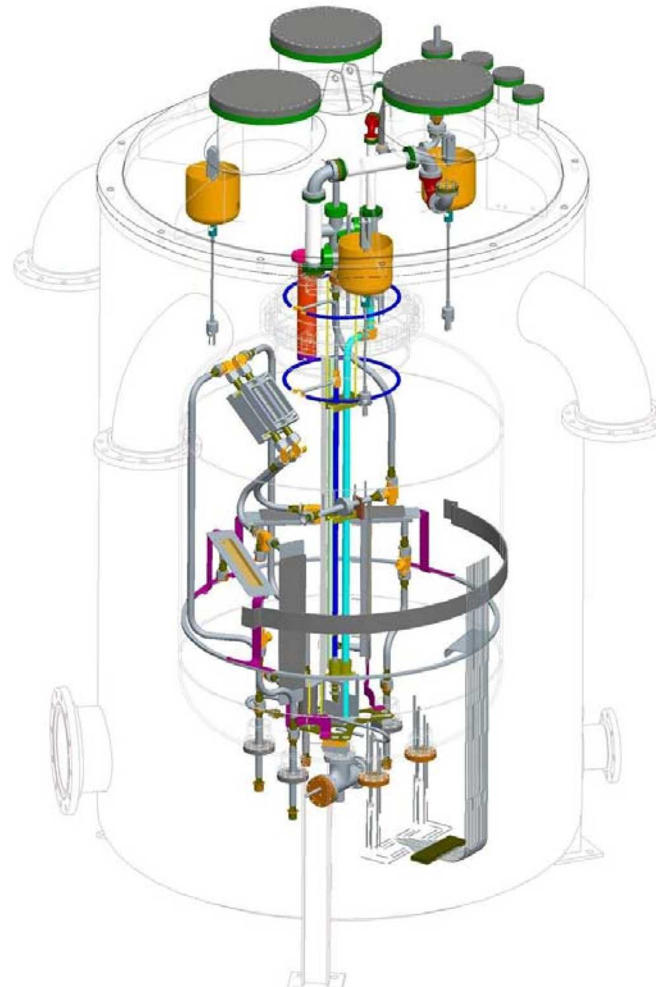
- Measure ΔP vs Q.
- Test Over Extended Range From 0.5 To 3 X Scaled LAT-2 Study Flow Rate
  - Screen Element 1” Diameter
  - 3 Taps Used For Pressure Loss Measurements
- Analysis:
  - For given screen/fluid: $\Delta P = A\,Q + B\,Q^2$

Bubble Breakthrough Tests

- Primary Purpose: Determine Conditions For Bubble Breakthrough (Gas Bubble Ingestion) In Terms Of Liquid Flow Rate and Liquid Height Along Screen Channel
  - Partially submerged in liquid
  - Low flow rate (~0.5 lb/s)
  - Must maintain $p_v < p_{channel} + p_{bpoint}$ to avoid gas ingestion
- From 0.4 To 3 X LAT-2 Study RCS Flow Rate
- Channel Geometry
  - 1 In High X 2 Inch Wide Channel
  - 19 In Long X 2 Inch Wide Screen Area
  - 2 Taps Used For Pressure Loss Measurements
- Cover Plate Configuration
  - One Channel With Covered Screened Area
  - One Channel Open To Bulk Liquid In Tank



High Flow LADs Test Hardware



Summary

- Significant progress has been made in understanding cryogenic Liquid Acquisition Devices both in screen bubble point characterization and preventing heat entrapment
- Concept designs indicate that cryogenic LAD designs are feasible for combining propellant storage of both main engine and reaction control system propellants
- Work planned for 2010 will lead to better modeling of the heat entrapment phenomena; extension of the screen bubble point database to higher pressures; and demonstration of the ability of screen channel LAD to handle the flow rates required by main engine feeds.

Cryogenic Fluid Management Liquid Supply research has improved our understanding of the liquid acquisition device design requirements necessary to meet the needs of the Exploration mission and will continue to develop the tools and technology required for mission success