Investigation of Vapor Cooling Enhancements for Applications on Large Cryogenic Systems

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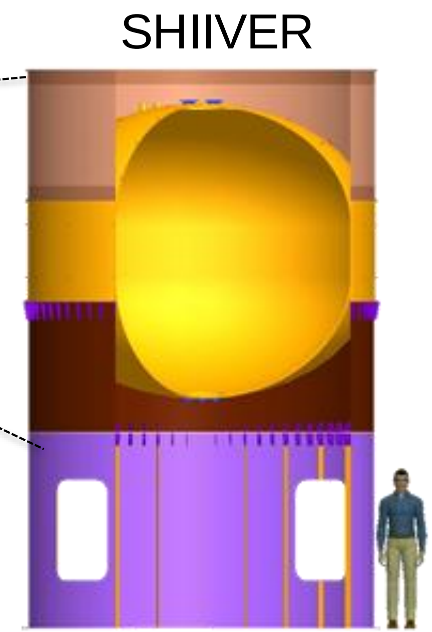
Structural Heat Intercept, Insulation, and Vibration Evaluation Rig (SHIIVER)



Large cryogenic tank assembly with geometry, support structure, skirt and fluid penetrations comparable to an actual space flight vehicle configuration. The basic tank and support structure are being developed as long term assets that can be reused for future testing beyond eCryo.

The test effort under eCryo will focus on three main areas:

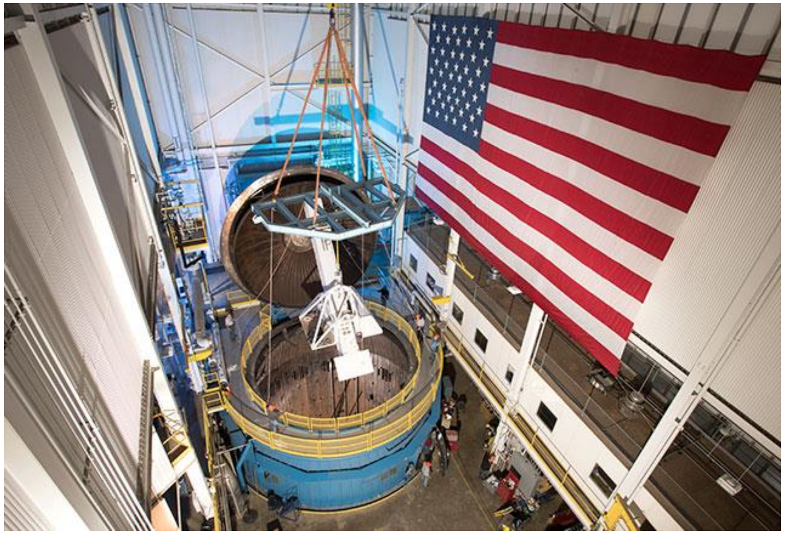
- Structural cooling using tank boil off vapor to intercept conductive heat leak
- Design, construction, and performance of MLI on a large flight tank configuration
- MLI blanket durability under launch acoustic vibration conditions

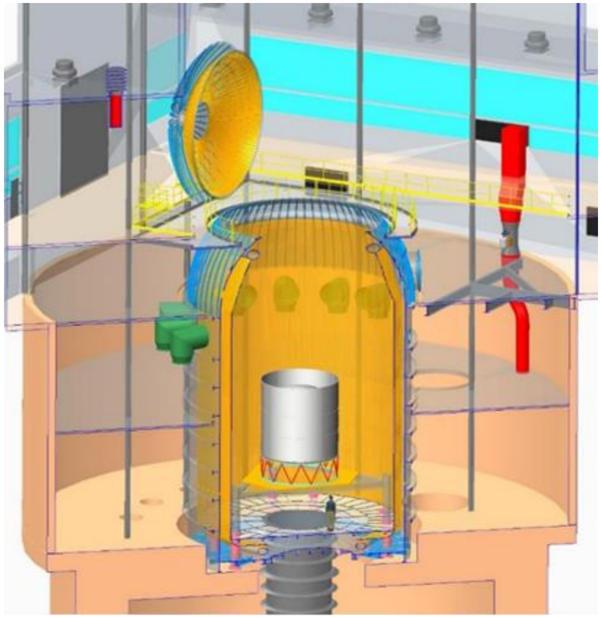
Vapor Heat Interception Rationale

- **SHIIVER design team seeks to demonstrate the applicability of vapor cooling on an upper stage like SLS's Exploration Upper Stage (EUS).**
  - SLS EUS, like most cryogenic upper stages, experiences significant heat leak which is counteracted by carrying excess propellant to accommodate boil-off loses.
  - Heat leaks through support structures reach and are absorbed by the liquid hydrogen in propellant tanks which generates boil-off.
  - If the cold boil-off vapor could be utilized for heat absorption at the structure of the tank – in our case the forward skirt – the extent of boil-off could be greatly reduced.
- **Future exploration missions will require cryogenic propellant resource utilization to increase from hours to days.**
- **Limited data exists for vapor heat interception for hydrogen on cylindrical flight-like support structures.**
  - Minimal effort has gone into intercepting heat on large structural surfaces associated with rocket stages.
- **Aim for vapor-cooling systems to have low mass and surface area relative to the upper stage (less than 5%).**

Demonstration on SHIIVER

- **The forward skirt will provide interface connections for tank venting and vapor cooling flow to the facility.**
- **The skirt will include:**
  - Insulation on the inside surface to minimize radiation to the cooling circuit from the inside.
  - Instrumentation with temperature sensors to measure the axial surface temperature gradients at multiple circumferential locations.
  - Heat flux sensors will be applied to the outer surface of the skirt to measure the radiation flux at several locations.
- **The vapor heat interception system will be integrated with a upper-stage representative MLI on the test tank and will be tested thermally in the Spacecraft Propulsion Research Facility at NASA's Plum Brook Station.**
- **Vapor cooling goal performance parameter calls for a 15% reduction in overall tank boil-off rate while also minimizing added weight.**

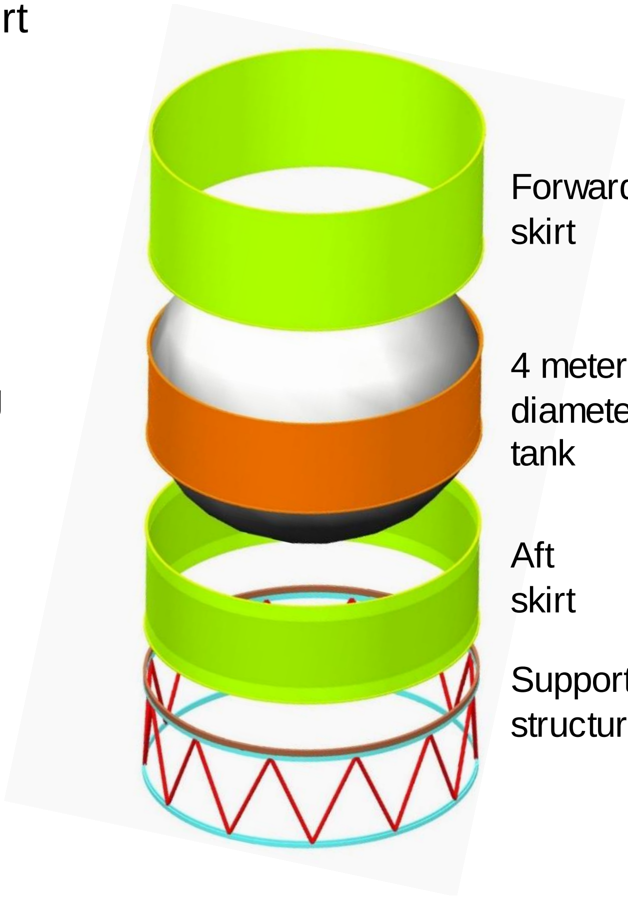




- Due to limited vapor cooling data to inform the SHIIVER forward skirt design, a formulated sub-scale testing effort is required to provide performance data on attachment methods

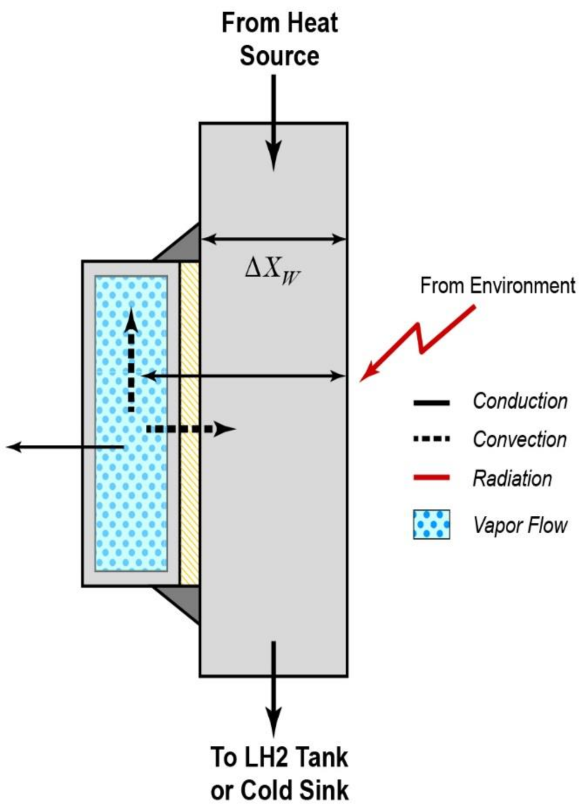
- Sub-scale Laboratory Investigation of Cooling Enhancements (SLICE) aims to:
  - Provide SHIIVER with information on material thermal resistance and heat transfer performance data when utilizing boil-off hydrogen for structural heat interception
  - Various design applications will be considered

- Preliminary analysis informed assumptions to predict vapor cooling effectiveness, which included the contact conductance achievable at the cooling circuit to skirt interface



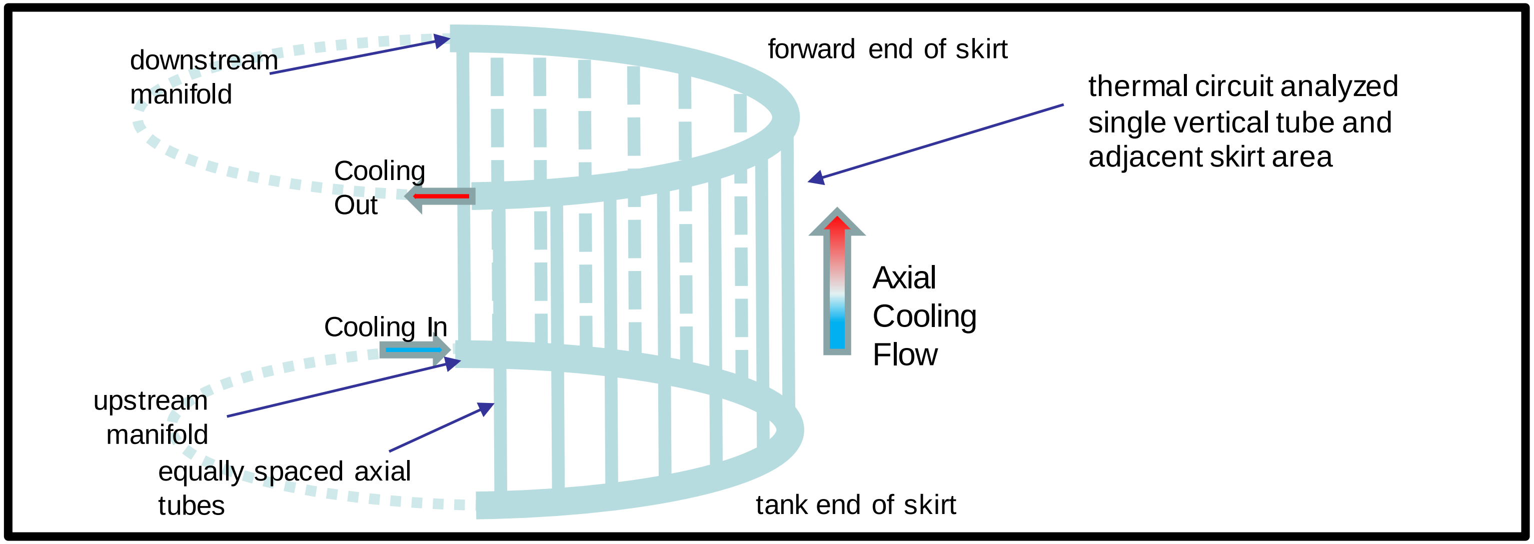
Skirt cooling analysis overview

- 1D model was developed to determine the axial temperature distribution along the skirt surface and understand how that distribution can be manipulated by applying cooling.
  - The change in the temperature distribution along the skirt affects the net heat transmission into the tank.
- The heat transmitted into the tank from one of the attached skirts is collected from the surrounding radiation environment and transferred by conduction into the tank.
- The average cooling heat transfer required along the cooling loop is estimated. The heat transmission from the skirt surface to the coolant is then modeled in one dimension.
- A second model to estimate the radial heat transfer to the coolant was set up to iterate between channel width, channel depth, fluid heat transfer coefficient, and inlet fluid temperature; mass flow rate was assumed based on previous modeling effort
- The key parameters to an effective solution include the **contact conductance, the contact area, and the convective heat transfer coefficient of the coolant in the channel.**



Application of Cooling Observations

- Any cooling of the skirt increases the radiative heat pickup by the skirt since the overall surface temperature profile is lowered.
- Previous modeling has indicated that full axial cooling of the skirt requires a relatively heavy fluid distribution system. Distribution of the cooling flow would be difficult to control in a non-uniform radiation exposure
- The simplest approach is likely a coil around the cylinder such that the flow circles the skirt, which modeling has shown to have similar effectiveness to axial flow cooling
- At a given circumferential location on the skirt, there will be one or more "optimal" cooling locations depending upon the number of turns in the cooling coil



Analysis Conclusions

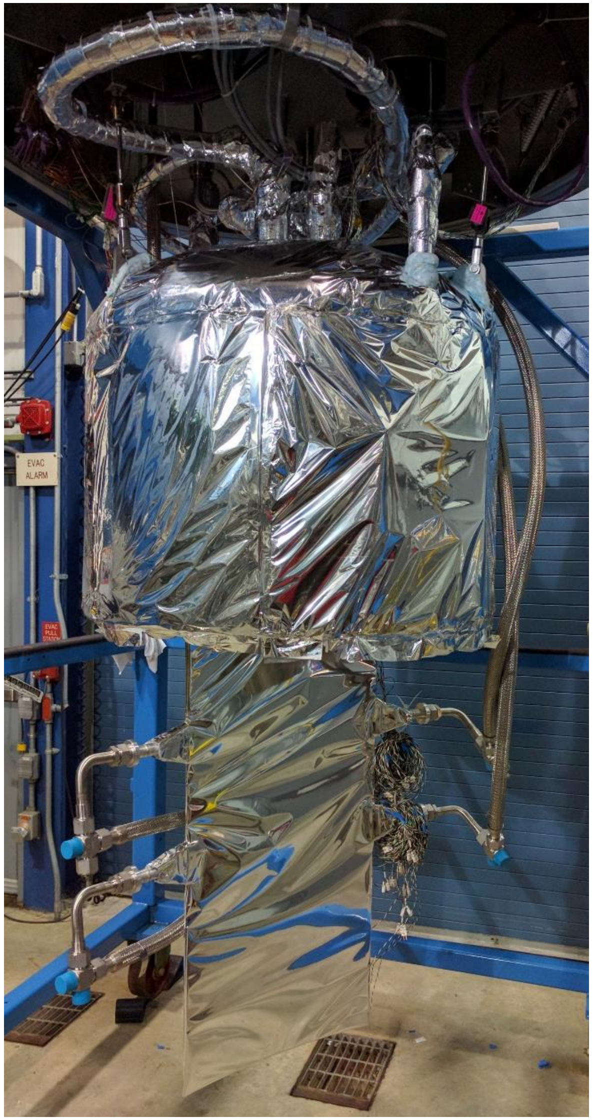
- It is desired to produce at least a 50% reduction in heat input to the SHIIVER tank.
  - This corresponds to an average heat input to the coolant per unit width of about 230 Watts per meter.
  - Surface temperature at the average cooling location on the skirt circumference should be around 100 K, with a range from about 65 K to 140 K at most.
  - Assuming a cooling inlet of 60 K, this implies a delta T over the conductive path on the order of 5 K

- Test data gained from SLICE testing will be used to update vapor-cooling analysis predictions for use in the SHIIVER vapor heat intercept and forward skirt designs

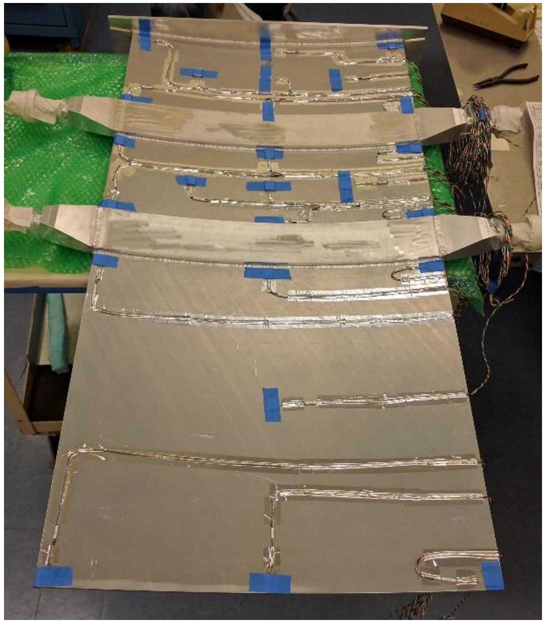
- Analysis predictions can be used to provide insight into how well the selected test concept designs meet mission goals
  - Designs based on selected conductance materials and attachment mechanism

SLICE Testing Overview

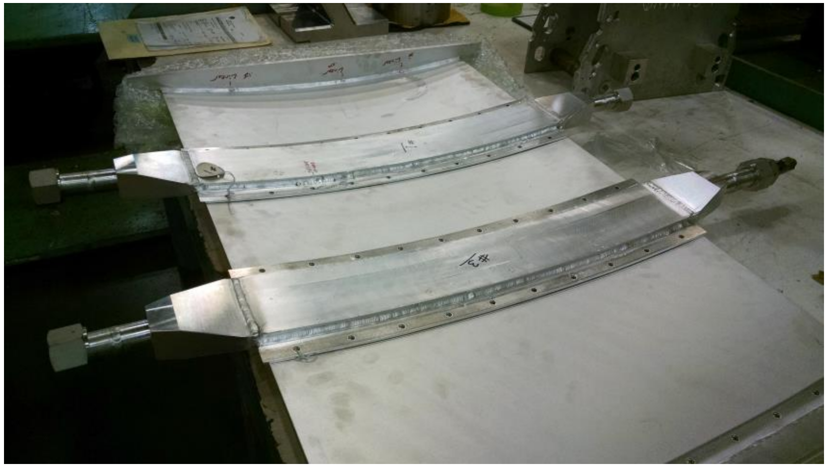
- Cooling applications on a 2'x4' Al2219 plate (3/16" thick) formed to a 2-meter radius of curvature, the same as the SHIIVER forward skirt.
- Test articles attached to LH2 flat plate calorimeter were installed in the vacuum chamber at SMiRF.
- The heat transmission from the plate to the calorimeter with and without cooling applied is calculated via boil-off measurement.
- MLI included on the channel side of all test articles.
- High-emissivity paint included on the non-channel side of test articles to enhance heat flux in skirt.
- Two channel configurations are in the test matrix:
  - Concept 1 (Baseline): C-Channel directly welded to the skirt section with fluid flow directly on skirt wall. *Predicted to provide best thermal result*
  - Concept 2: Preformed closed channel that is mechanically attached to the skirt section. Thermal contact resistance was intended to be controlled through application of thermal coatings.



SLICE Test Articles



Concept 1

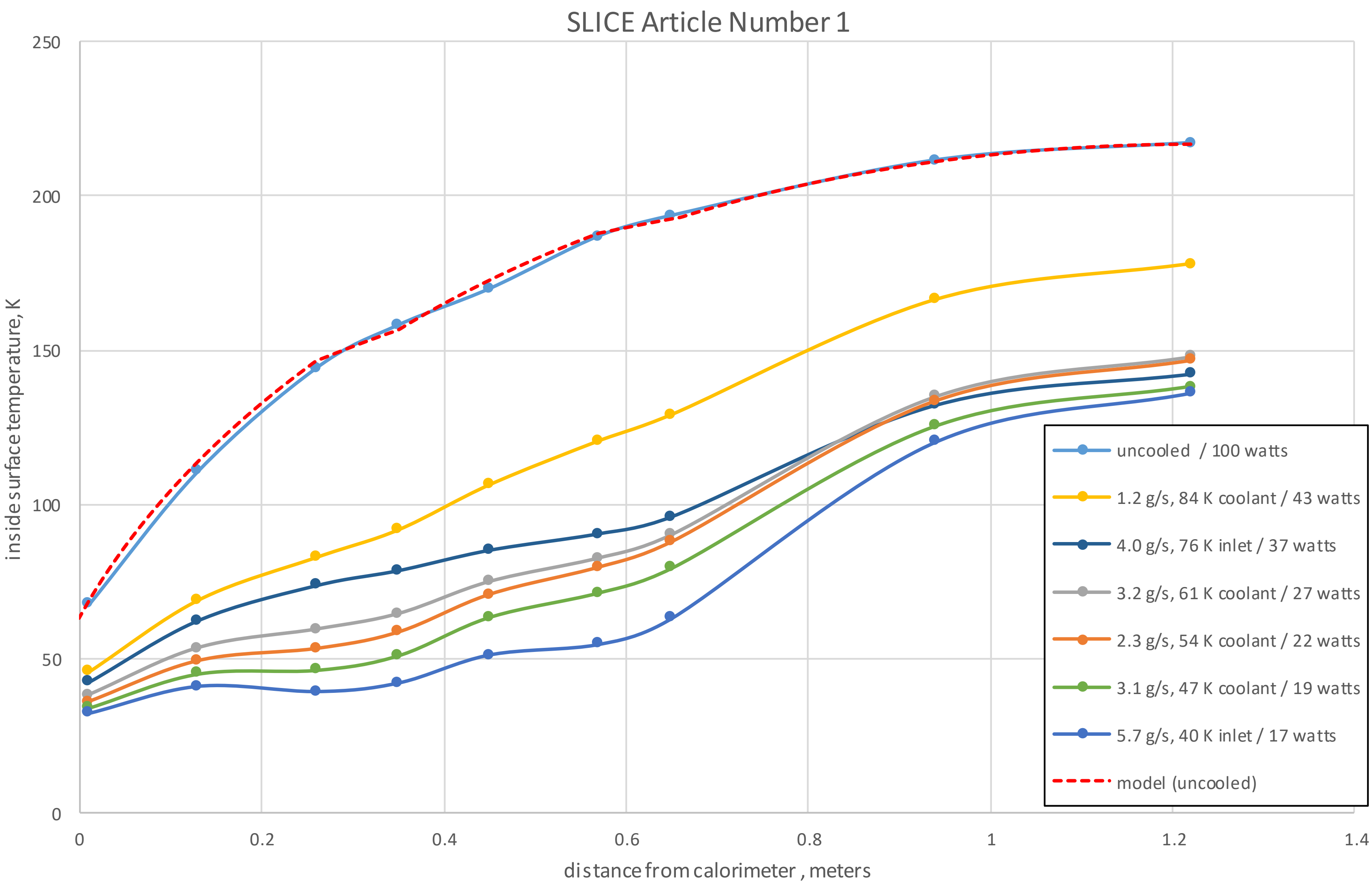


Concept 2

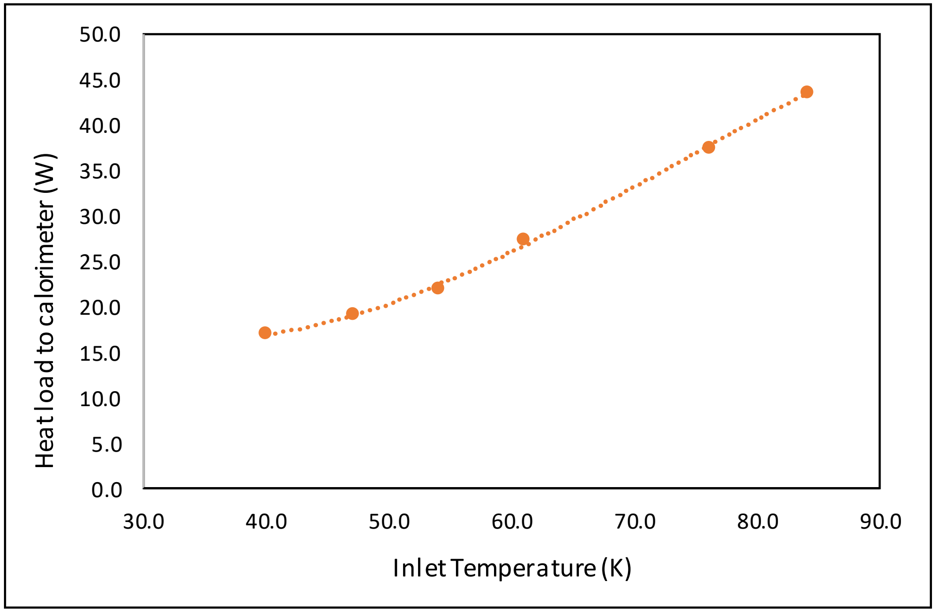
Testing Results vs. Predictions

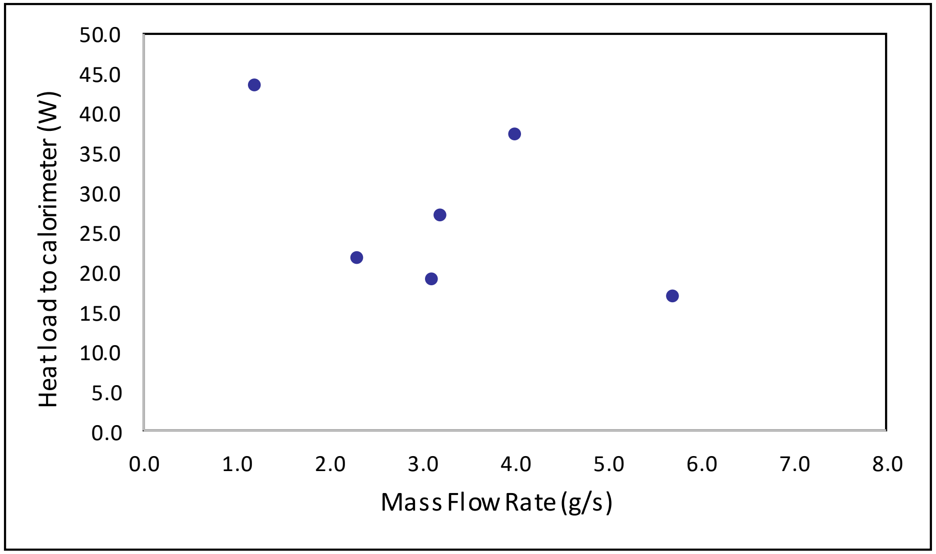
- **Completed testing of welded-type test article in May 2017**
- **Test series proved that vapor-cooling is capable of removing structural based heat in skirt-type structures (demonstrated on next slide)**
- **Preliminary results from welded flow channel show at least a 50% reduction in heat load through the skirt. Heat load appears to be more strongly correlated to the inlet coolant temperature.**
  - Heat transfer effectiveness shows small correlation with fluid flow rate
  - More test points are required to understand relationship with flow rate
- **Predictive model conservative in comparison to testing results**
  - Overestimates the heat input to the calorimeter
  - Underestimates the heat transfer from skirt to cooling channel
    - Due to SLICE plate being shadowed by the calorimeter, causing temperature profiles near the cold attachment end to be slightly cooler than predicted
- **SLICE team hypothesizing that cooling results will be correlated with cooling channel contact precision**
  - Demonstrated by mechanically attached testing

Testing Results vs. Predictions

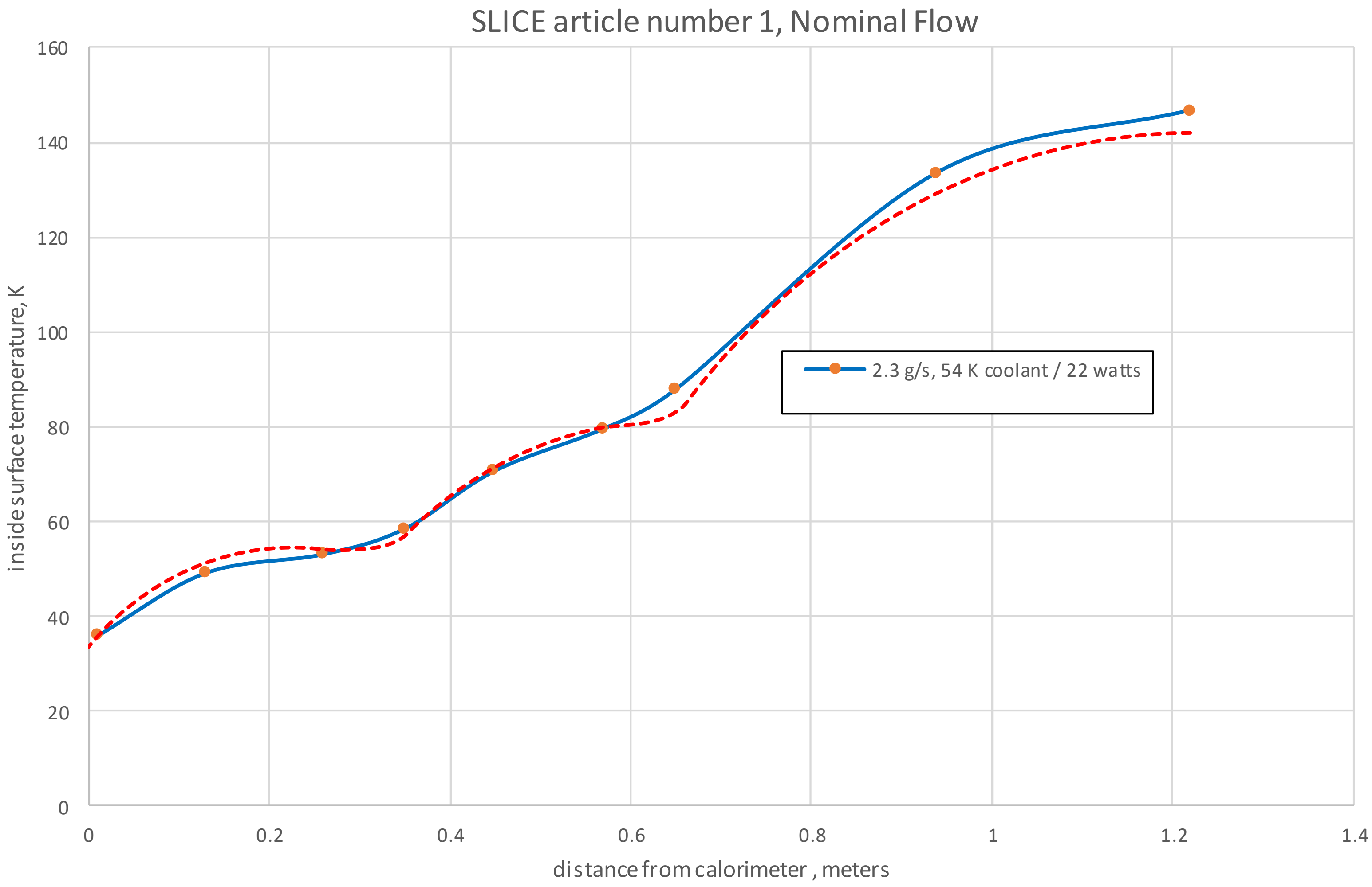


Testing Results vs. Predictions





Testing Results vs. Predictions (Nominal Flow)



Forward Work

- Completion of mechanically-attached vapor cooling test article
  - Evaluation of how less than perfect contact affects heat reduction in skirt.
  - Expected that welded design will provide best heat transfer and subsequent heat reduction.
- Upon completion of testing, modeling to predict applicability of vapor-cooling on complex structural skirts (isogrid/orthogrid).
- Utilize sub-scale testing data for SHIIVER test skirt design.