Development Test Module – Full-Scale Environmental Testing for Dragonfly Lander

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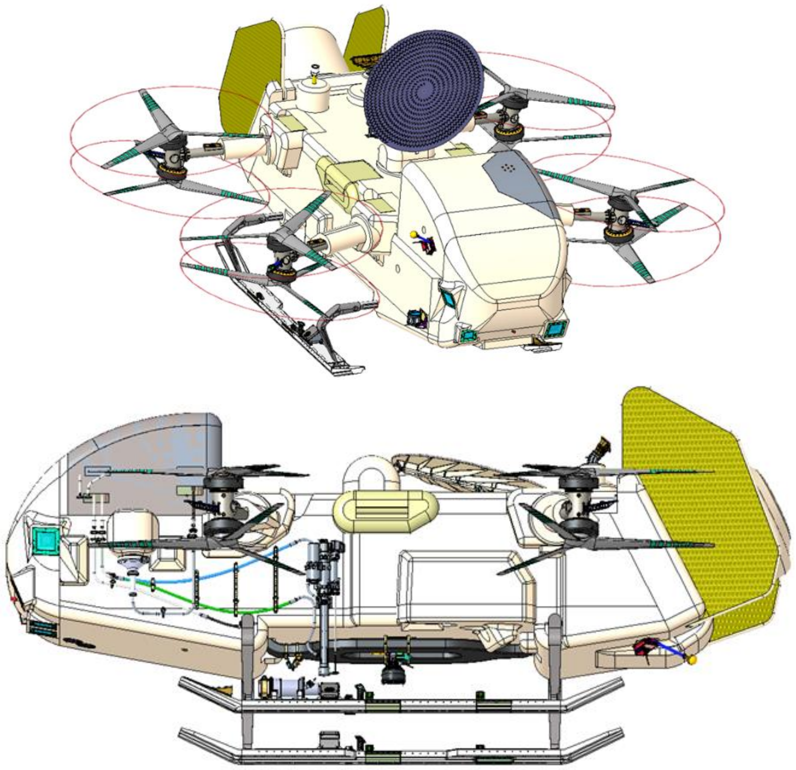
Outline

- This presentation will discuss the initial phases of testing for the Dragonfly Development Test Module (DTM)
- **Dragonfly Mission**
  - Overview of Dragonfly’s operational environment, along with introduction to thermal control system
  - TITAN chamber
- **Development Thermal Module**
  - Overview of DTM construction and purpose
  - Test Article/Test Chamber configuration
  - Test Methodology
  - Test Results
  - Future work and upcoming testing

Dragonfly – Background

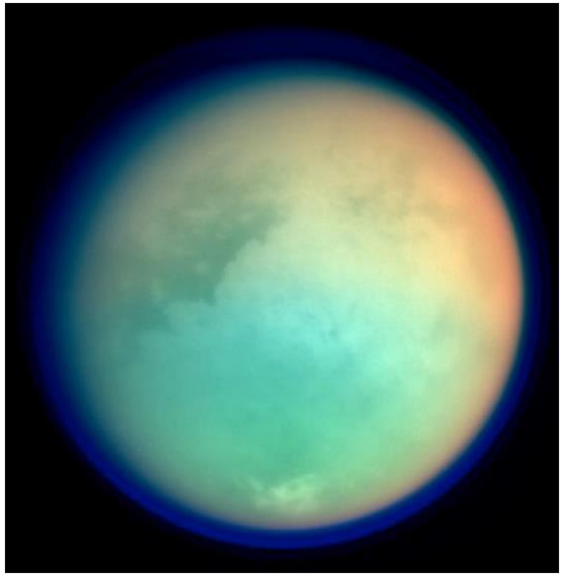
- Dragonfly is a New Frontiers mission to study Saturn's moon, Titan
  - Octocopter lander will fly on the Titan surface, taking advantage of its thick atmosphere and low gravity…
  - Conversely, the thick atmosphere and cryogenic surface temperatures make thermal design challenging
- Electrical power is supplied through an MMRTG, which also provides ~1800W of "waste" heat
  - Thermal control system (TCS) utilizes foam insulation in order to insulate against cryogenic Titan atmosphere
  - Warm MMRTG air is circulated throughout the lander using a warm duct system
  - **TCS features a cold duct "thermal trim device" for heat rejection** to regulate lander internal temperature – device diverts warm MMRTG air to an exposed "cold duct" in order to cool down the lander.



Dragonfly Lander

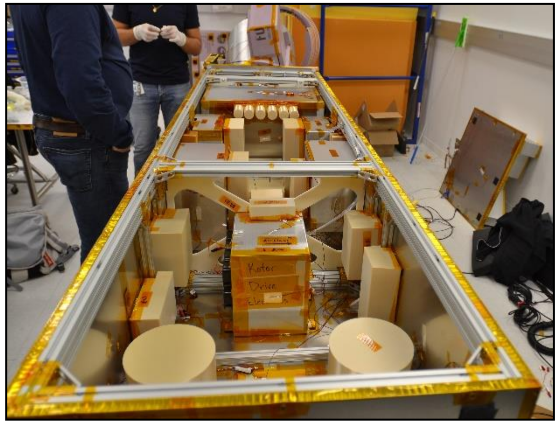
Titan's Environment

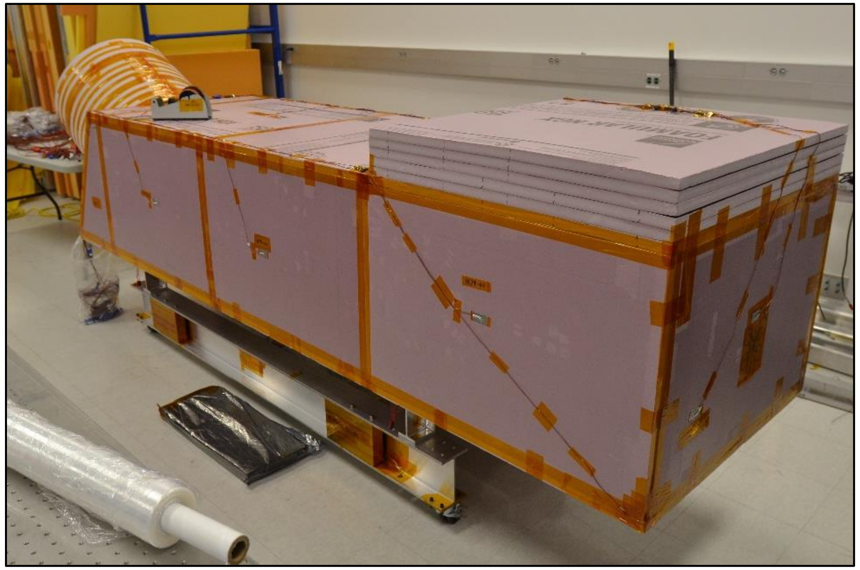
- Surface Temperature: 94K (-179C)
  - This temperature is fairly stable with little diurnal/seasonal variation, an important trait for testing purposes
  - Small possibility of methane rain, wind conditions are typically < 1 m/s
- Surface Gravity: 0.14g (1.352 m/s^2)
  - 1/7th Earth gravity
- Surface Pressure of 146 kPa, density of 5.44 kg/m^3
  - Titan atmosphere is largely Nitrogen
  - ~1.5 times Earth atmospheric pressure (101 kPa)
  - ~4.5 times Earth atmospheric density (1.2 kg/m^3)



Development Test Module (DTM)

- DTM is a full-scale thermal mock-up of the Dragonfly Lander:
  - Structure is constructed of 80/20 beams and honeycomb panels with flight-like thickness
  - Test foam insulation is polystyrene, attached with Velcro in two layers
  - Internal boxes and 3D-printed parts mimic airflow blockages from lander components
  - Heater unit mimics thermal output from MMRTG
  - 3D-printed Ultem duct system circulates heated air from MMRTG throughout DTM body
- Two phases of testing have been conducted relating to the thermal trim device
  - Future tests will focus on foam insulation and other protrusions



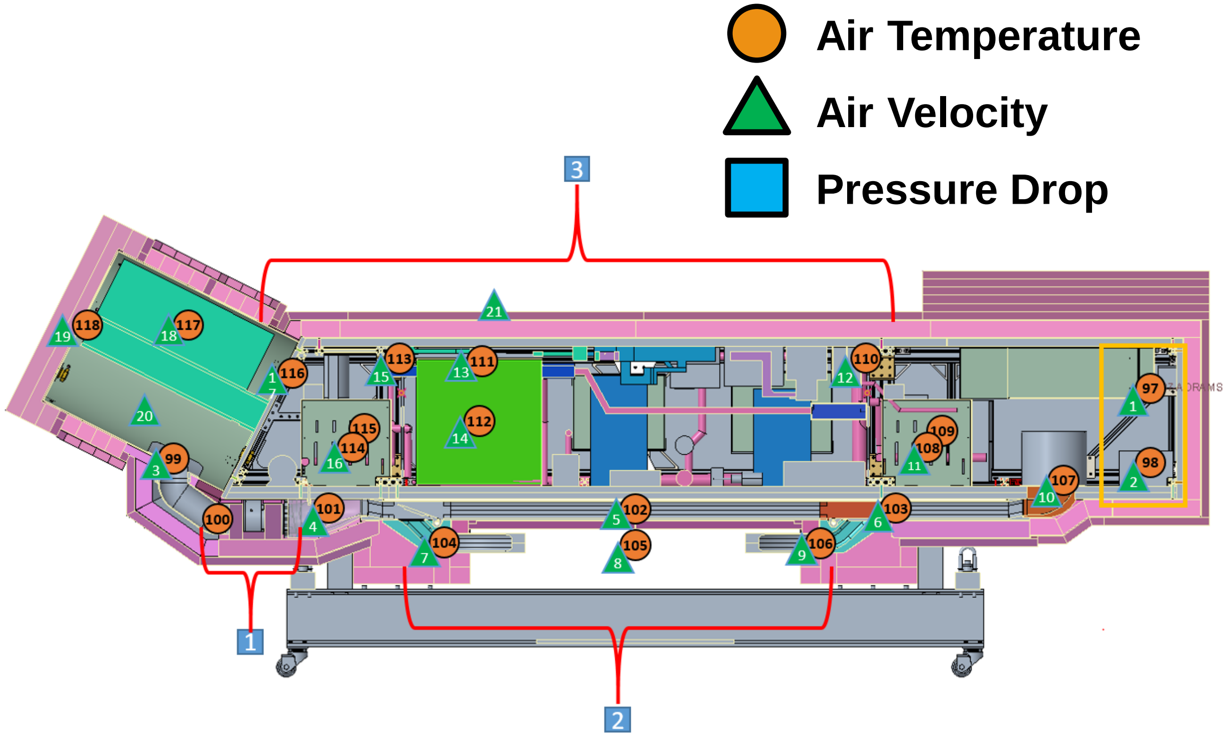


DTM – Test Objectives

1. Determine the heat rejection capacity of the 3D-printed cold duct trim device
   - While capacity of Ultem duct is not flight-like, behavior of the test duct is sufficient to validate the cold duct trim device concept
2. Collect transient temperature data for warm air flowing into “cold” cold duct
   - Flow choking: how long will it take to establish flow with cold, dense air in the cold duct?
3. Determine the effect of fan speed on heater unit temperature
   - Test data sets the stage for fan cooling tests on the MMRTG Thermal Simulator

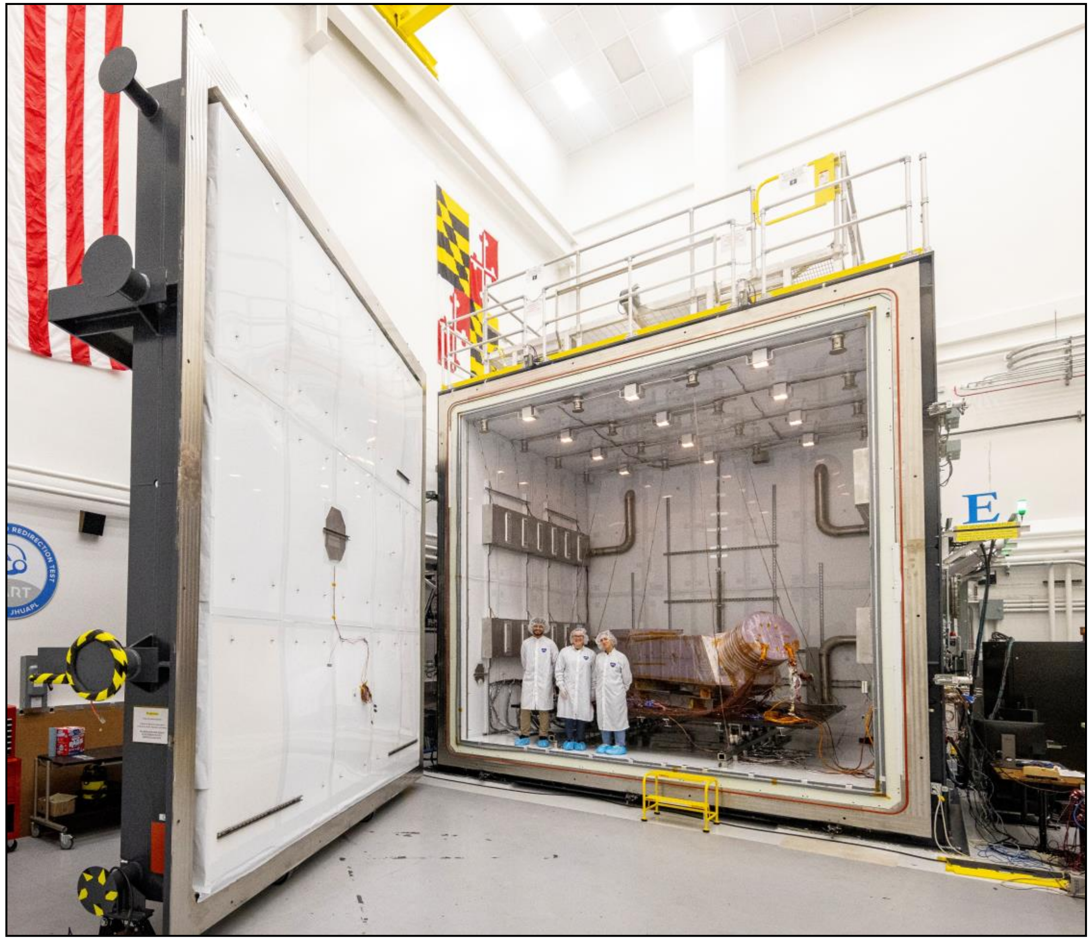
DTM - Instrumentation

- DTM features 203 thermocouples, along with 15 air velocity sensors and 4 differential pressure sensors
  - Thermocouples collect temperature data for post-test model correlation and for test troubleshooting
  - Pressure sensors measure the pressure drop across the flow loop to support CFD correlation
- Chamber convection measured with convection sensors and air temperature thermocouples
- Air Velocity and pressure data used to correlate Ansys Fluent™ CFD model.
  - Ansys Thermal Desktop™ model is WIP



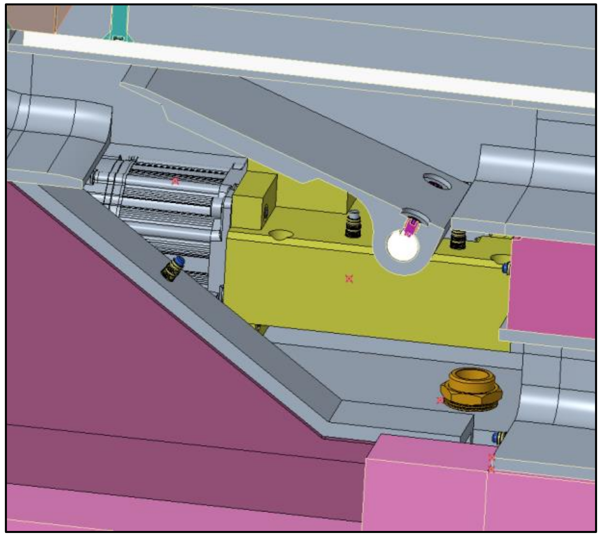
TITAN Chamber

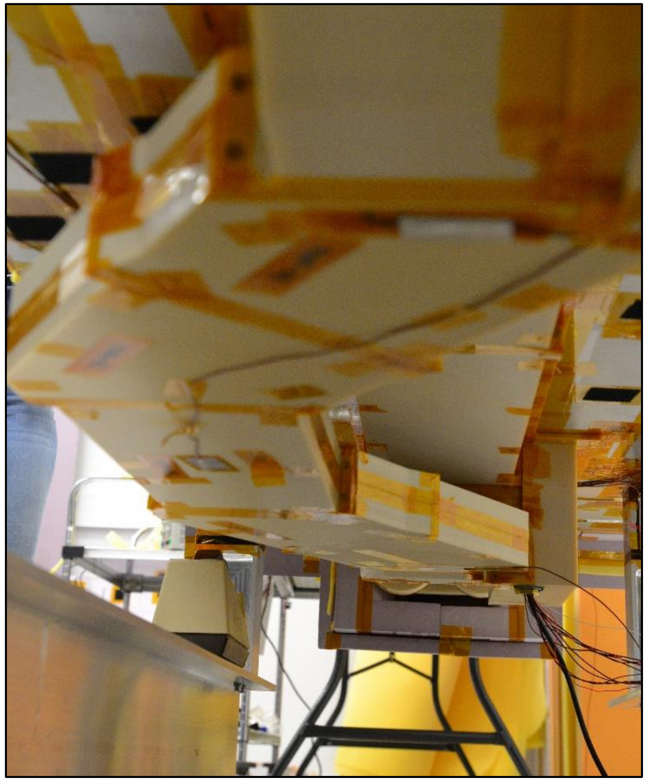
- TITAN Chamber is the flagship thermal test chamber for Dragonfly:
  - 15ft. x 15ft. x 15ft. (4.6m) internal working volume, large enough to test flight lander
  - Nitrogen cryogenic environment allows for convection heat transfer to evaluate lander TCS
  - Temperature range: -180C to +150C
  - Pressure range: 380 Torr to 700 Torr
  - Chamber feedthrough and data system accommodates 240 Type-T thermocouples, additional feedthrough ports allow for other connections to test equipment



Test Methodology

- Trim Device capacity is determined via a series of thermal balance tests:
  - Initial thermal balance performed with closed duct: no thermal trimming
  - Subsequent thermal balance performed with fully-opened duct: maximum trim
  - **Difference in power between the two tests taken as trim device heat rejection capacity**
- Trim Device behavior over a range of angles were tested to determine trim device sensitivity





Test Summary

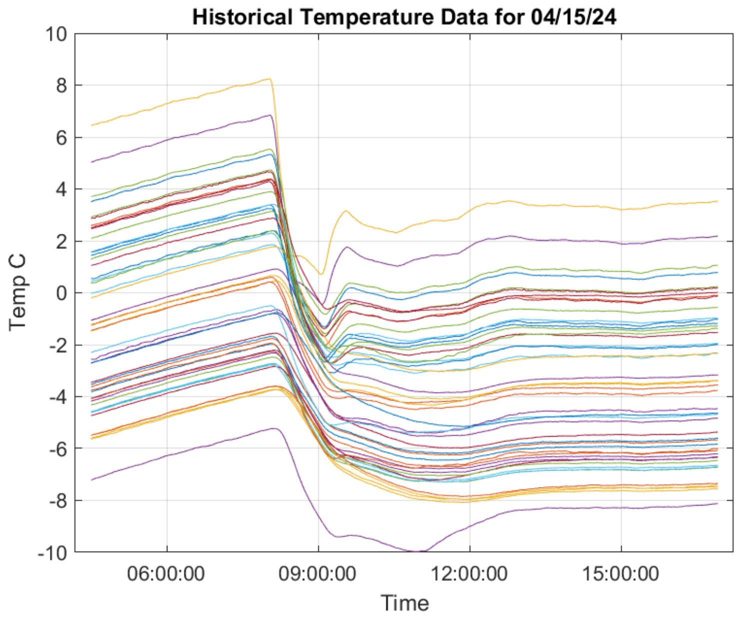
- 22 test cases were conducted over a 2-week test period
  - All test objectives were completed, producing data for model correlations
- Despite testing occurring over 2 separate phases and with a near-complete disassembly of foam insulation between phases, thermal performance between the two phases of testing were virtually identical.
  - Indicates that test foam attachment methodology is repeatable

Phase	Heater Power	Cold Duct Condition	Battery Temp	Test Stability (degC/hr)
1.1	460 W	Closed	0.67 C	0.07
1.2	460 W	Closed	0.32 C	0.02
Delta	**0 W**		**-0.35 C**	**-0.05**
1.1	720 W	Open	0.67 C	1.1
1.2	668 W	Open	0.34 C	-0.05
Delta	**-52 W**		**-0.33 C**	**-1.15**
1.1	720 W	Open	0.67 C	1.1
1.2	720 W	Open	13.76 C	0.18
Delta	**0 W**		**13.09 C**	**-0.92**

Extraneous Heat Leaks

- Properly installed foam insulation should result in fairly even temperature distributions within the DTM – cold spots indicate that there are heat leaks through insulation which can contribute to error in modeling.
  - Honeycomb panel temperatures are a good indicator of these extraneous heat leaks – leaks result in high temp gradients.

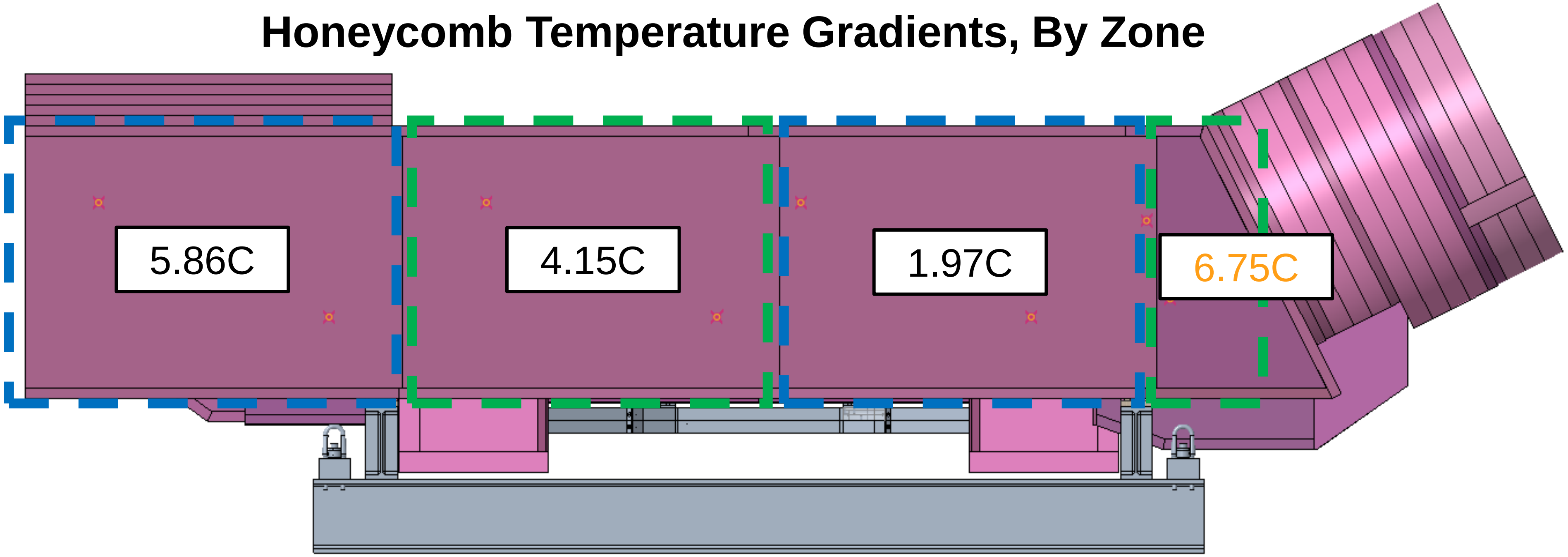
- DTM sees an 11C spread of honeycomb temperatures along its length:
  - Temperatures are hotter towards the nose and the heater plate, and are cooler near the middle of the body.
  - Similar temperature distribution to lander models
  - Previous sub-scale testing resulted in < 3C of gradient in honeycomb paneling



Extraneous Heat Leaks Cont.

- Honeycomb panel temperature distributions along the length of DTM seem to be reasonable and are generally uniform.
  - Higher distribution towards the nose is due to hot duct air impinging on the front panel, not a cold spot.
  - Aft-most honeycomb location developed a cold spot near the left leg bracket, 4C colder than surroundings

Honeycomb Temperature Gradients, By Zone

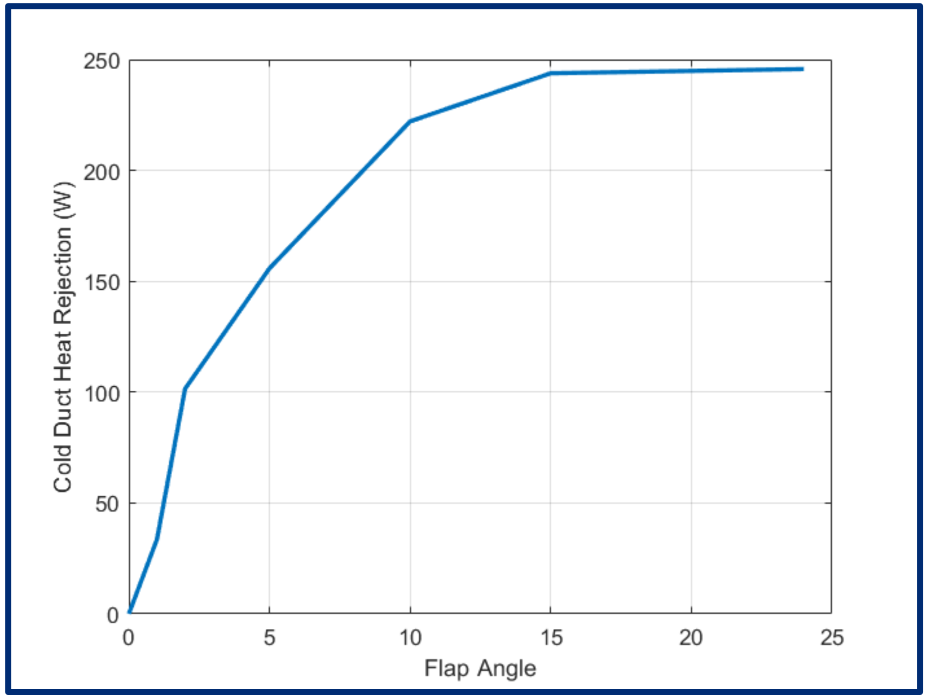


Cold Duct Heat Rejection Curve

- Cold duct capacity experiences large initial increase in rejection capacity, rate reduces as flap angle increases.
- Future testing will utilize a composite duct system, which will greatly increase rejection capacity.

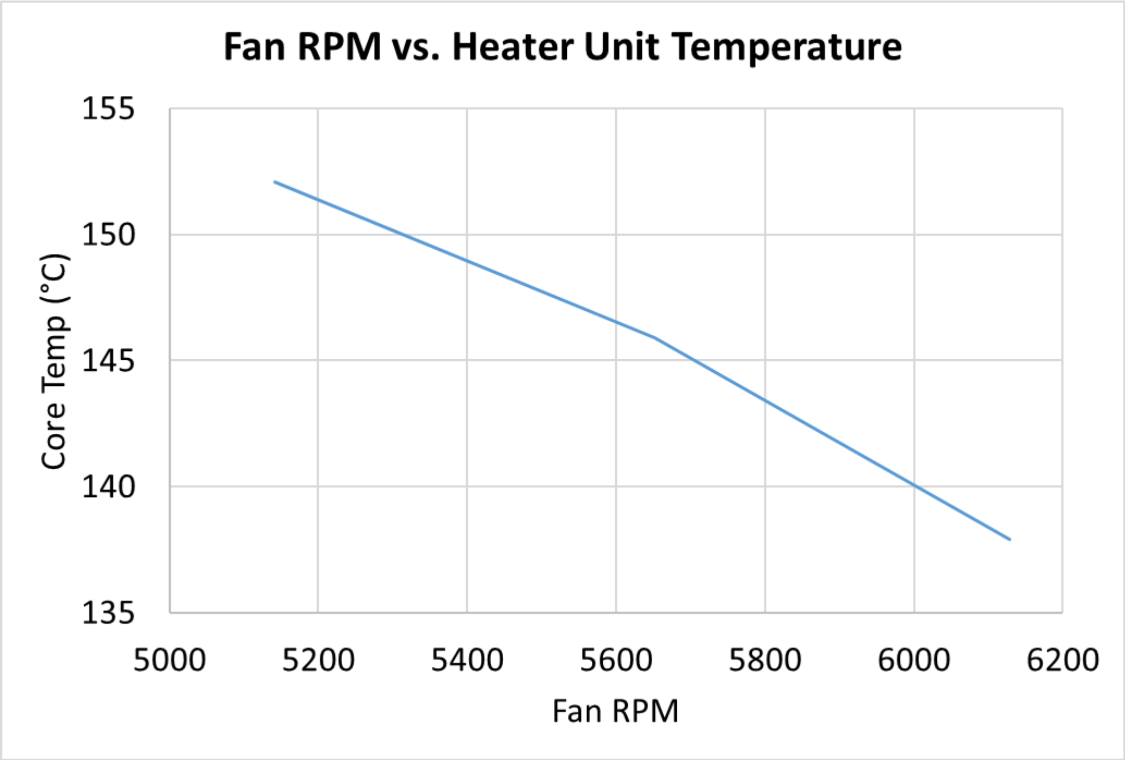
Flap Angle (Deg)	Required Heater Power (W)	Heat Rejection (W)
0	611	0
1	644.6	33.6
2	712.5	101.5
5	766.8	155.8
10	833.1	222.1
15	854.8	243.8
23.7	856.7	245.7

Cold Duct Flap Angle vs. Heat Rejection



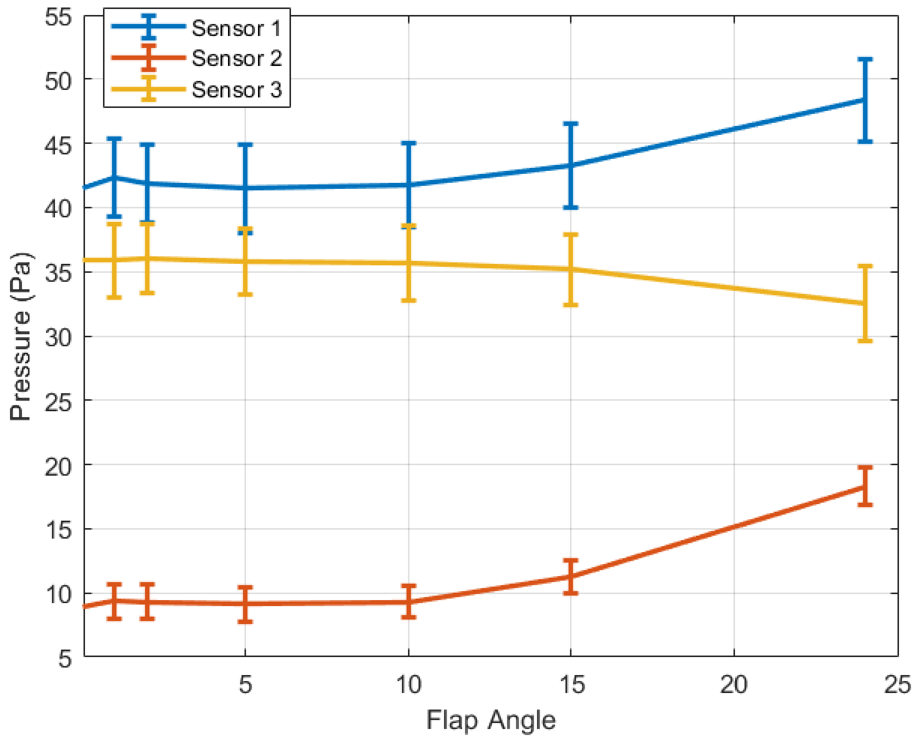
Fan Cooling

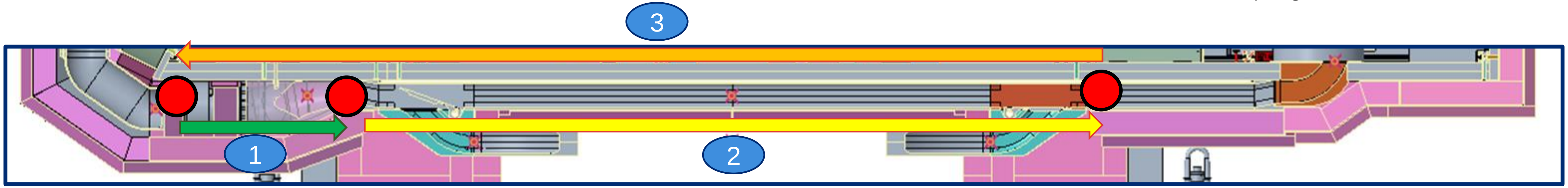
- Cooling test demonstrates that flight-like fan is capable of cooling down the heater unit
  - Maintaining proper fin-root temperatures is critical on flight MMRTG: duct fan is the primary method of controlling this temperature.
  - Heater unit is not flight-like, but is roughly analogous in size to MMRTG



Pressure Drop Data

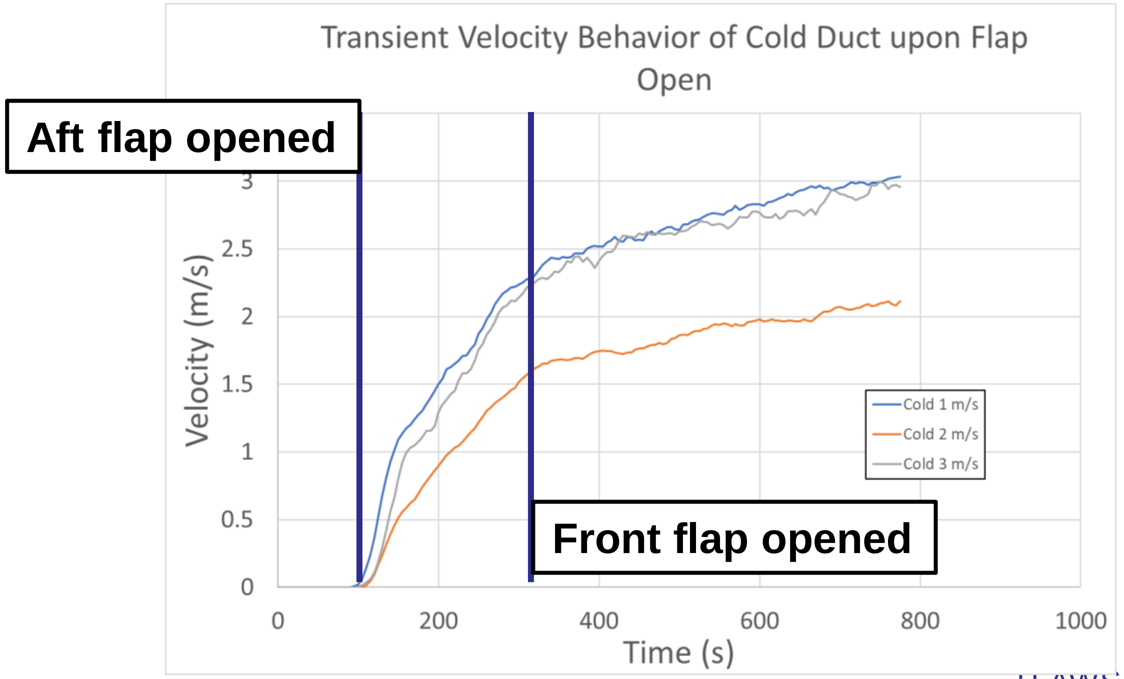
- Pressures shown are absolute value differences
  - Sensor 1 represents a rise in pressure across fan zone
  - Sensors 2 represents a drop in pressure across ducting
  - Sensors 3 represents a drop in pressure across DTM body
- Significant system and duct pressure increases only visible at 10+ degree flap angles
- With 10+ degree flap angles, the air flow speed reduces, which results in lower pressure drop across DTM body
  - Error bars shown represent 2σ uncertainty, represents ~7% of total measured value, higher than expected ~1%

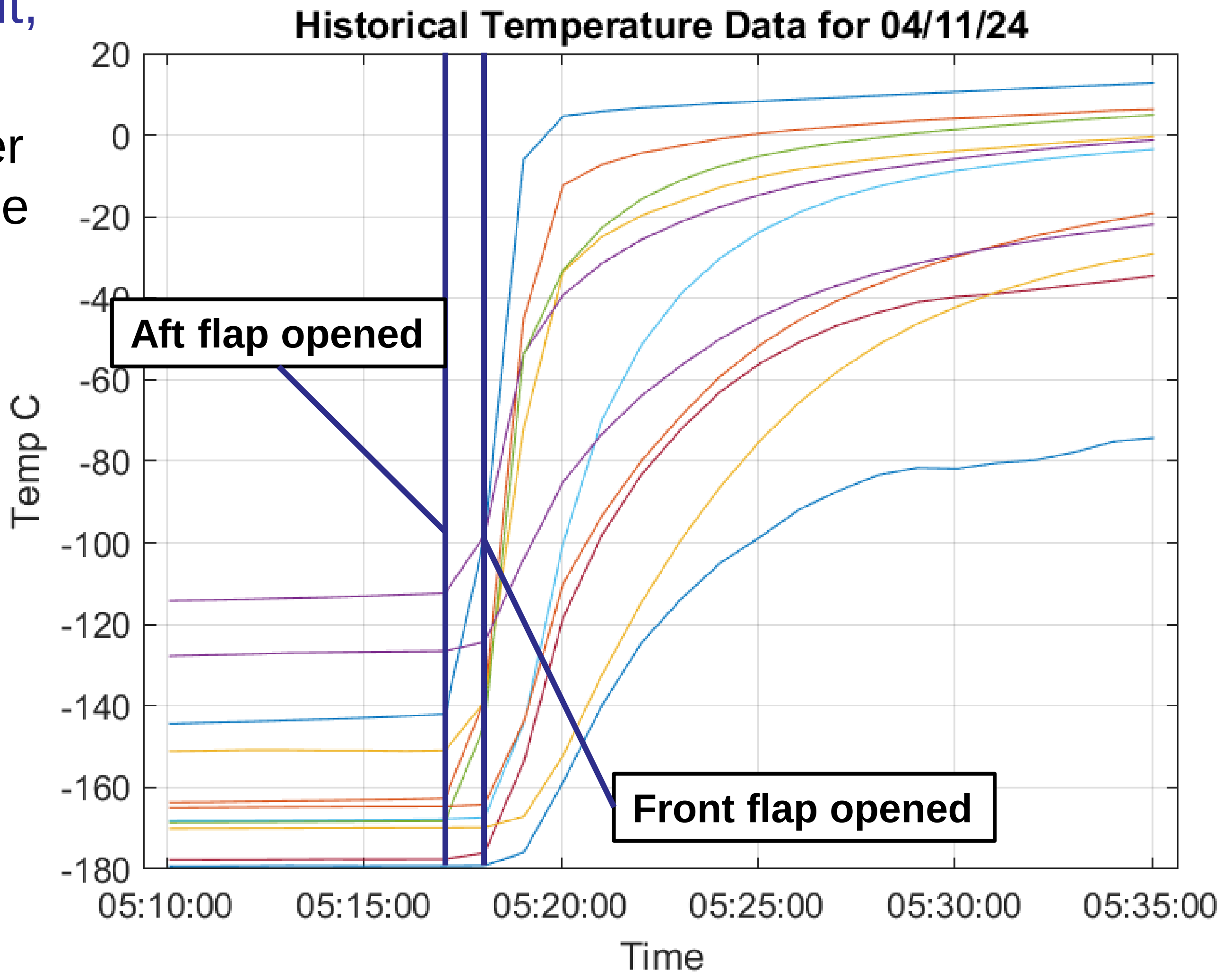




Transient Cold Duct "Choking"

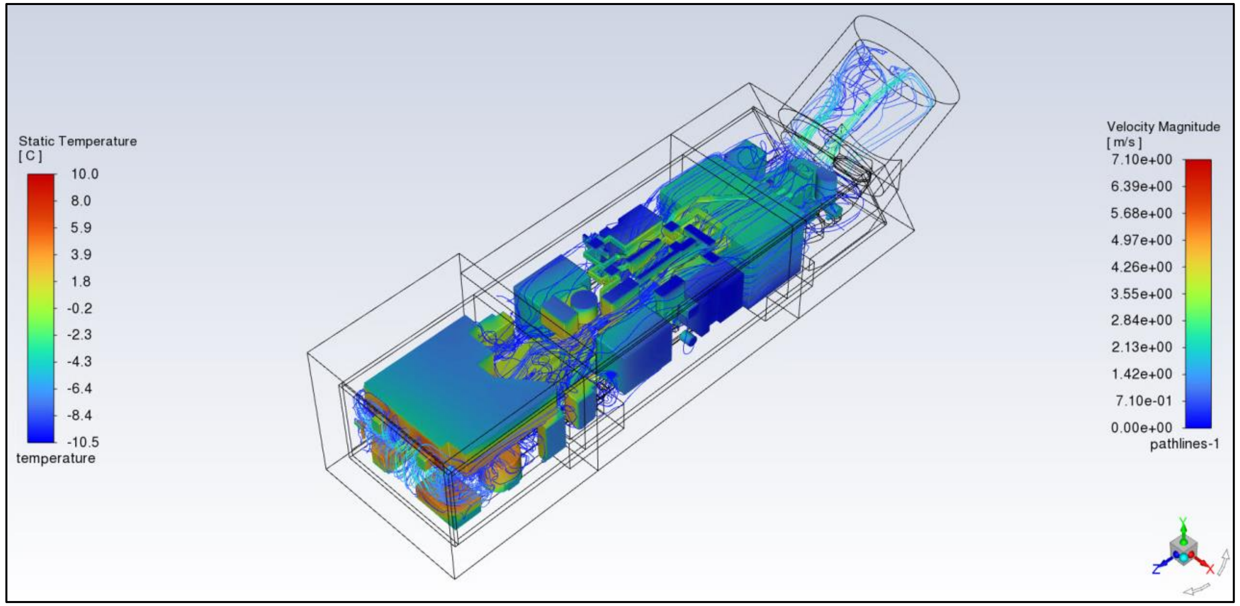
- Cold duct surface and air temperatures are graphed to the right, velocity below:
  - Rapid rise upon opening both diverter flaps, which indicates that cold, dense air does not pose a large flow resistance.





CFD Correlation

- CFD model resulted in fully converged cases behaving similarly to the Titan Chamber experiments
  - Model was stable, with a well-refined mesh, high level of details, and affordable computational costs
- CFD predicted pressure drop within ±11% of DTM Test results, providing confidence in fan power prediction for the Lander model.
- CFD predicted cold duct heat rejection within ±12% of test results, supporting confidence in split cold duct heat rejection prediction for the Lander model.
- Temperatures prediction ranges:
  - Surface temperatures: **±7C**
  - Air temperatures: **±12C**



Future Work

- As a full-scale test article, DTM will prove invaluable for future phases of thermal testing:
  - DTM will be used to test the total heat leak of flight-like foam, along with providing practice for flight foam integration
  - The true heat rejection capacity of the trim device will be tested with a flight-like prototype
  - The MMRTG Thermal Simulator (TSIM) will be installed on DTM in order to evaluate flight-like fin-root cooling
  - DraMS attic, as well as arm/leg protrusion testing is planned for future test phases
- Improvements to chamber instrumentation will improve CFD model fidelity
  - Cryogenic pitot tube system will measure chamber air velocities, and will confirm boundary conditions for future testing
  - Improved methodology for measuring LN2 flowrate within chamber will also improve CFD fidelity