



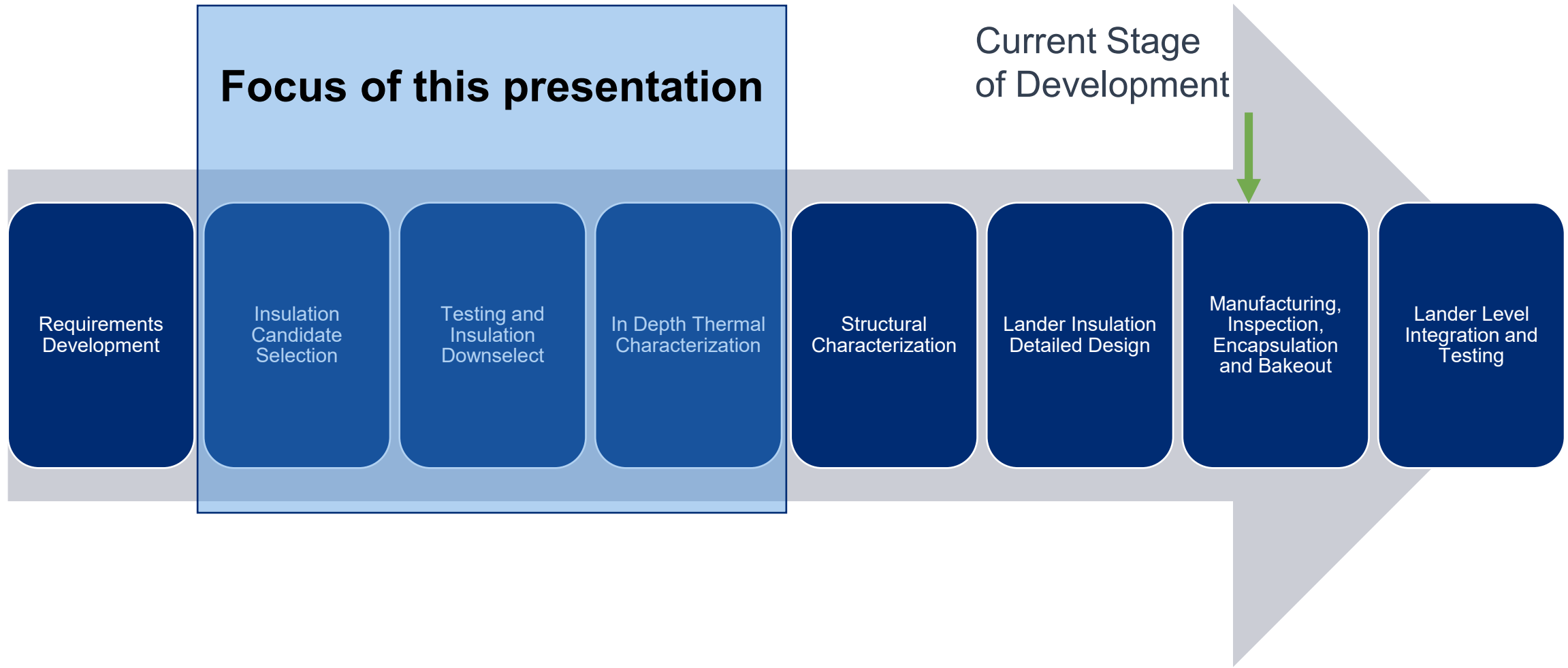
Thermal Insulation Development for NASA's Dragonfly Mission

Focused on Thermal Testing and Foam
Downselect

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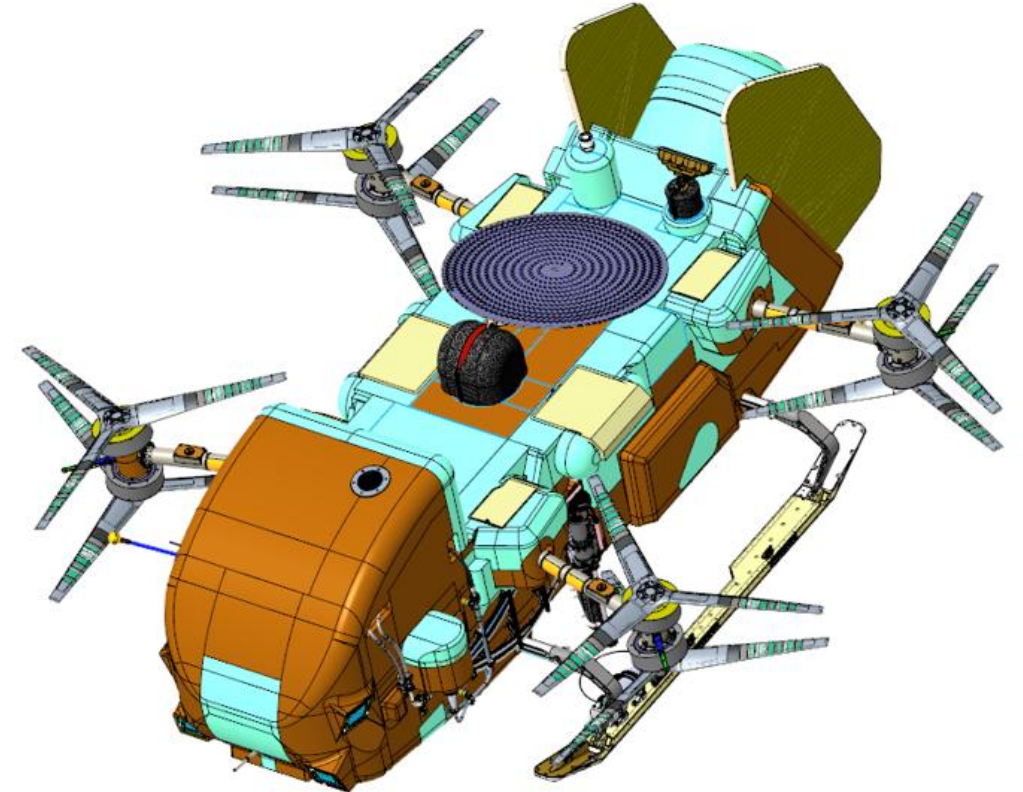
Subsystem Lifecycle



Foam Overview



- The Dragonfly foam subsystem will **consist of approximately 800 foam tiles** that will cover almost every external surface of the lander.
- The foam's **main goal is protect the lander from the -180 C, 1.5 atm environment**, on the surface of Titan and to keep the inside of the lander above 0 degrees C.
- The foam **performs this function by adding a large thermal resistance** between the internal environment of the lander and the outside Titan environment in order to minimize heat leak.



Selection Criteria for Thermal Insulation



Selection Criteria	Relevance to Application	How it was tested
Thermal Conductivity at 1.5 atm	Minimizes thermal insulation needed for the same amount of heat leak once lander is on Titan.	Foam blocks were machined to surround a heater plate and tested in the TPEC chamber at 1.5 atm and -180 C.
Susceptibility to Internal Convection	Thermal insulation that is susceptible to internal convection will result in increase heat leaks for the lander and will be much more difficult to predict its thermal performance once the lander is on Titan.	Testing of foam blocks was done vertically and horizontally to check for difference that result when internal convection is present.
Thermal Distortion and Brittleness at Cryo	A brittle material can result in cracks that open seams and allow air flow between the honeycomb and the environment leading to large heat leaks. Large thermal distortion leads to seams opening which allow air to flow.	Tested foam blocks brittleness by having foam sample submerged in LN2 and checking for thermal distortion and brittleness.
Density	Dragonfly is a mass constrained mission so a lighter insulation material is a priority	Data sheets and weighing tiles to confirm data sheet.
Thermal Conductivity at Vacuum	Dictates how much heat leak the thermal insulation will have when the lander is in its cruise stage. This has implications on the battery temperature.	Foam blocks were machined to surround a heater plate and tested in a vacuum chamber at -120 C.
Change in Thermal Conductivity Over Time after a Pressure Change	Thermal insulation that reacts slowly after a pressure change can be hard to model and would make the thermal control system harder for the lander.	Heat leak of foam blocks was measured over the course of a week after a pressure change in a vacuum chamber had been applied.
Manufacturability of Features on Foam	Thermal insulation tiles on the lander will require some features that must be machined with decent tolerances so a foam that is machinable is crucial.	Coupons were sent out to machine shops to test what features could be machined on foam samples.

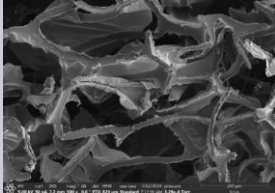

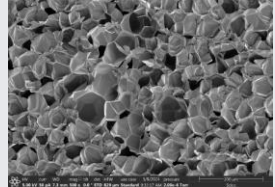









Foams/Materials Considered



Foam/Material	Density kg/m^3	Was it a good candidate for testing?
Rohacell HP 31 HT	32.0	Yes, and it was tested
Solimide AC-530 (yellow)	5.4	Yes, but high levels of internal convection
Solimide HT-340 (orange)	6.4	Yes, but high levels of internal convection
Densified Solimide- 16 kg/m3	16	Yes, and it was tested
Basotect G+, C, UL and B	5.6-9.2	Yes, and it was tested
Aerogel Blanket	Vary	Yes, and it was tested
VIP	Vary	Yes, and it was tested
Formular NGX 150	20.8	Not Vacuum Compatible, too much outgassing, Low Max Temp
Zotek F30	30.0	Poor Dimensional Stability, degraded performance at 1.5 atm (Tested by NASA)
Thermal Wrap TW800*	70	Too dense
Kingspan Threshold VIP	256	Too dense
Spray foam, MSFC-SPEC-3686	42.2	Too dense and there were major I&T concerns with its use.
Mix and pour foam	42.2	Too dense and there were major I&T concerns with its use.
Ultem XP60, XP 80 and XP 110 Foam	60, 80, 110	Too dense

Foams Tested

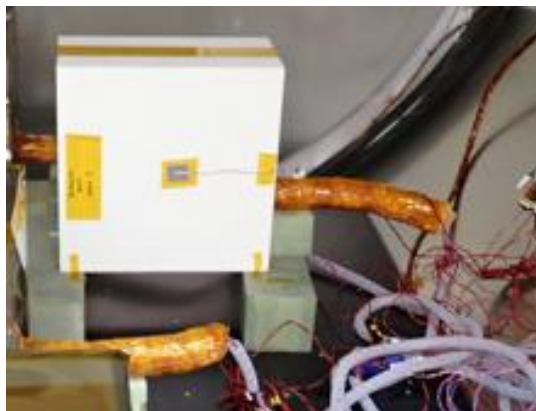


Foam/Material	Structure	History/Heritage/Uses	Photos
Solimide 16	Open Cell Foam	Developed by NASA to have a non flammable foam in the ISS. Currently in use in the Space Station. Retains its flexibility at cryo conditions. Current applications include cryogenic insulation for fuel tanks on major rocket propulsion systems.	 
Rohacell	Closed Cell Foam	Used extensively for RF applications, like in our HGA dish. Used extensively to sandwiched composite structures. Has aerospace heritage. Known to be hygroscopic.	 
Zotek F30	Closed Cell Foam	Used in the Space Station Delivery Pod Wall Lining. Low flammability and outgassing. 15 year aging and shelf life and good manufacturability. Degraded thermal performance at 1.5 atm. Poor dimensional stability	 
Aerogel Blankets	Crushed Aerogel in Blanket Material	Used in medical supplies and cryogenic hoses. Is flexible so its good to wrap around cylindrical surfaces. Known to be “breathable” so it suffers from internal convection.	 
Basotect G+	Open Cell Foam	Used in Huygens. Resulted in issues due to internal convection.	 
VIP	Sealed Mylar Bags	Due to the vacuum inside it, at large scale (much larger than the tiles we need for Dragonfly) and thin panels, it can perform better than foam but its significantly heavier.	 

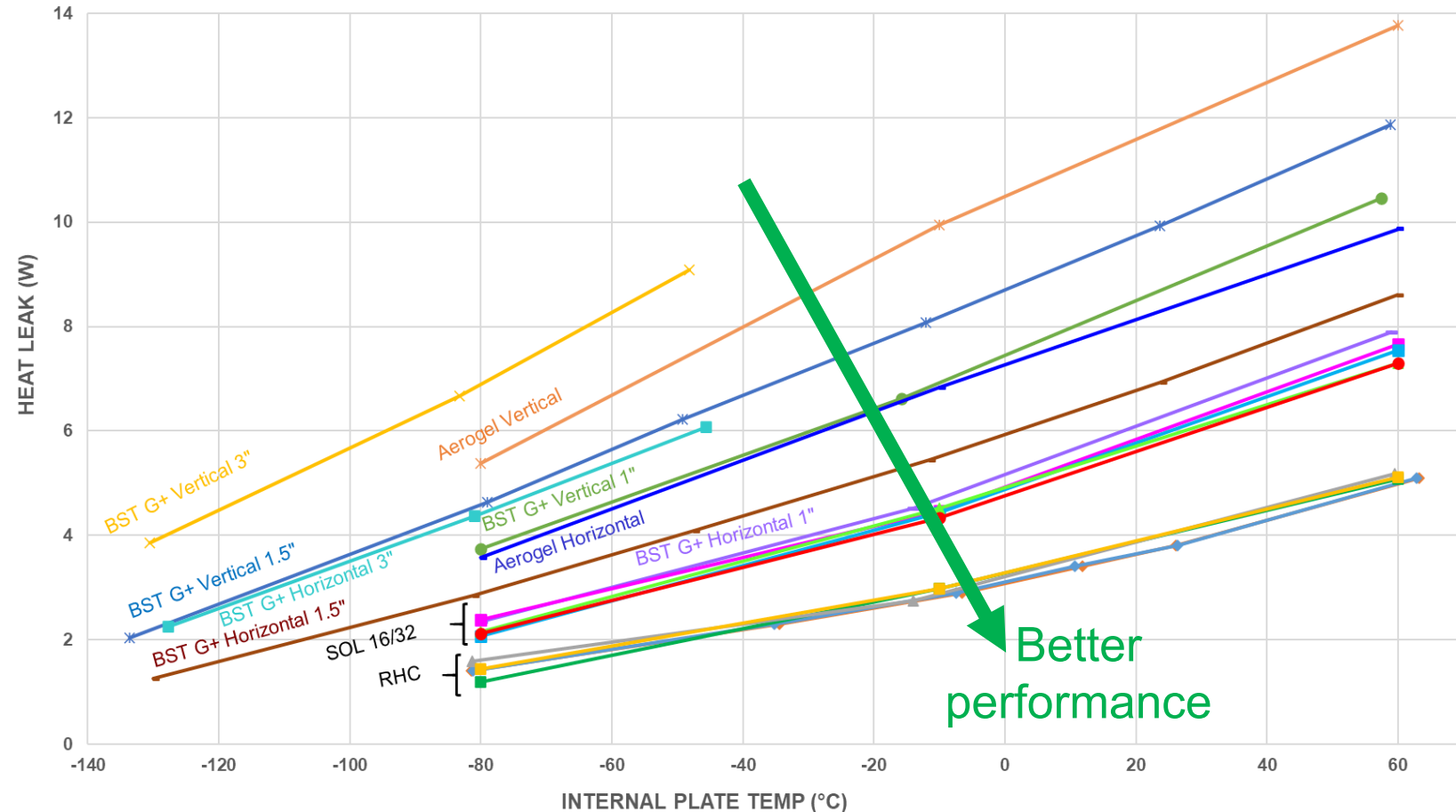
Thermal Conductivity Results



- Best performing foam in order:
 1. Rohacell
 2. Solimide 16 and 32
 3. Basotect (when subdivided)
 4. Aerogel blankets
 5. VIP (not shown in graph)
- When tested in different orientations some foam experienced different amounts of heat leak, indicating that they suffered from internal convection.



THERMAL CONDUCTIVITY TESTING - RAW DATA
NOVEMBER 2023 - MAY 2024



Better performance

Flow Resistance and Internal Convection

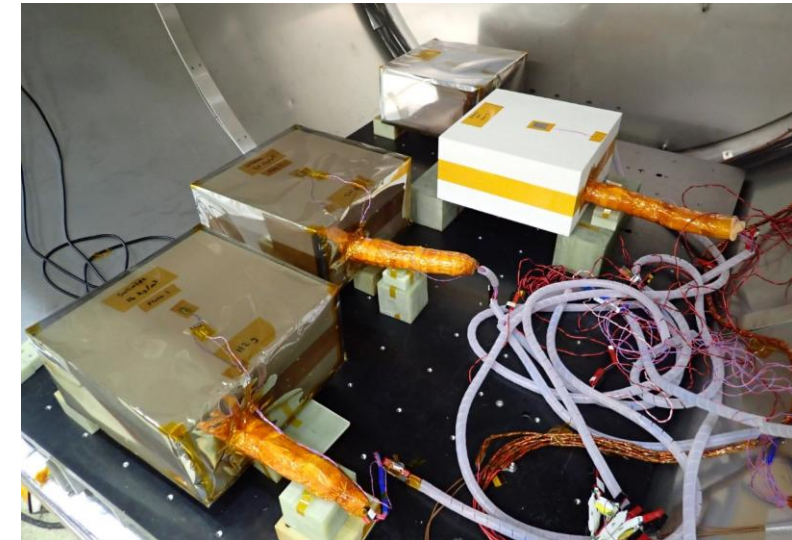


- Theory:

- Natural Convection internal to the foam (if present) is highly dependent on the test unit orientation to the gravity vector.
- Conduction through the foam and stagnant air should be independent of the gravity vector.
- Foams that are susceptible to natural convection would make the modeling of the lander heat leak very difficult to predict and will generally result in higher heat leaks than foams that don't experience natural convection.



Test articles in the vertical configuration



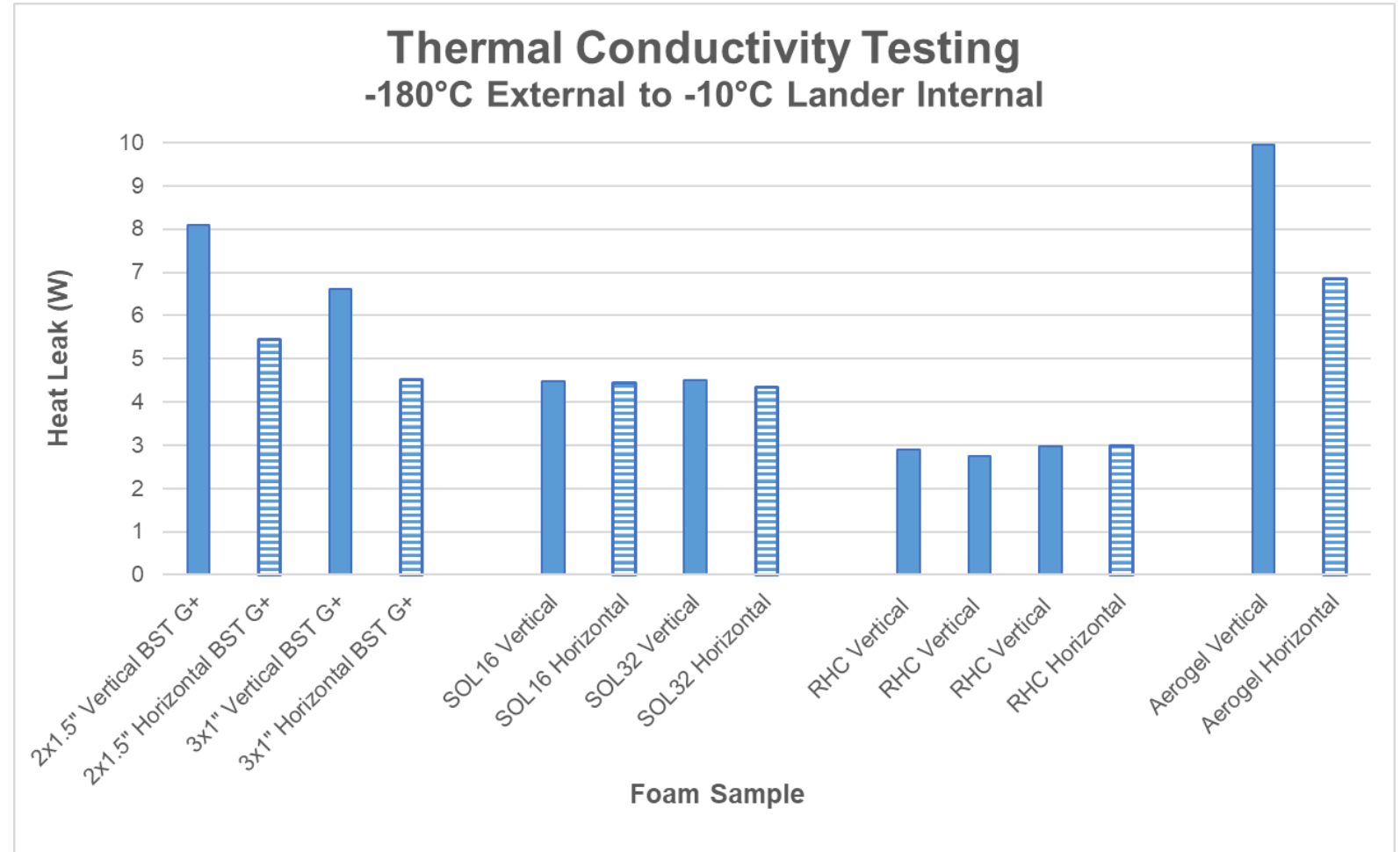
Test articles in the horizontal configuration

Flow Resistance and Internal Convection



- Key Findings:

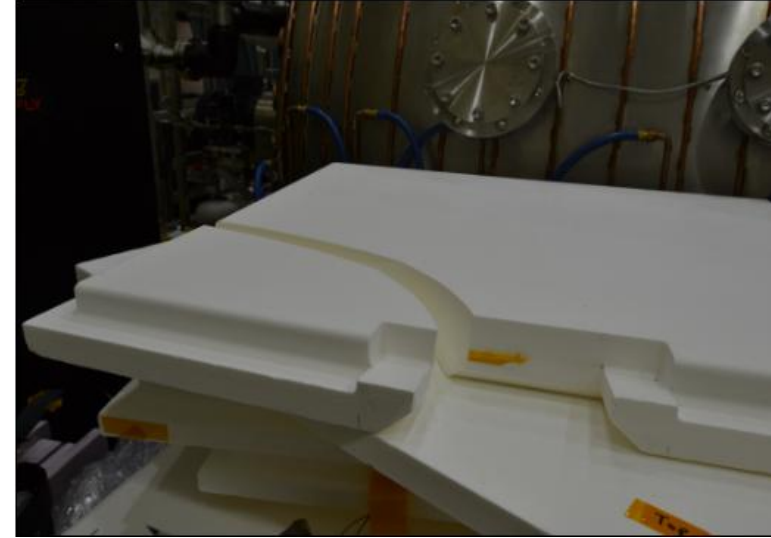
1. A change in effective thermal conductivity between the vertical and horizontal configurations indicates heat transfer occurring by natural convection inside the foam.
2. **Basotect G+ and Aerogel experience internal convection** which increases the heat transfer through the foam.
3. **Solimide** (at least the 16 and 32 version) and **Rohacell do not seem to experience internal convection.**



Brittleness at Cryo Conditions



- During thermal testing we noticed that Rohacell would crack in areas with thermal gradients that were mechanically constrained.
 - Cracks usually initiated near adhesive bondlines and near Kapton tape.
- To date we have not seen Solimide break or split under thermal loads
 - We have dunked also performed tests were we dunk Solimide in LN2 and it maintains most of its flexibility.



Foam Selection

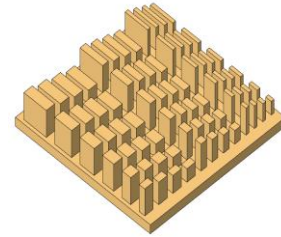


	Solimide 16	Rohacell	Basotect G+	Aerogel Blanket
Thermal Conductivity at 1.5 atm (k_effective)	.019 W/mK	.013 W/mK	>.025 W/mK	>.025 W/mK
Susceptibility to Internal Convection	No significant internal convection measured	No significant internal convection measured	Severe internal convection	Severe internal convection
Brittleness at Cryo	Not brittle at Cryo, remains very flexible	Very brittle at Cryo	Not brittle at Cryo	Not Tested
Density of Foam	16 kg/m ³	31 kg/m ³	9 kg/m ³	>50 kg/m ³
Thermal Conductivity at Vacuum (k_effective)	~.002 W/mK	~ .004 W/mK	Not Tested	Not Tested
Change in Thermal Conductivity Over Time after a Pressure Change	Change occurs within seconds due to open cell matrix.	Change occurs slowly, taking on the order of days to equilibrate after a pressure change due to close cell matrix.	Not Tested	Not Tested
Manufacturability of Feature on Foam	Good, most features can be machined but features can't be too thin or hanging off.	Good but stress concentration leads to cracking.	Not Tested	Not Tested
Bottom Line	Even though it had the second lowest thermal conductivity at 1.5 atm, it was the only foam without red flags.	Lowest thermal conductivity but its slow reaction time to changes in pressure, higher weight and brittleness made it less suitable for the mission.	Experienced natural convection and had a poor thermal performance at 1.5 atm	Experienced natural convection, had a poor thermal performance at 1.5 atm and is prohibitively dense.

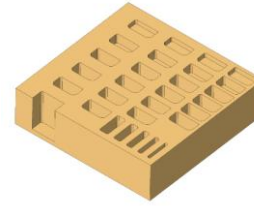
Manufacturing



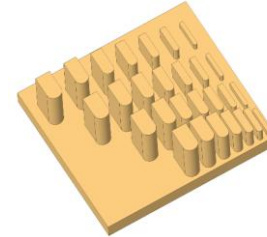
- Before deciding to move forward with Solimide 16 we performed simple machining tests to find any potential show stoppers.
- After selecting Solimide as the foam insulation material, we sent coupon tests to different machine shops to stress test the limits of what features could be machined.
- These limits on feature size were then passed to the design team to guide the design of the flight tiles.



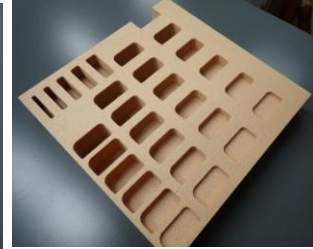
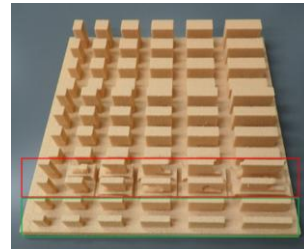
Coupon Test:
Varied Extrusion
Aspect Ratios



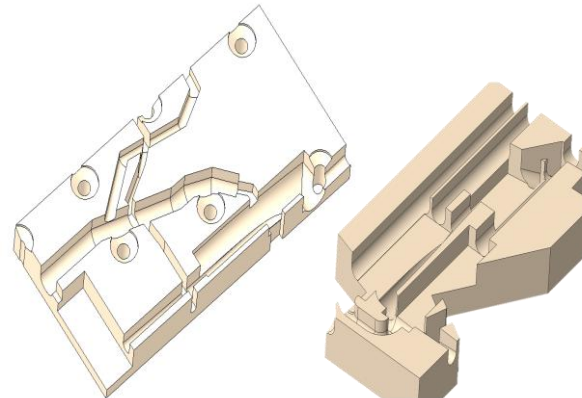
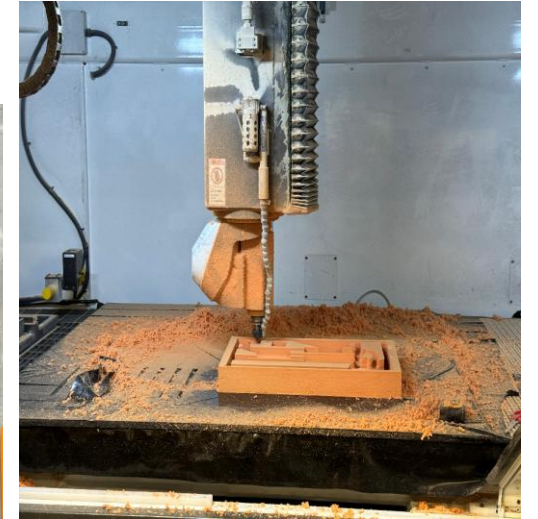
Coupon Test: Varied
Pocket Depth
and Internal Radii



Coupon Test: Varied
Extrusion
Height and Spacing

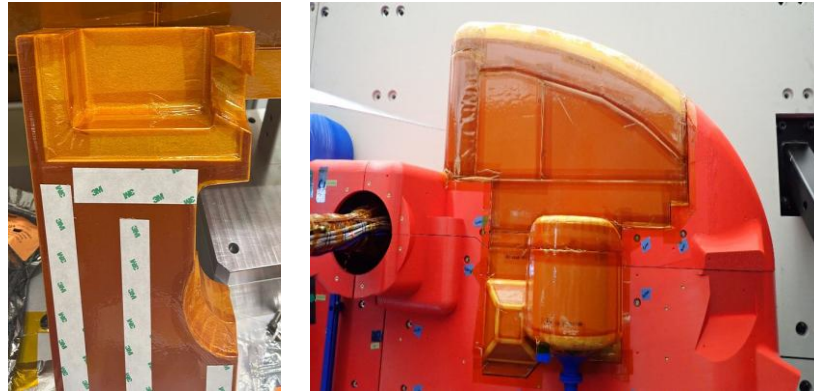


Small tear out



Stress Test Pieces

Encapsulation, Venting and Contamination Concerns



V/A 4500 can be applied to the total Lander foam volume based on the local foam thickness using

$$\text{the equation Hole Spacing} = \sqrt{\frac{\text{Hole Area (in}^2\text{)} \cdot (V/A)}{\text{Foam Thickness}}}$$

$$2.25" = \sqrt{\frac{0.00113 \cdot 4500}{1"}}$$

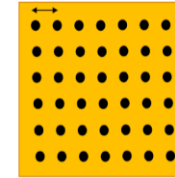
$$1.12" = \sqrt{\frac{0.00113 \cdot 4500}{4"}}$$

$$1.71" = \sqrt{\frac{0.00113 \cdot 4500}{2"}}$$

$$1.08" = \sqrt{\frac{0.00113 \cdot 4500}{5"}}$$

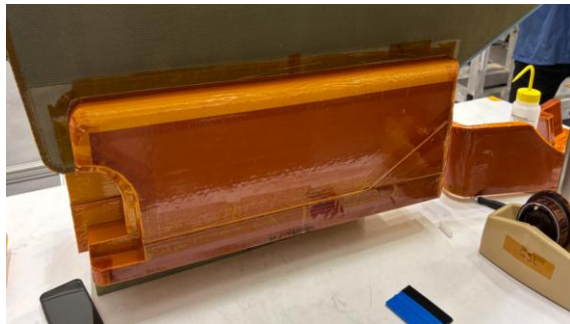
$$1.30" = \sqrt{\frac{0.00113 \cdot 4500}{3"}}$$

$$0.98" = \sqrt{\frac{0.00113 \cdot 4500}{6"}}$$

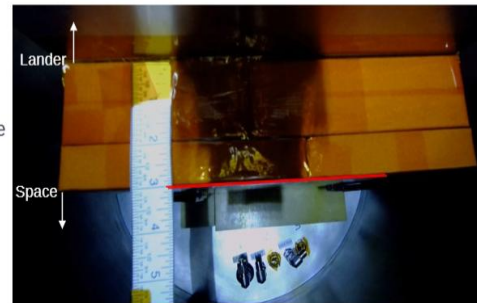


Assuming a grid hole pattern

- Blocks treated for 192 hrs at 110°C
- Assembly tested with all adhesives and epoxies that will be used on flight
- Vent holes present for this test



During depressurization, there was some shifting, but no measurable deflection



We performed test in a quick depressurization chamber to ensure foam tiles have sufficient venting to not deform significantly during launch while still meeting contamination control requirements for the mission.

Total evolved mass ~ 0.25g
Molecular contamination budget ~ 0.42g

We performed bakeout and outgassing tests with contamination control engineers to ensure the encapsulation of the tiles enabled the foam assembly to pass its contamination requirements.

To meet contamination requirements we use two methods of encapsulation, which one is employed in each surface depends on whether or not that surface is in the structural load path.

