Testing of Heat Flux Sensors at Cryogenic Temperatures

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SHIIVER tank prior to application of SOFI.

SHIIVER tank being installed into the In-Space Propulsion Facility.

In order to measure heat loads through the insulation system (spray-on foam insulation (SOFI) and multilayer insulation (MLI)) on the Structural Heat Intercept, Insulation, and Vibration Evaluation Rig (SHIIVER), the team needed a method to measure local heat fluxes on the tank at 20 K. It is expected that the heat flux will not be constant around the tank due to the presence of structural elements.

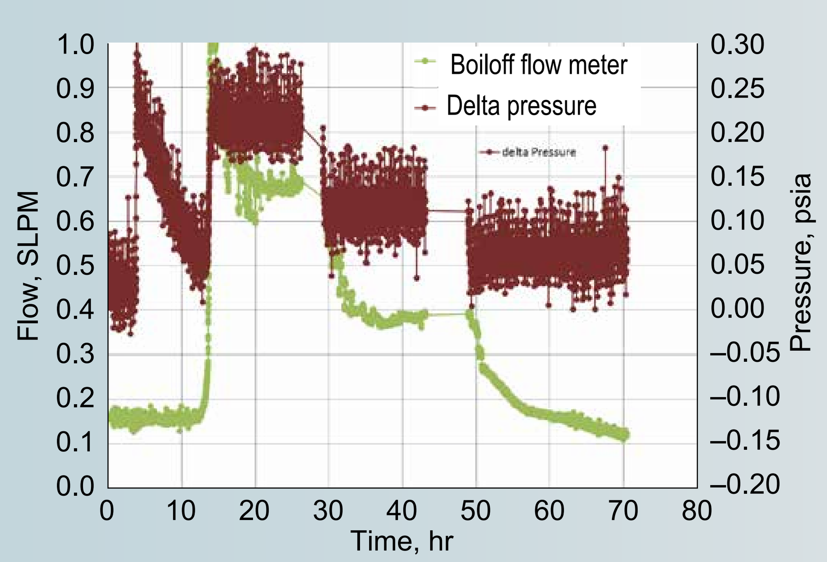
An investigation into different heat flux sensors showed that the sensors did seem to work at 20 K and a sensor was selected for the application.

Of the 20 sensors purchased, 16 would end up on the tank. It was desired to measure the performance of all sensors at 20 K prior to installation on the tank.

ASTM C–1130 is designed for calibration of heat flux sensors individually. The use of a cryocooler as the cooling source would allow the sensors to be calibrated down to 20 K.

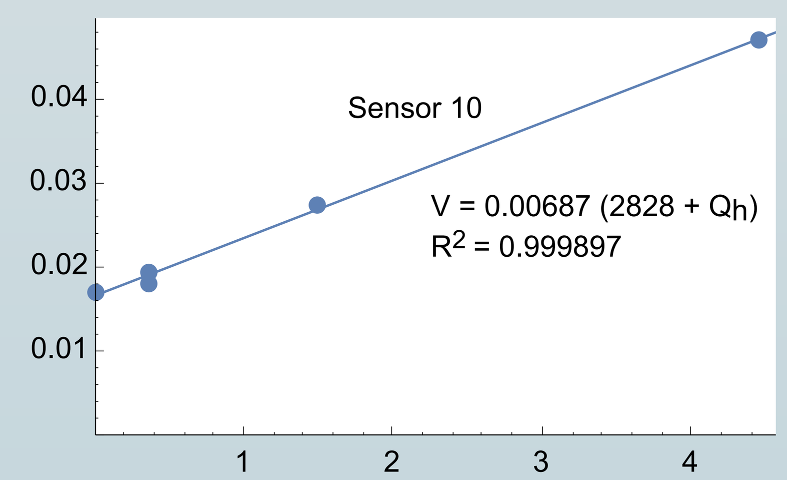
ASTM C–1774 is designed to measure heat loads at cryogenic temperatures. By placing the heat flux sensors in series with the insulation, a cryogenic fluid (nitrogen and hydrogen) would give data at specific temperatures.

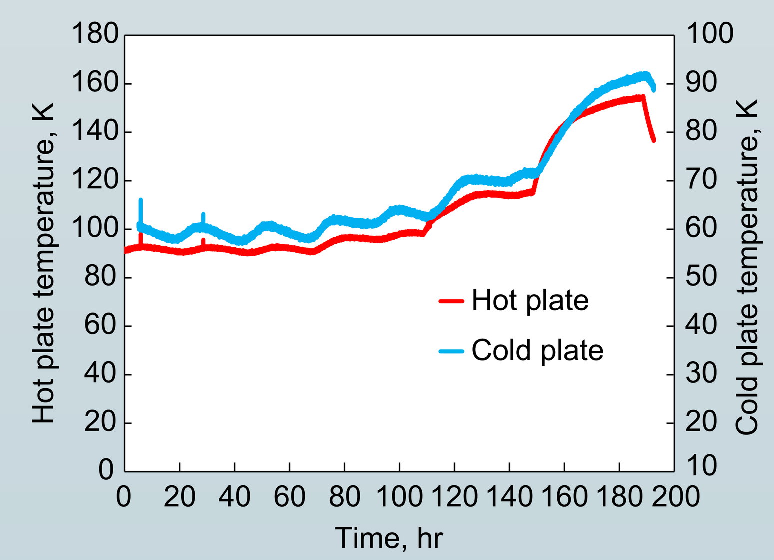
During ASTM C–1774 testing, it was discovered that the calorimeter was not responding properly and that changing the pressure difference between the guard and test chambers changed the boiloff flow rate. This indicated there was a thermal short between the chambers.



The heat flux sensor was installed between two copper plates and a nylon block. The nylon and copper were made several inches wider than the heat flux sensor to provide a guarded area.

The copper plates were maintained at different temperatures by a cryocooler in the top plate and a heater in the bottom plate. The heater and nylon block controlled the heat flux and temperature differences between the plates. The system was allowed to come to steady state and then the heater set point was changed.





Three different heat flux sensors were tested, with the data from number 11 shown above.

t start	t end	dT	Tavg	T_Hot	T_Cold	HF Sensor	P_Heater
hr	hr	K	K	K	K	V	W
58	68	32.94	75.16	91.63	58.69	1.76E-02	0
80	90	35.00	78.83	96.33	61.33	1.96E-02	0.372
130	140	44.43	92.15	114.36	69.93	2.66E-02	1.480
175	185	62.53	121.39	152.66	90.13	4.40E-02	4.317

The results from sensors 10 and 11 are shown here at temperatures between 60 and 100 K, compared to the manufacturer's room temperature sensitivity.

Sensor	Measured Sensitivity (μV/(W/m2))	Vendor Sensitivity (μV/(W/m2))
No. 10	359	358
No. 11	321	359

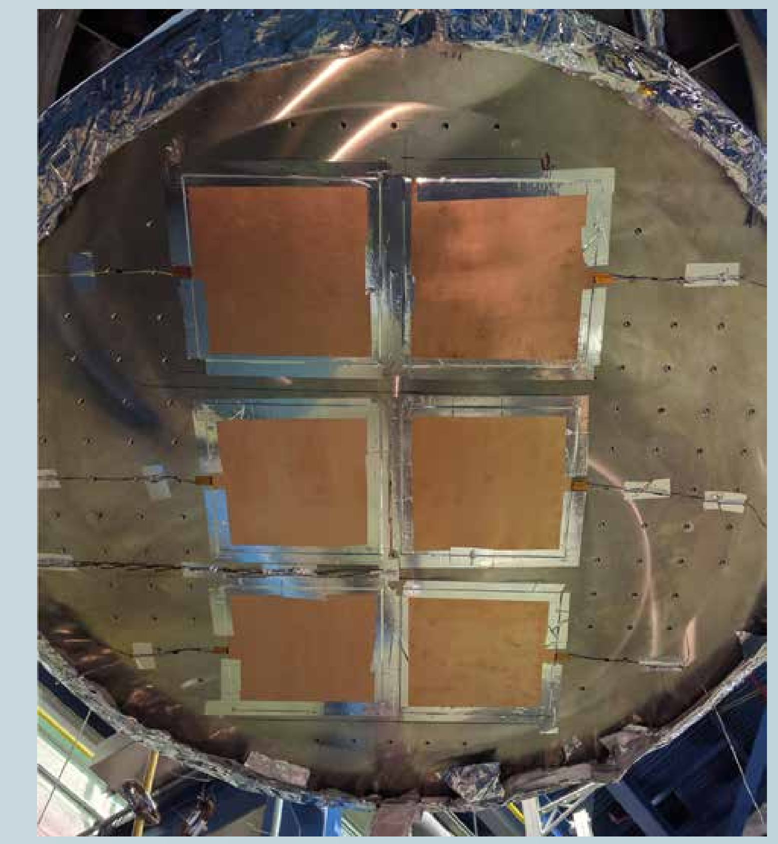
Initially, it was expected that this would be the main test method used. After initial testing was taking ~ 200 hours per sensor, an alternative was sought to speed up the testing.

Conclusions

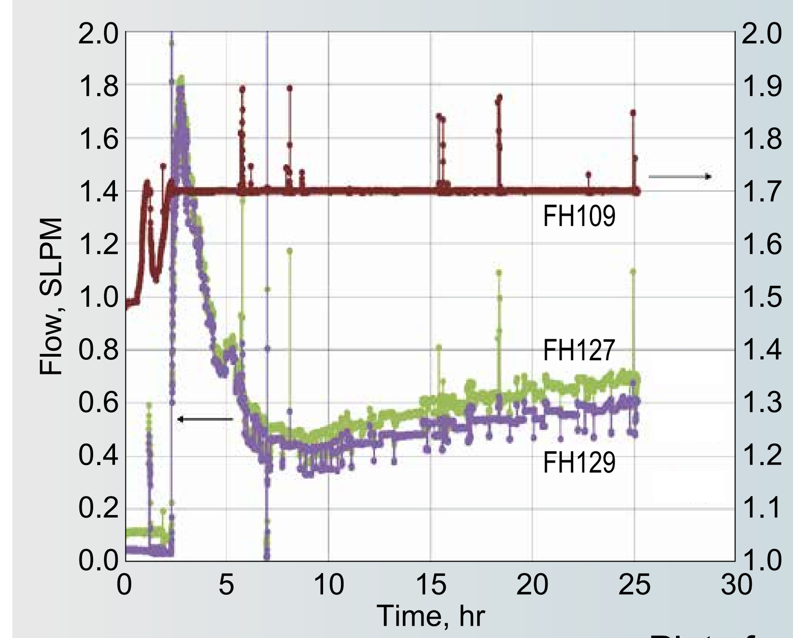
Heat flux sensors were demonstrated to work at temperatures as low as 20 K. ASTM C–1130 proved to be workable at cryogenic temperatures, but took much longer due to the required use of a thermal insulator between the two copper plates. The results from C–1130 testing showed the sensors to have a cryogenic linear sensitivity very similar to the room temperature values with a zero-flux offset. While there is some concern with the general repeatability of the sensors, they were shown to be in general in line with each other when tested on a flat plate calorimeter with magnitudes approximately in line with the measured heat load. Uncertainty with the heat load onto the flat plate calorimeter prevented a more thorough investigation of the data. As a result of the testing, 16 sensors were installed onto the SHIIVER tank for testing expected to begin the summer of 2019.

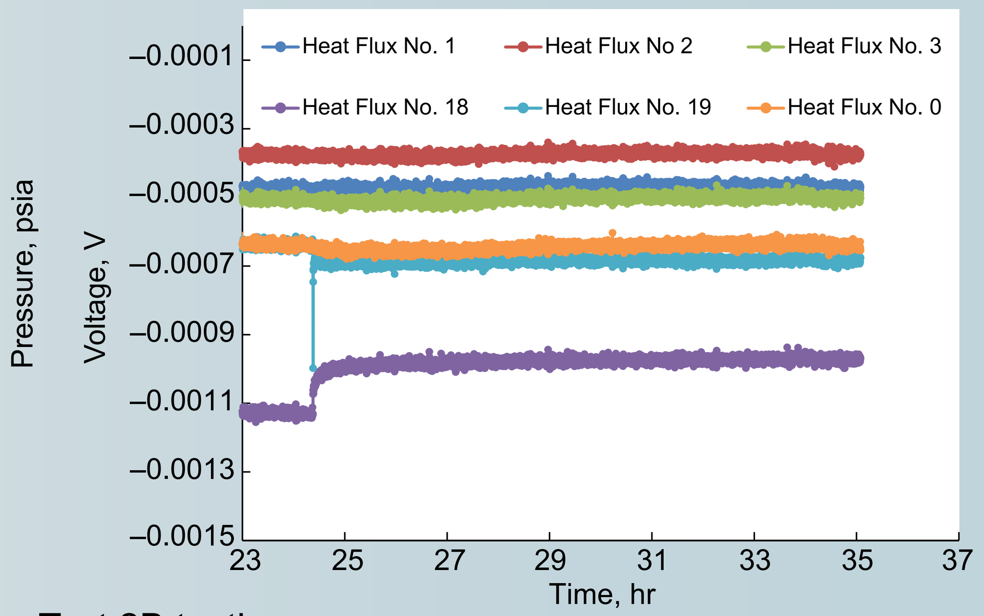
A flat plate calorimeter at Glenn was used that was already essentially plumbed up from vapor-cooled skirt subscale testing. Six sensors (0 initial sample, 1, 2, 3, 18, and 19) were installed onto the bottom of the calorimeter. LN_2 test results were compared to LH_2. Two different heat fluxes were achieved by controlling the number of MLI layers and running a soft vacuum case to get a really high heat load.

Phase/Title	Fluid	Number Reflector Layers	Vacuum Pressure
Phase 1A	Liquid Nitrogen	1	$< 10^{-6}$ Torr
Phase 1B	Liquid Hydrogen	1	$< 10^{-6}$ Torr
Phase 2A	Liquid Nitrogen	20	
Phase 2B	Liquid Hydrogen	20	
Phase 3	Liquid Nitrogen	20	12 Torr
Room Temp	None	1	1 ATM



Flat plate calorimeter at the Small Multipurpose Research Facility.



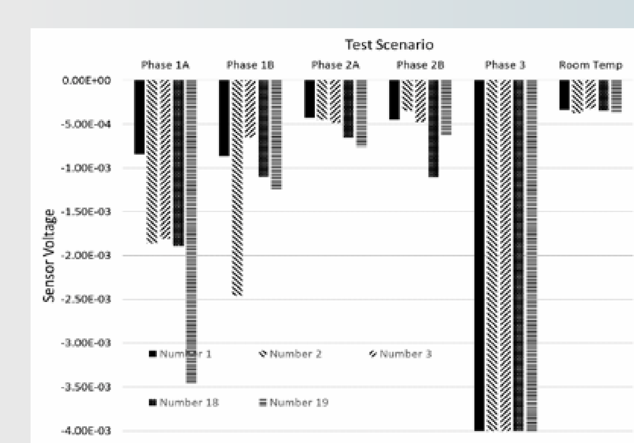


Plots from Test 2B testing

The heat fluxes for the different tests are shown here. Interestingly, the hydrogen heat fluxes are lower than the nitrogen heat fluxes.

Phase/Title	Start Time (hr)	Stop Time (hr)	Temperature (K)	Flow Meter	Heat Flux (W/m²)
Phase 1A	17.5	18.1	77.8	FH129	8.6
Phase 1B	27.0	32.64	20.6	FH127	4.5
Phase 2A	21.0	33.0	77.8	FH129	3.2
Phase 2B	25.0	33.0	20.6	FH127	2.2
Phase 3	15.0	20.0	99.8	FH127	55.3
Room Temp	0.0	0.1	293.7	N/A	0.0

The statistical analysis of the different sensors (shown below) indicates that the sensors responded similarly amongst the group. This was good as there was some concern about biases of the sensors being different for each. The general differences in the outputs was much higher at 20 and 77 K than at room temperature. But the concern was in the validity of the measure heat fluxes, so no numerical data could be extracted.



	Average	Min	Max	St. Dev	Range	Uncertainty
Phase 1A	-1.97E-03	-3.46E-03	-8.39E-04	8.42E-04	2.62E-03	-66%
Phase 1B	-1.26E-03	-2.46E-03	-6.53E-04	6.31E-04	1.81E-03	-71%
Phase 2A	-5.56E-04	-7.61E-04	-4.28E-04	1.28E-04	3.33E-04	-30%
Phase 2B	-6.00E-04	-1.10E-03	-3.47E-04	2.67E-04	7.58E-04	-63%
Phase 3	-9.37E-03	-1.34E-02	-6.73E-03	2.48E-03	6.65E-03	-36%
Room Temp	-3.52E-04	-3.75E-04	-3.27E-04	1.92E-05	4.82E-05	-7%

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