Dragonfly: Pushing The Boundary of Spacecraft Thermal Design, Analysis and Testing

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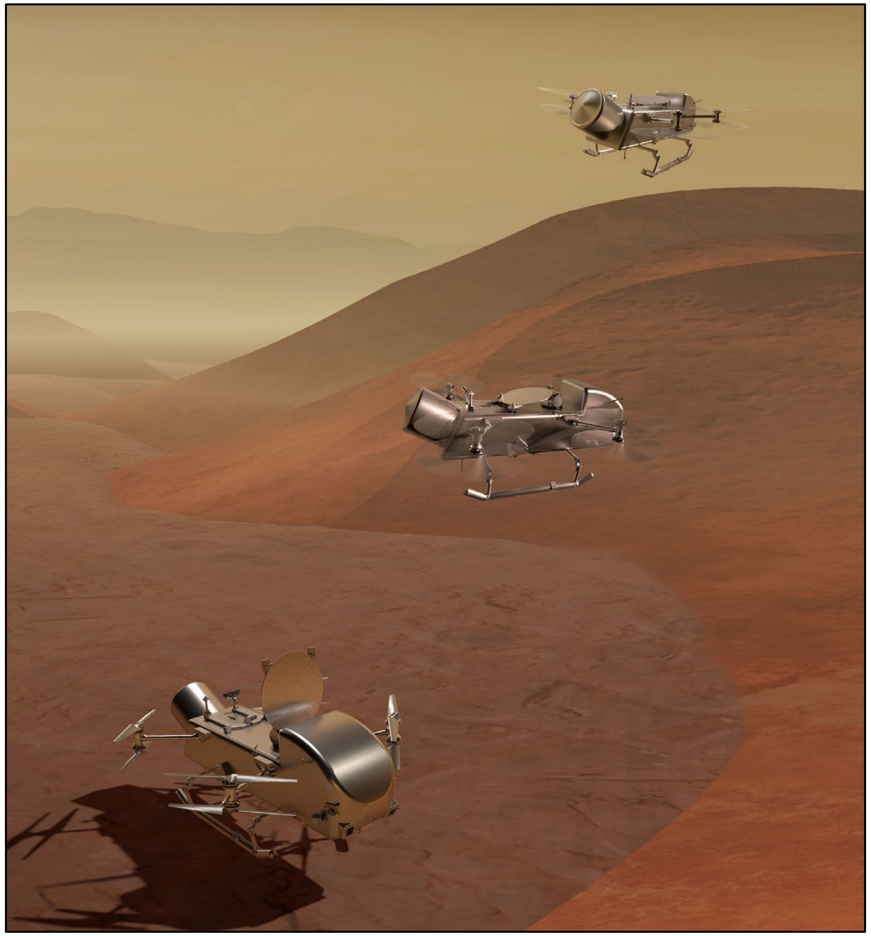
DRAGONFLY

A relocatable lander to explore Titan's prebiotic chemistry and habitability

Agenda

- Dragonfly Mission Overview
- Titan Thermal Environment and Challenges
- Lander Thermal Control System (TCS) Design
- Thermal Analysis, Testing & Correlation
- Lessons Learned



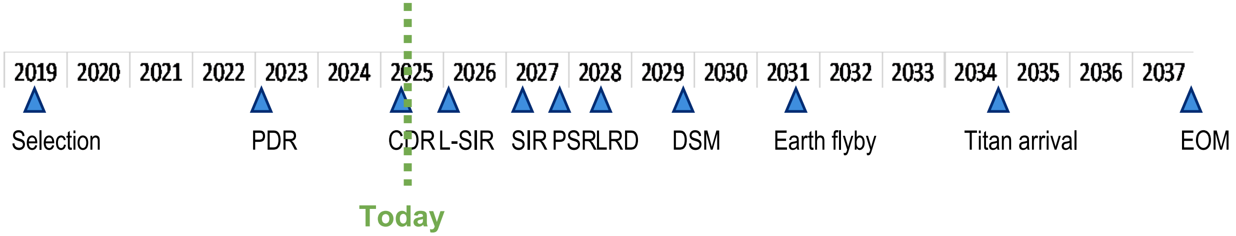
Dragonfly Mission Overview

NASA New Frontiers program to explore the largest moon of Saturn using a rotorcraft

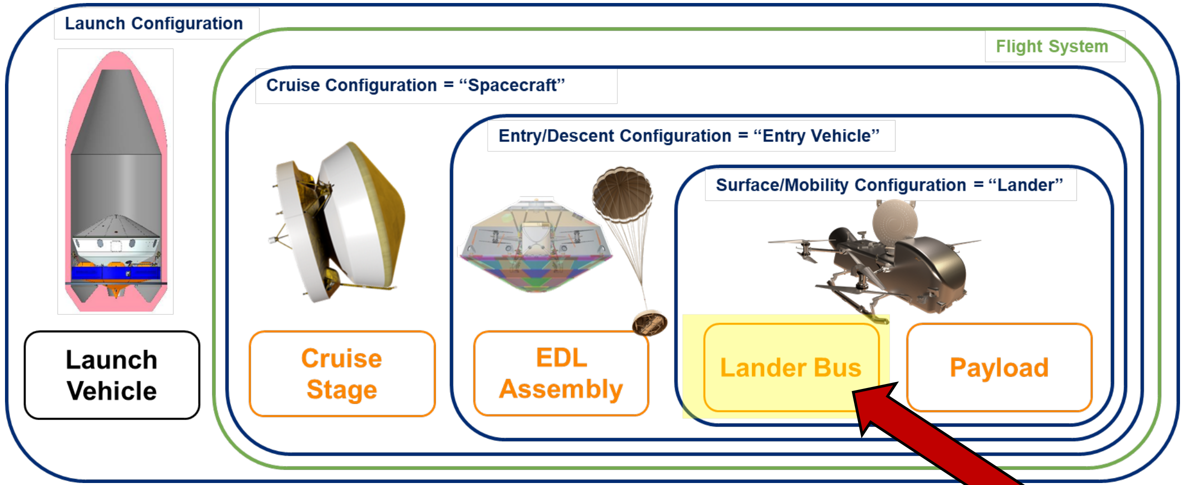
Mission Goals

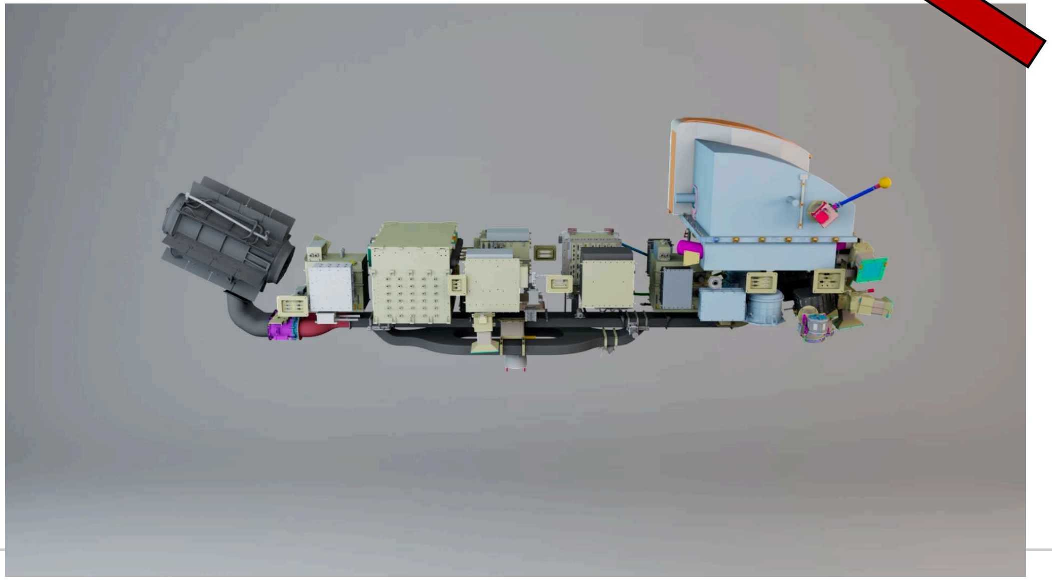
- Studying the complex organic chemistry on Titan
- Investigating the moon's habitable environments, exploring its geology and meteorology.
- Searching for biosignatures: chemical evidence of water- or hydrocarbon-based life

Mission Timeline



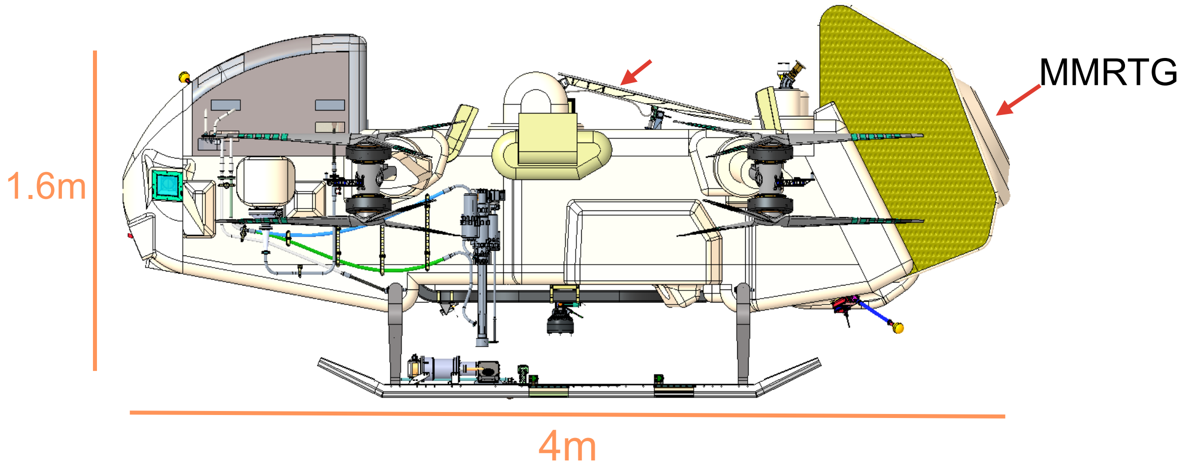
Flight System Configuration

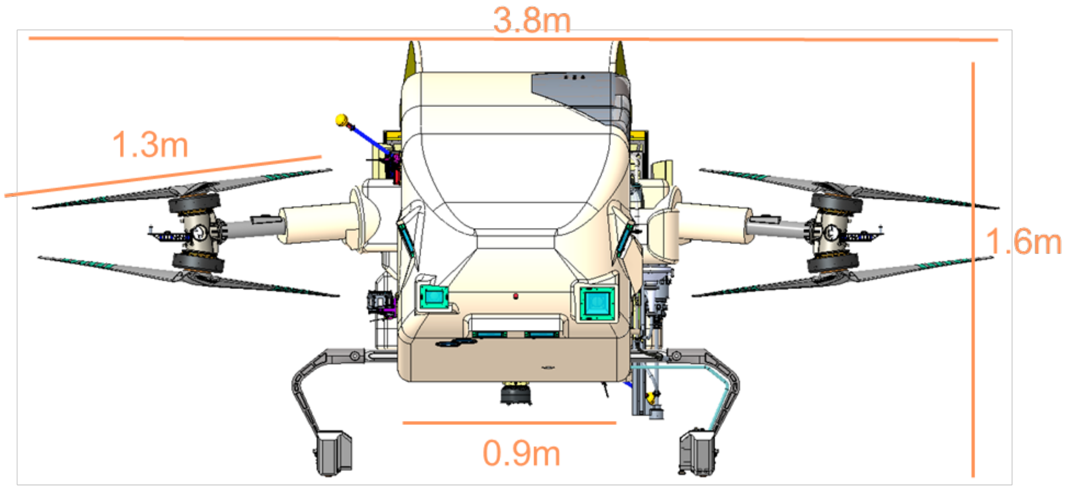




Today's Focus

Lander Configuration





- Mass: 995 kg
- Uses 4 pairs of rotors for mobility on Titan surface
- Aluminum honeycomb panel structure, sealed (not hermetic)
- Solimide foam covering fuselage for thermal control and aerodynamic shaping
- MMRTG powered

Titan Surface Environment & TCS Implications

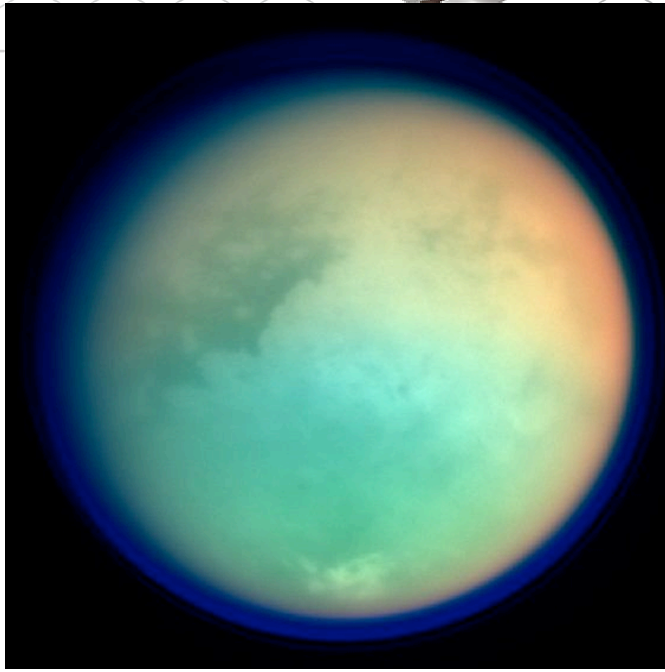
Environmental Parameters

- Extreme but stable environment, unlike Earth or Mars
- A dense convective environment, with no prior thermal control system design for such environment.
- Radiative heat transfer is negligible compared to convection

- **Temperature**: 92 to 96K (-181 to -177 °C)
- **Gravity**: 1.35 m/s^2 , 14% or 1/7 of Earth's surface gravity
- **Atmospheric pressure:** 1.45 atm
- **Atmospheric density:** 5.3 kg/m^3 , 4.3x density of Earth's atmosphere
- **Wind**: 0-2m/s;
- **Precipitation**: Methane rainfall is rare
- **Titan air composition**: 94.3% nitrogen, 5.6% methane and 0.1% hydrogen

Thermal Control System (TCS) Implications

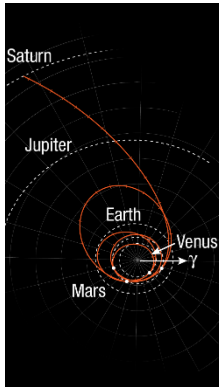
- **Design:** What is the right design for this dense convective environment? Is this like a system on earth?
- **Analysis:** What is the right software to use? How to validate it? What are the uncertainties and sensitivities for this environment?
- **Testing, V&V:** How can we test-as-we-fly on earth factoring in the different gravity and pressure?

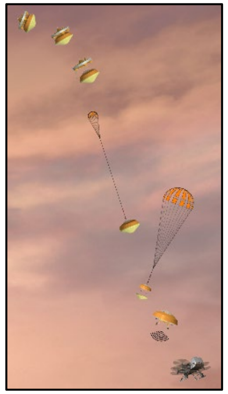


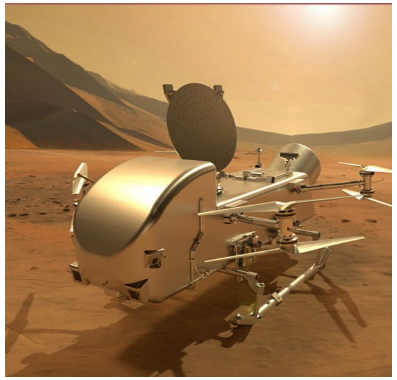
- Titan is the largest of Saturn's 146 Moons
- Titan day is 16 Earth days
- Distance from Sun varies 9.5-10.5 AU, one way light travel time 70-90 minutes

Lander Thermal Environment Overview

Today's Focus





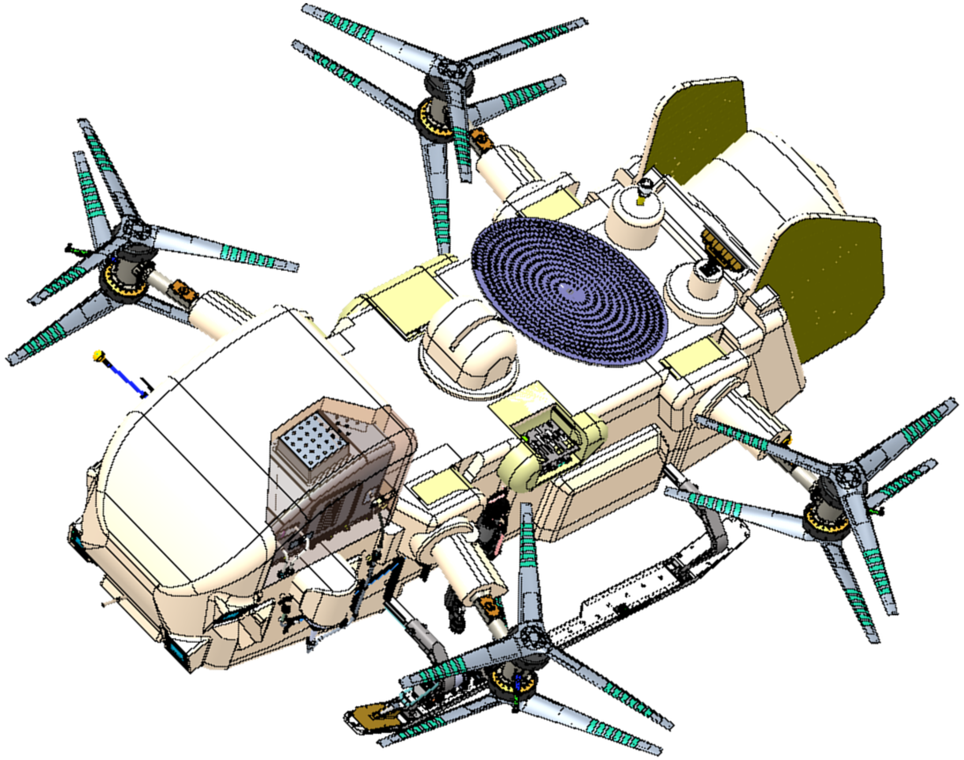


Phases	Prelaunch/Launch	Cruise	EDL	**Titan Surface Operations**
Organization	LM+APL	LM	LM+APL	APL
Environment	Convective	Vacuum	Vacuum + convective	Convective
Temperatures	~20°C	~-100 °C	-186 to 160 °C	-179 ± 2°C
Pressure	1 atm	Vacuum	0-1.5 atm	1.5 atm
Wind	Aeroshell environment	NA	Aeroshell to Titan surface	0-2 m/s for hibernation Up to 10m/s for flights
Gravity	Earth gravity	0	0- 1/7 earth gravity	1/7 earth gravity
Unique Challenges	Insulated MMRTG and battery in "warm" earth environment	Survival on fluid loop with limited electrical power and no heaters	2 hour transient, thermal control system transition	Extreme heat loss to cryo convective environment

Spacecraft

Rotorcraft

Dragonfly Lander Thermal Control System Design



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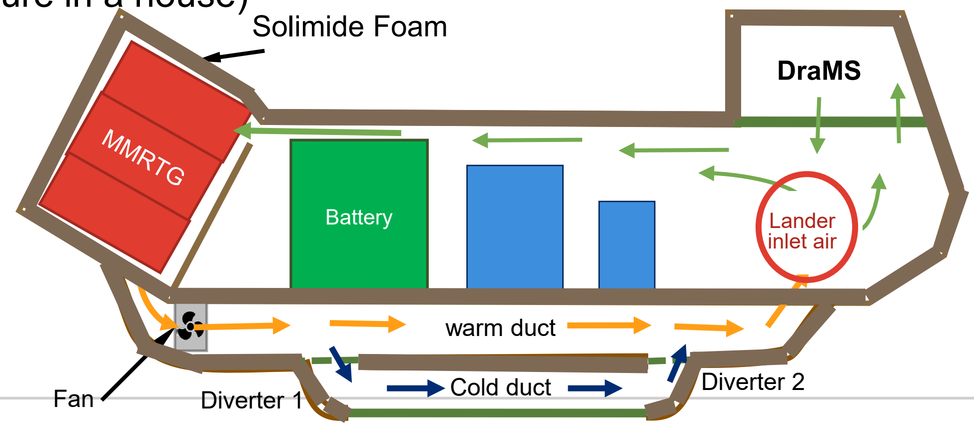
Lander Thermal Design - Rotorcraft

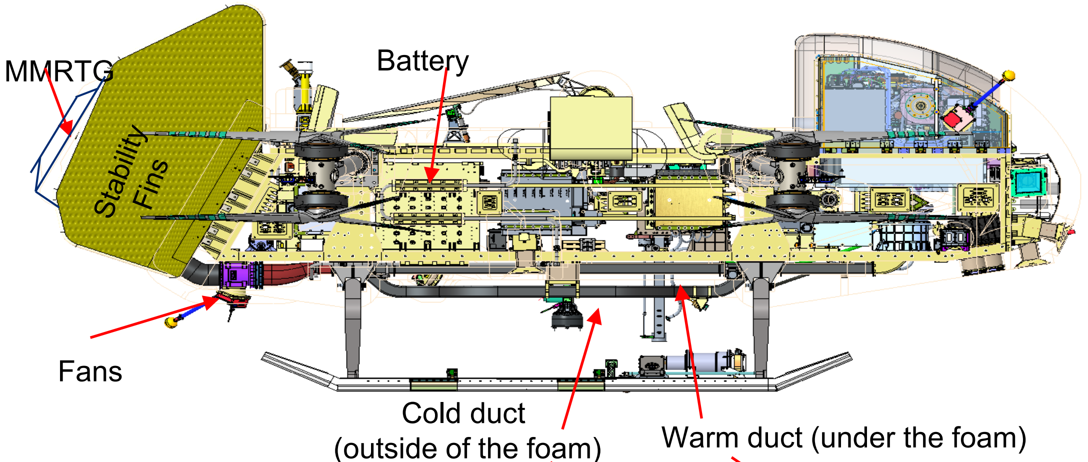
Titan Surface (APL)

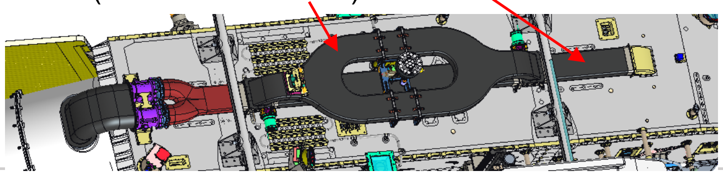
- **Fan driven air circulation creates one thermal zone throughout the lander**
- **Thermal control system key components**
  - **MMRTG decay heat** is the primary heat source for the Lander, ~1800 W
  - **Solimide foam enclosure** conserves the MMRTG decay heat
  - **Fan & ducting** ensure air circulation and heat distribution, nominal flowrate 50 CFM
  - **Cold duct thermal trim:** no foam insulation and exposed to Titan extreme cold. By changing the diverter angle to control the airflow passes through the cold duct, thereby regulating the temperature of the Lander inlet air (just like the HVAC system regulates the supply air temperature in a house)

Control Philosophy: PID control of the diverter angles

- **Primary control inputs: Battery temperature**
  - Battery is the most temperature sensitive component inside the lander, temperature requirement 0-20°C during hibernation
  - Battery temperature changes slowly (~hours) due to its large mass (~300 lbs)
- **Control limit setpoint: Lander inlet air temperature**
  - 0 to 60 °C
  - Can fluctuate rapidly (~ mins)
  - Override battery control if exceeded







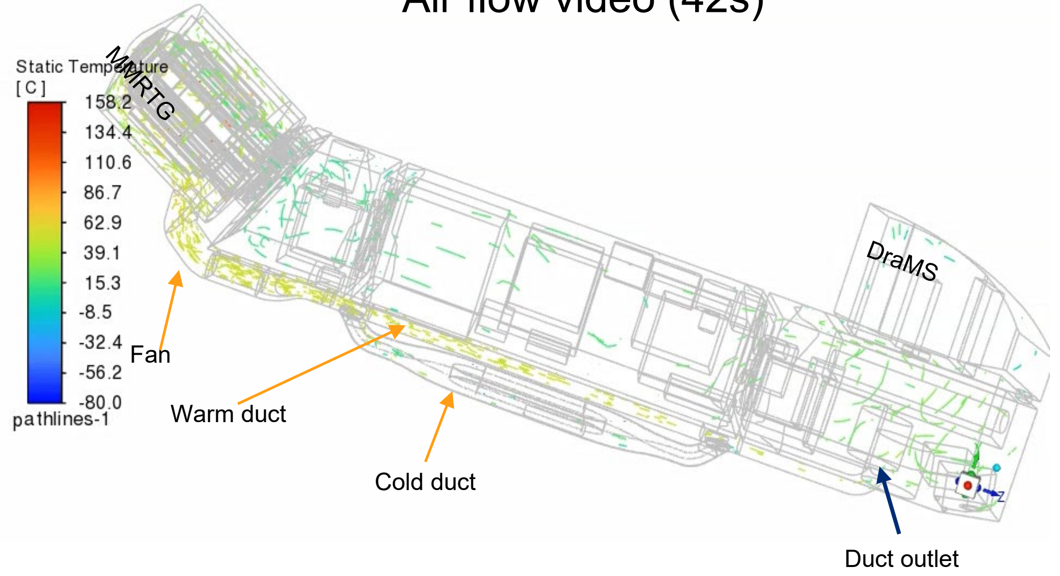
Bottom view: Ducting under the bottom deck

TCS Design Major Challenges

Titan Surface (APL)

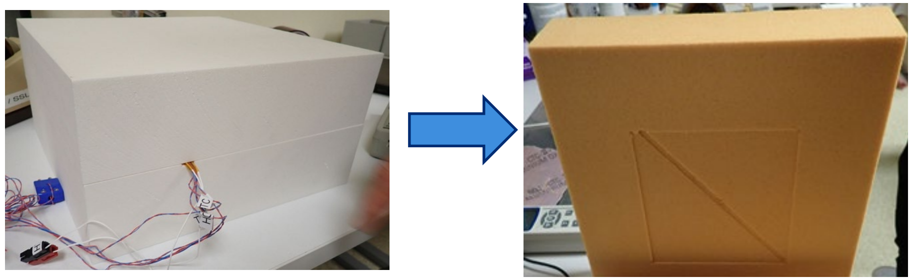
- **Dense convective environment: The Lander is not a traditional spacecraft in vacuum, and no prior mission reference exists!**
- **Foam in a convective environment behaves differently than MLI blankets, and requires significant technology development efforts.**
- **Battery has tight temperature requirements that need to be maintained through extremely varied thermal environments across the mission.**
- **Limited survival heater allocation due to power constraints (prioritize battery charging)**
  - Design can not rely on heaters for temperature control using a typical cold biased design strategy.
  - The foam is sized for a hot biased design, relying on the cold duct to always reject heat, even in cold cases.

Air flow video (42s)



Foam Overview

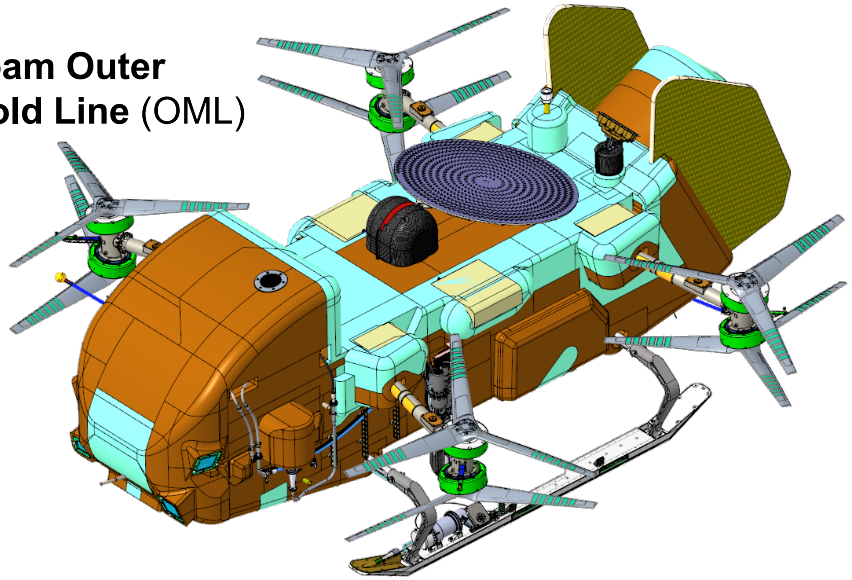
- **Baseline: Solimide 16**
  - Flexible foam, low density, good thermal performance
  - Previous baseline was Rohacell, but due to cracking under restraint high heat leaks were observed during APL testing. Foam was changed to Solimide in 2024 after an extensive insulation trade study.
  - Comprehensive foam technology development effort has been completed to meet thermal, mechanical, structural, contamination, grounding, electrical, I&T requirements
  - Foam CDR is scheduled in August 2025
- **2 layer design for better thermal performance in convective environment**
  - Encapsulation: Kapton sheet with FM300 film adhesive for contamination control
  - Attachment: Y966 pressure sensitive adhesive as the attachment mechanism with 9394 epoxy staked outside Kapton bands
- The Dragonfly foam will **consist of approximately ~600 foam tiles** that will cover almost every external surface of the lander (but not the cold duct!)



Rohacell 31

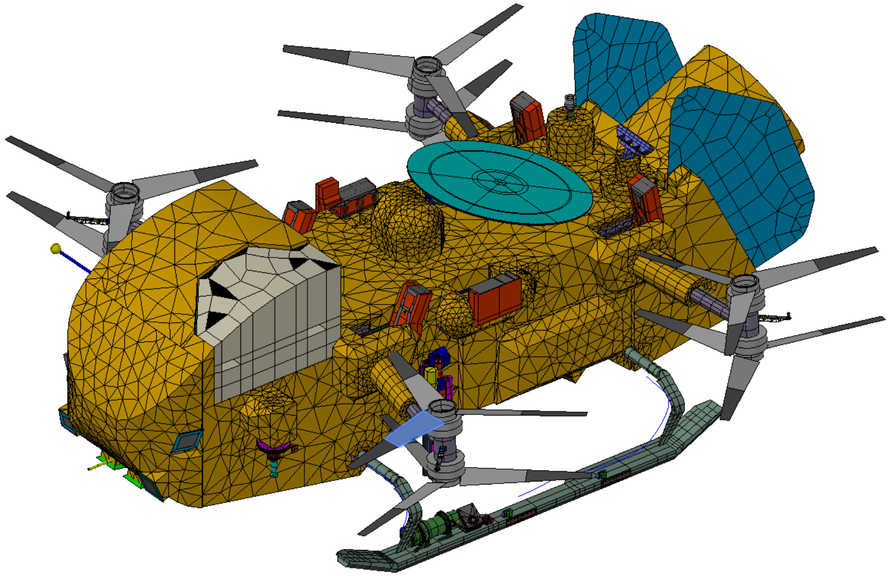
Solimide 16

Foam Outer Mold Line (OML)



🟦 : I&T removal tiles

Dragonfly Lander Thermal Analysis & Testing



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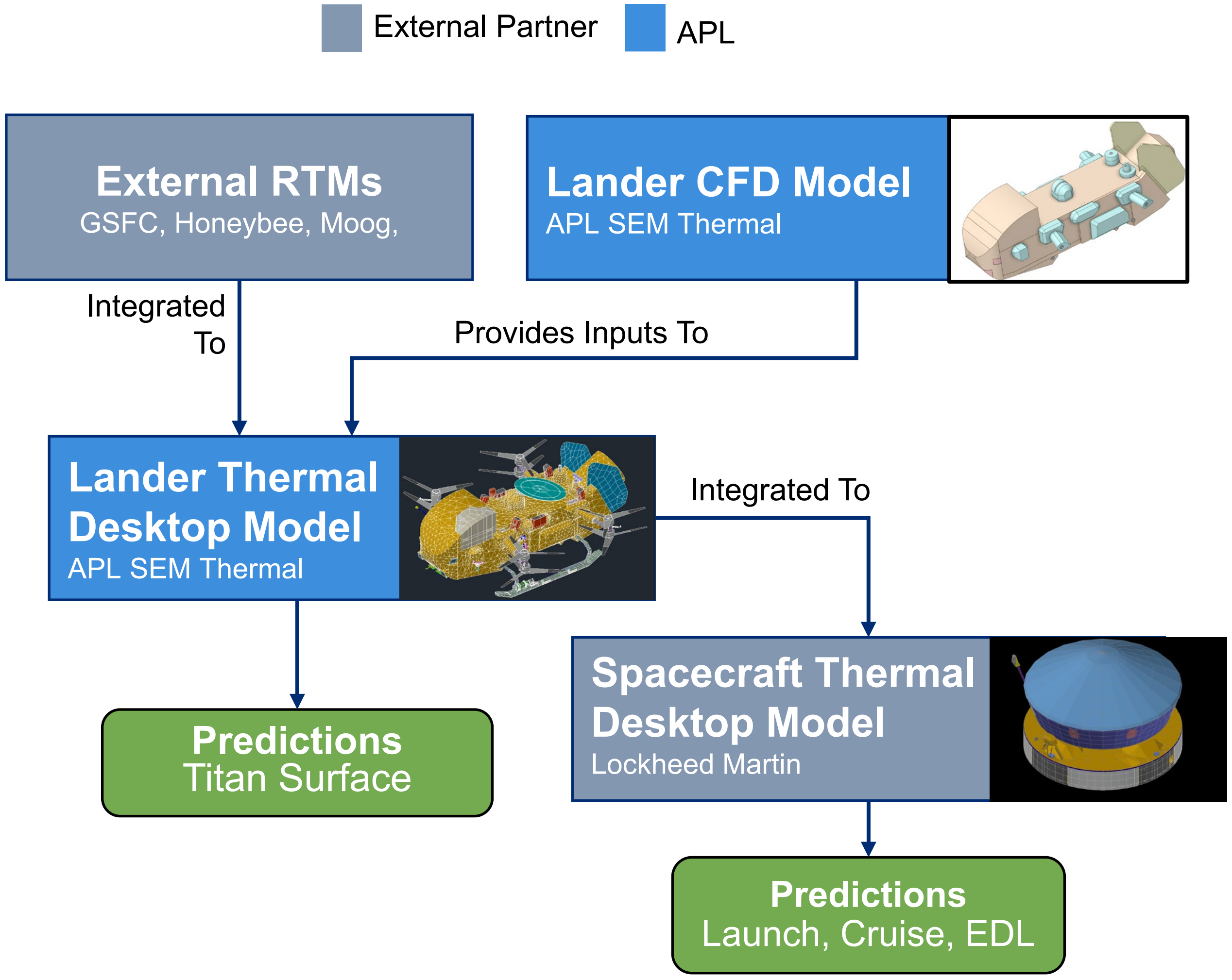
Dragonfly Analysis Architecture

- Thermal analysis for Dragonfly combines heritage analysis practices with novel approaches developed specifically to meet unique mission needs
  - **Thermal Desktop** is ubiquitous in the spacecraft thermal discipline, is fast and flexible, but does not natively model airflow.
    - Users must impose convection assumptions in the model.
  - **Ansys Fluent** is a thermal CFD tool capable of simulating airflow, allowing the user to directly model and discover convection physics.
    - Downsides: Long runtime, huge mesh, resource hungry, costly, less flexible, and not used by external partners.

- **APL has developed a hand-in-hand TD and CFD analysis approach to generate temperature predictions**
  - CFD and TD models are benchmarked for accuracy and agreement
  - CFD informs and cross-checks the TD model; TD provides final predicts



■ External Partner ■ APL

External RTMs
GSFC, Honeybee, Moog,

Lander CFD Model
APL SEM Thermal

Integrated To

Provides Inputs To

Lander Thermal Desktop Model
APL SEM Thermal

Integrated To

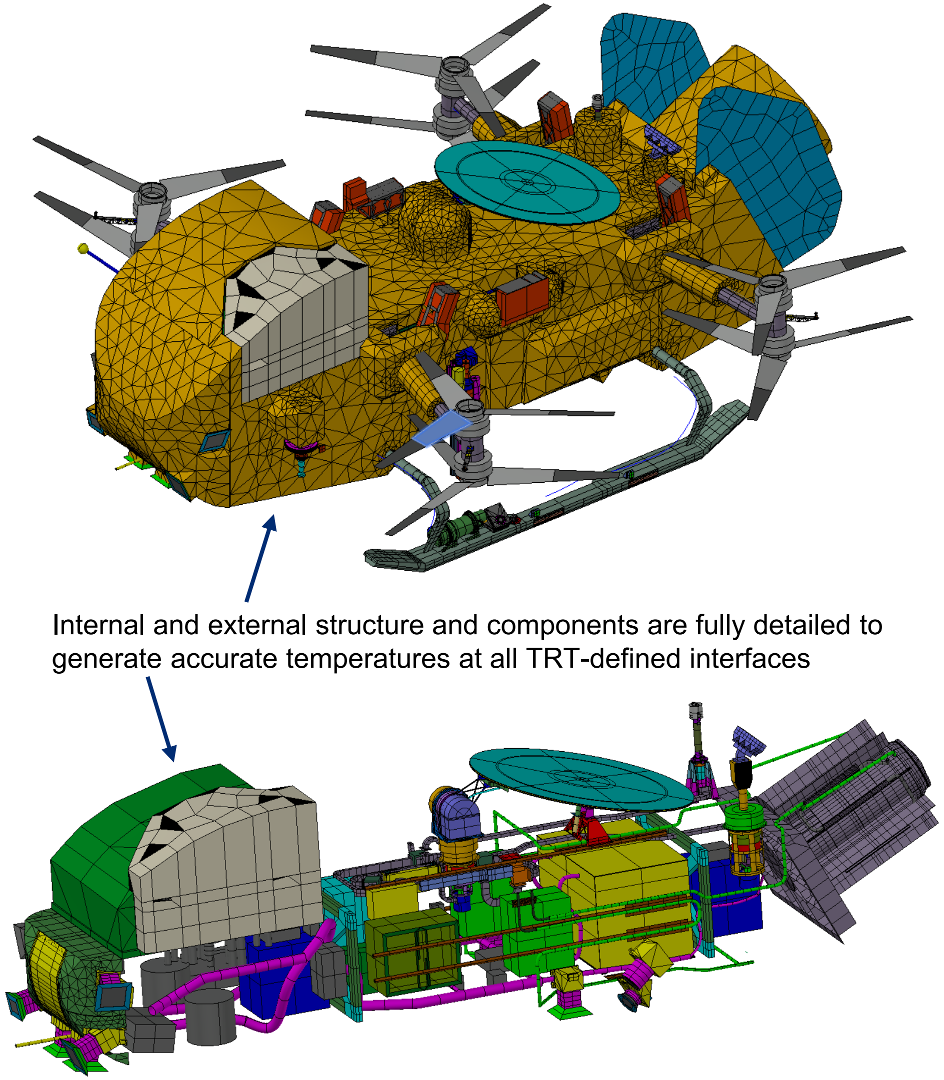
Predictions
Titan Surface

Spacecraft Thermal Desktop Model
Lockheed Martin

Predictions
Launch, Cruise, EDL

Lander Thermal Desktop Model

- **Primary thermal analysis tool for mission predictions**
  - Cases are run across all mission phases
  - **Driving design cases**: Launch, EDL, Titan Flight, DraMS operation
- **Model incorporates significant detail at the system level**
  - Foam previously modeled using primitives, but now a SpaceClaim® mesh is used to allow **rapid foam design iteration**
  - Airflow and convection use a discretized flow path of ~30 air nodes connected with one-way mass/energy flow conductors
  - Hosts imported, reduced models from **instrument teams**
  - **Detailed MMRTG model** provided by INL and Aerojet Rocketdyne Thermal
- **Key Metrics**
  - 42,680 Nodes, 33,837 Elements, 759 Conductors, 137 Heat Loads
  - 21 Heaters, 88 Pipes, 674 Contactors
  - Runtimes: 20 minutes (steady state cases), 4-12 hours (transient cases)



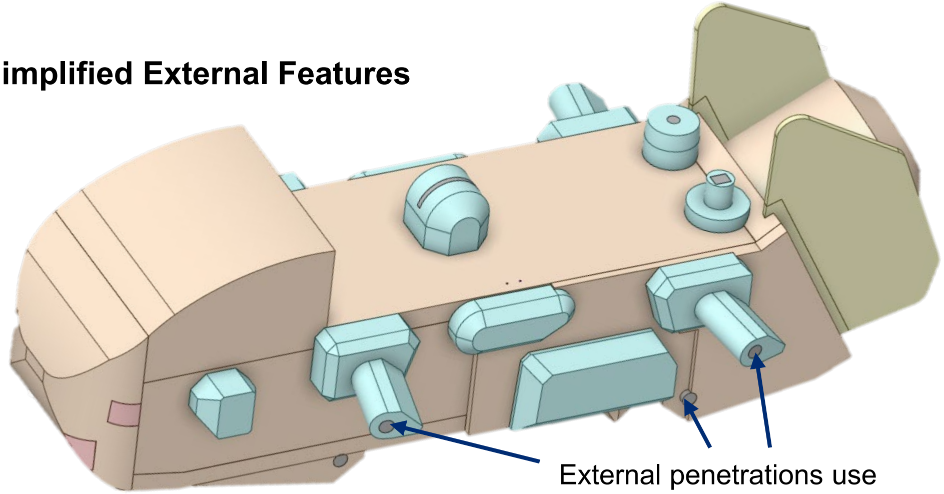
Internal and external structure and components are fully detailed to generate accurate temperatures at all TRT-defined interfaces

Lander CFD Model

- Lander CFD model is developed in ANSYS® Fluent
  - Finite volume method using approximately 30 million elements
- Runs a **subset of steady state lander cases** (Pre-launch, Titan Hibernation)
  - Some transient point studies have been run (EDL)
- Provides key outputs to Lander TD model listed below:

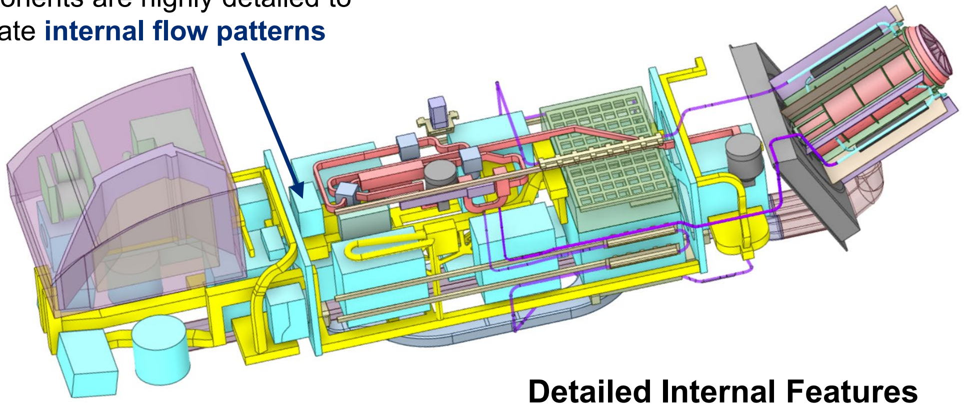
Key CFD Outputs	Purpose
System air mass flow, $\dot{m}$	Direct input for TD
Air velocity & temperature distributions	Validates TD's discretized network of lumped air nodes and internal flow structure
Convection couplings (h-values) for lander external and internal components	Inform & validate TD's convective heat transfer assumptions
Key internal component temperatures	Validate & cross check TD's temperature predictions

Simplified External Features



External penetrations use **effective conductivity** to simulate heat leaks based on **flow-insensitive TD predictions**

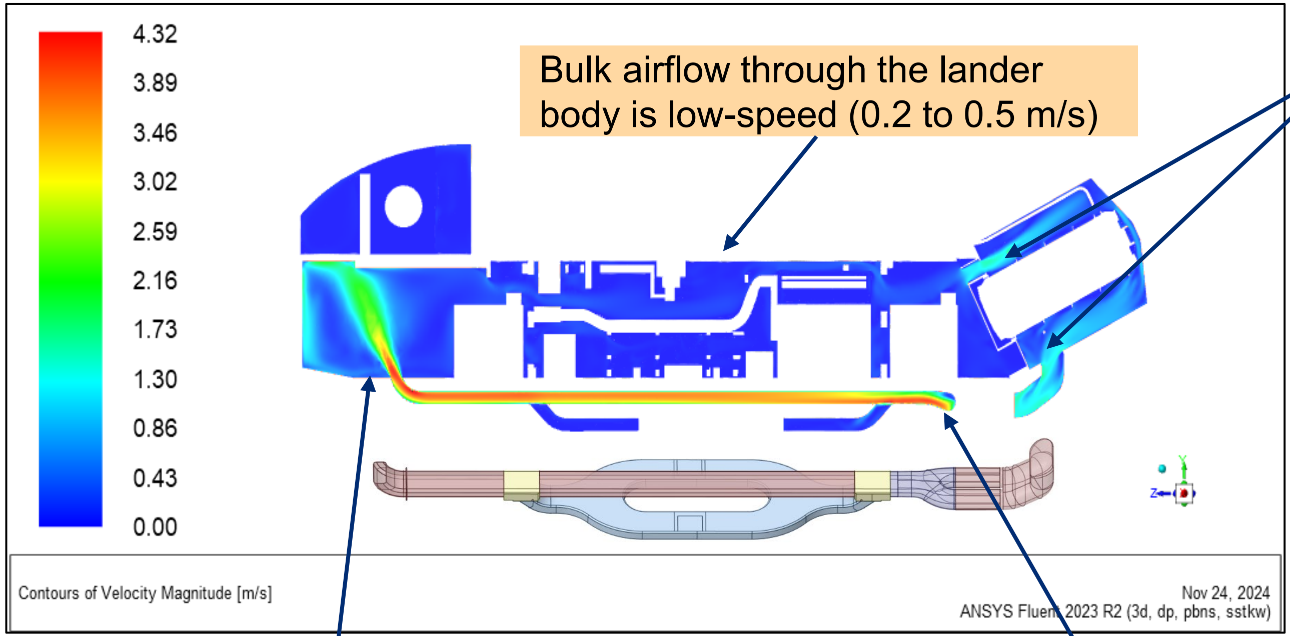
Internal structure and components are highly detailed to simulate **internal flow patterns**



Detailed Internal Features

Cold Hibernation CFD Results

Midplane Air Velocity (m/s)



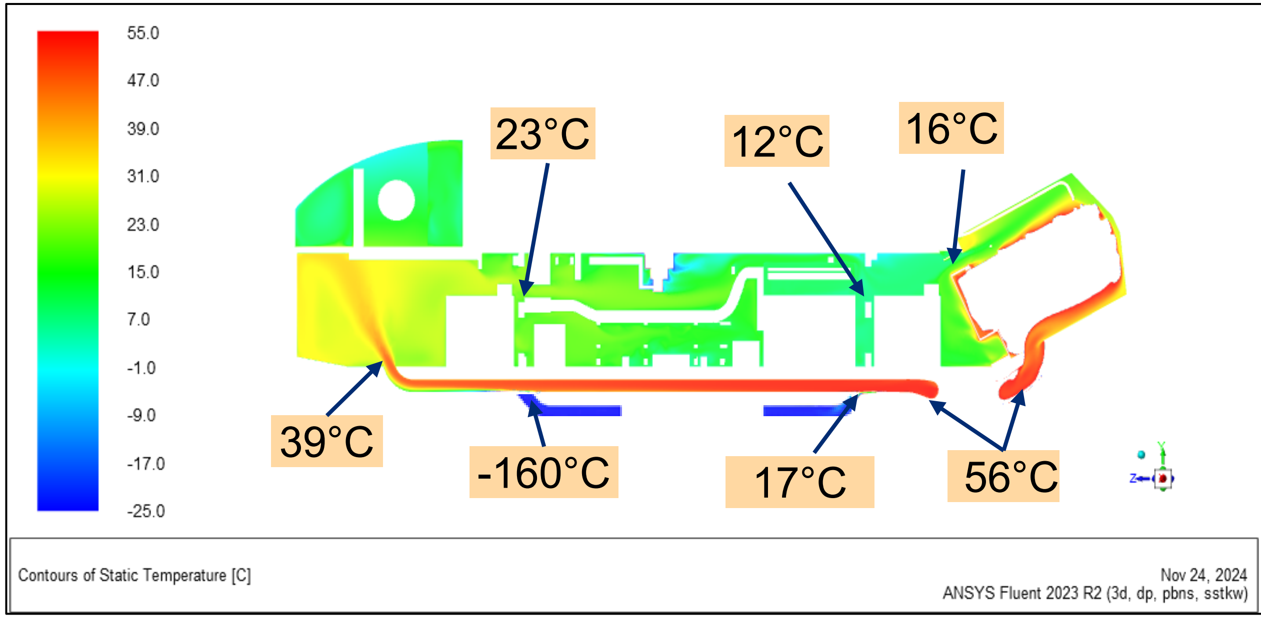
Bulk airflow through the lander body is low-speed (0.2 to 0.5 m/s)

medium-speed airflow (1.3 m/s) enters and exits MMRTG cavity

High-speed airflow enters lander internal volume, circulating near the nose and flowing towards the aft section

fan generates high-speed airflow (3.3 m/s)

Midplane Air Temperature (°C)



23°C

12°C

16°C

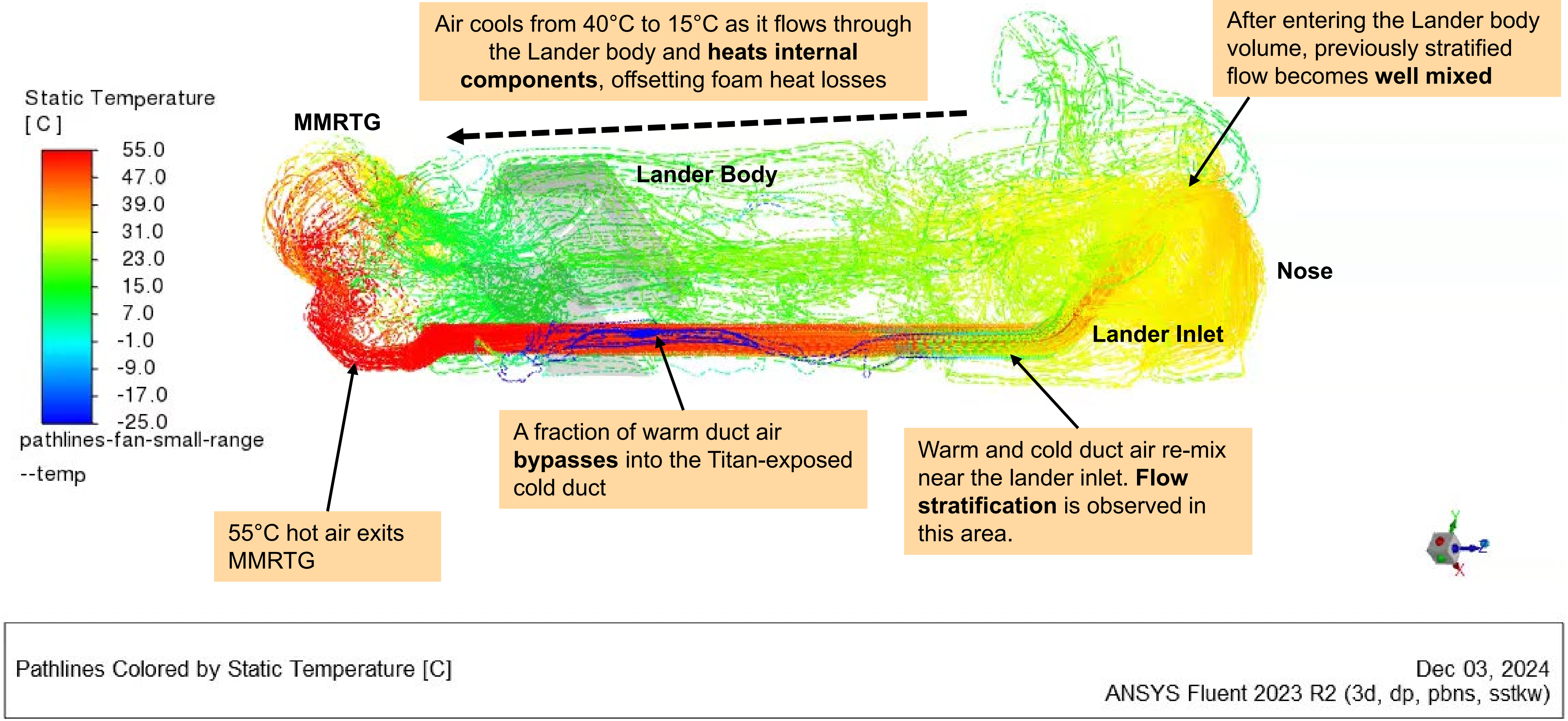
39°C

-160°C

17°C

56°C

Cold Hibernation CFD Results



Air cools from 40°C to 15°C as it flows through the Lander body and **heats internal components**, offsetting foam heat losses

After entering the Lander body volume, previously stratified flow becomes **well mixed**

55°C hot air exits MMRTG

A fraction of warm duct air **bypasses** into the Titan-exposed cold duct

Warm and cold duct air re-mix near the lander inlet. **Flow stratification** is observed in this area.

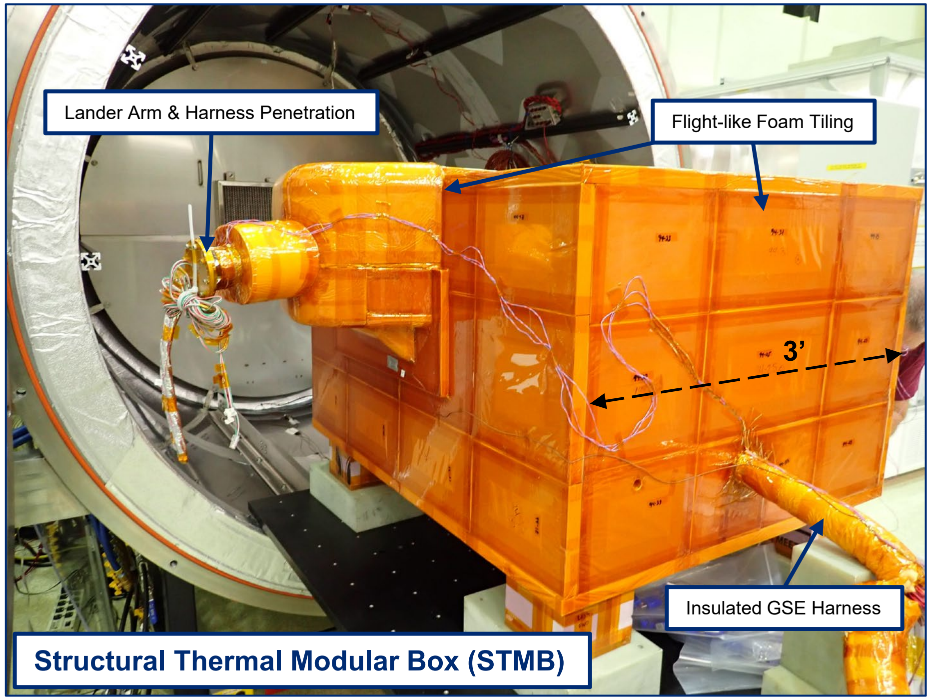
Pathlines Colored by Static Temperature [C]

Dec 03, 2024
ANSYS Fluent 2023 R2 (3d, dp, pbns, sstkw)

Analysis Uncertainty & Design Closure

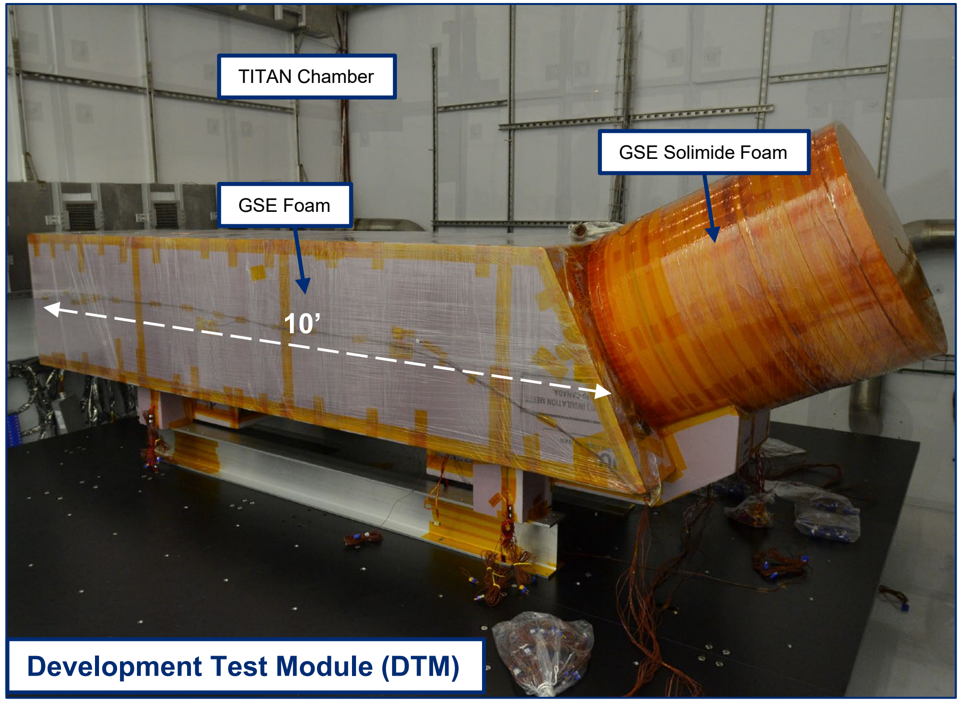
- **What about analysis uncertainty?**
  - On prior space missions, APL thermal has budgeted 10°C towards analysis uncertainty
  - Pathfinder test correlation & analysis have indicated that this is insufficient for Dragonfly at this stage of the program
  - Budget **increased to 20°C** at recommendation of thermal analysis team, with a plan to burn-down uncertainty through upcoming testing campaigns
- **Does this design still close?**
  - Majority of components and cases **close within acceptable margins**
  - At Lander CDR, a few concern areas remained, with closure plans identified:
    - Pre-launch internal component temperatures (MMRTG inside thermos bottle in Earth environment)
    - TWTA overheating during 2 hour EDL transient (loss of heat pipe functionality in EDL acceleration environment)
    - Foam peak temperatures during EDL (low margin to adhesive/material limits due to low thermal mass)
    - Flight case margins (3 kW internal dissipation for 20 minutes heats system significantly)

Testing Platforms: Modular Box & Development Test Module

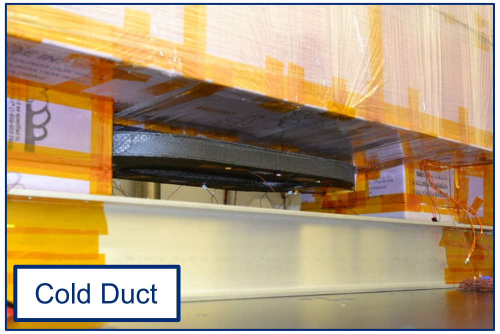


Structural Thermal Modular Box (STMB)

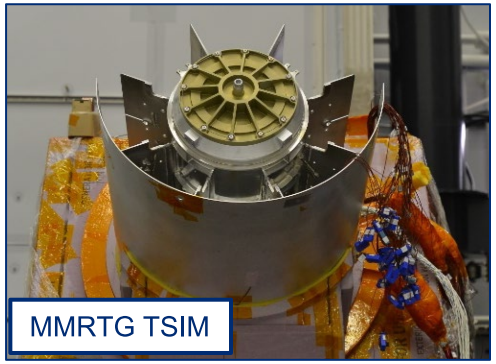
- Simulates insulated segment of internal lander volume using flight-like foam layup to supports heat leak and thermal balance testing
- Typical test flow: Heat leak → Vibe → Heat leak
- *Pictured above: Lander arm, EDL cover, and rotor motor cable STMB test entering Titan pressure thermal chamber (TPEC) at APL*



Development Test Module (DTM)



Cold Duct



MMRTG TSIM

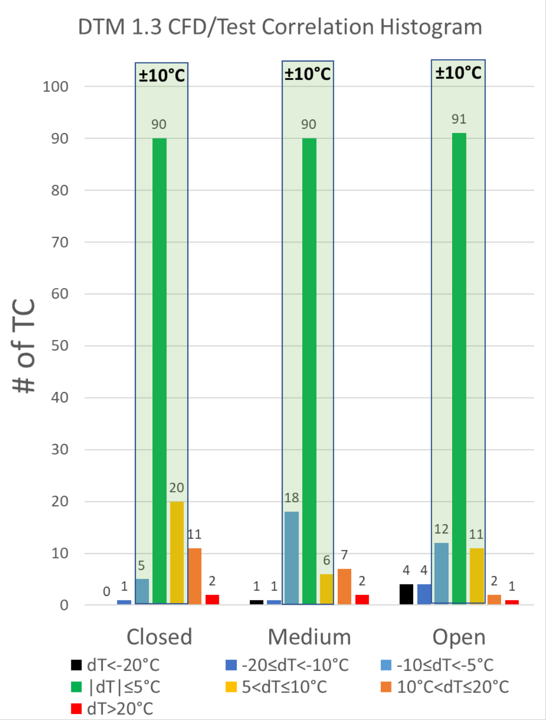
- Full scale, system level lander thermal testbed to support internal airflow characterization, external heat loss measurement, and system-level thermal testing
- DTM 1.0 campaign largely used non-flight foam (pictured above); 2.0 campaign will use flight like tiled Solimide 16 foam.
- Preliminary TCS performance has been demonstrated as of DTM 1.3
- *Pictured above: DTM 1.3 prior to testing in TITAN chamber at APL showing non-flight foam, flight-like Cold Duct, and Flight-like TSIM heat source*

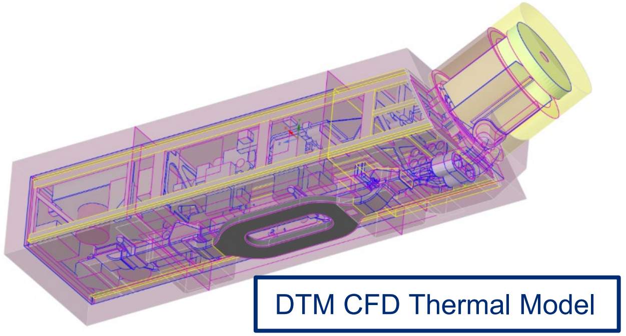
Correlation Summary & Lessons Learned

- **DTM 1.3 Campaign – Pathfinder Correlation**
  - CFD and TD both undertook pathfinder correlation efforts for ~15 test cases run during the DTM 1.3 campaign. Both correlations achieved good results across varying diverter position, TSIM power, ambient pressure, and fan speed.

Key Lessons Learned

- Convection and steep gradients significantly increase uncertainty and modeling complexity
- CFD correlations are both easier and harder: fewer correlation parameters that can be tuned (unlike TD)
- GSE foam performance is variable and adds unnecessary complexity
- High speed chamber flow simplifies external convection assumptions (system becomes insensitive to h_{ext}
- Flow stratification is present in the cold duct and even at the lander inlet
- System sensitivity to h_{int} is low (foam is the choke point)





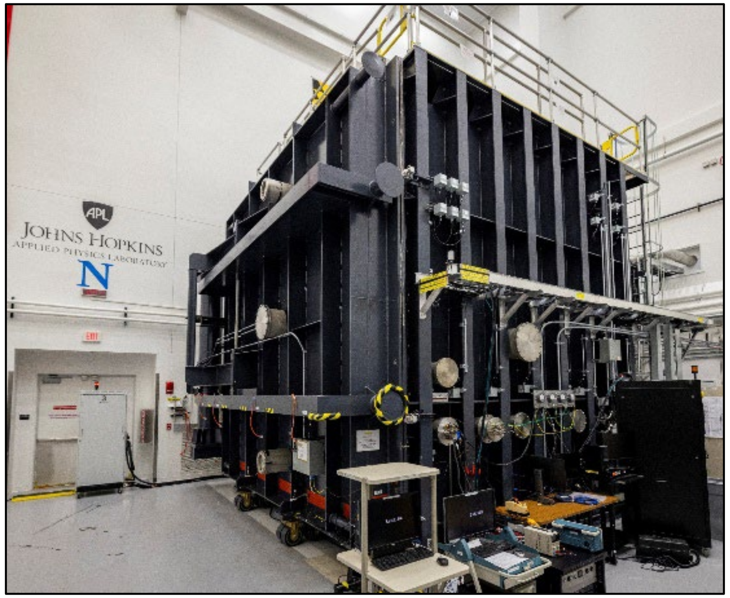
DTM CFD Thermal Model

Test-as-you-fly Exceptions for Dragonfly

- While Dragonfly uses custom-built environment chambers to achieve the most flight-like environment possible, some unavoidable exceptions remain.

TAYF Exception	Impact
Earth gravity vs. Titan surface gravity (1/7th g)	Natural convection on Earth will be higher than on Titan and non-conservative for the hot case. TITAN chamber can be operated at 0.5 atm to compensate.
Pressure differences in TITAN chamber (0.5 to 0.92 atm vs 1.5 atm on Titan)	Internal mass flow and forced convection couplings are scaled down due to pressure impact. Fan speed may be adjusted to compensate.
No powered flight inside the chamber	Slow speed rotor spinning is planned; system expected to be insensitive to external convection above a certain wind speed
EDL thermal profile (peak heating + heatshield separation) at system level	Fully integrated system will not be subject to EDL thermal profile including peak heating (near vacuum) and heatshield separation (1.2 atm). Component level TVAC and thermal shock testing are planned.

Flight predictions rely on a test-correlated model.
Model correlation is essential to bridge the gap between testing and flight environments!



Titan chamber
Dimensions: 15’x15’x15’
Minimum Temperature: -180°C
Pressure Range: 0.5 – 0.92 atm

Overall Lessons Learned

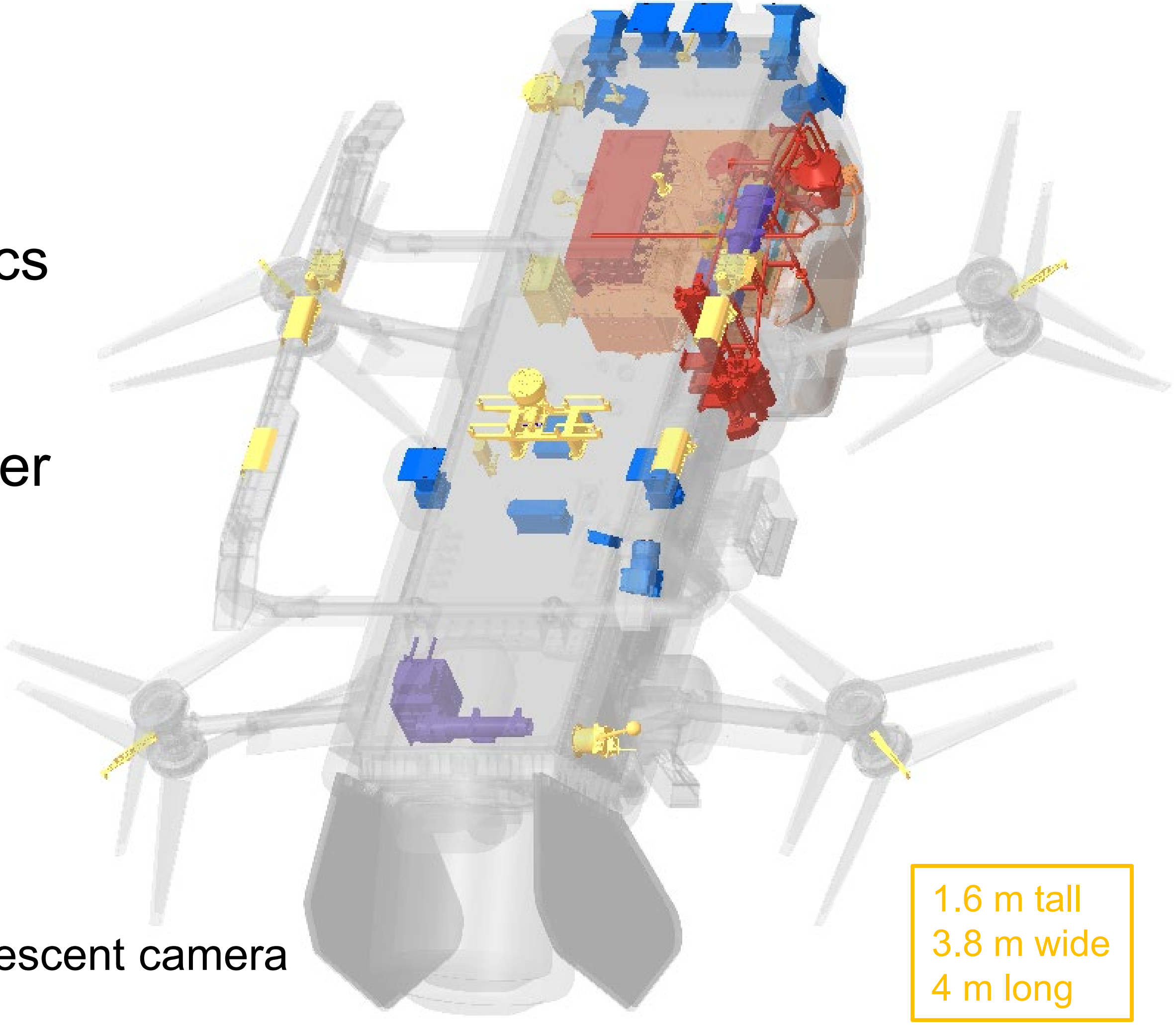
- Standard industry practices and assumptions often do not apply – **a heritage mindset is not going to work** for this mission!
  - Design approaches, analysis uncertainty, testing philosophies…
  - The thermal engineer must fall back on first principles to figure out what the right thing to do is.
- Design for the **primary modes of heat transfer** in a given environment.
  - Put your convection hat on! A proper mental model requires this. Do not ignore convection for convenience or conservatism. Extreme conservatism is not a design enabler.
- **Engage with CFD as soon as possible** to avoid going down the wrong design path.
  - Late changes yield sub-optimal implementations, for example the cold duct shape and location (highly constrained by preexisting hardware.)
- Find a **robust method to absorb key uncertainties.**
  - PDR design had limited heat rejection capability. Cold duct dramatically increased capability and absorbs possible foam performance variations.
- **Foam is a major challenge** and is not like MLI.
  - Cannot underestimate how difficult a flight design is, which is constrained by multiple stakeholders: structural, thermal, contamination, systems (mass). A robust development effort is needed to drive design to closure. Selecting the right material is key.
- Push for **wide hardware capability envelopes** early in the design phase
  - Pays dividends later on when system resource budgets are thin and eliminates problems before they happen.
- When in uncharted territory, **ask for help** and be honest about issues.
  - Lander thermal has reached out for help across institutions: thermal advisory board was stood up to provide expert feedback.
  - Thermal team recognized insufficient analysis uncertainty budget and raised flag at CDR.

DRAGONFLY

Backup

Multidisciplinary Science Measurements

- **DraMS**: Mass Spectrometer
  - GSFC – MSL SAM, ExoMars MOMA
- **DrACO**: Drill for Acquisition of Complex Organics
  - Honeybee Robotics
- **DraGNS**: Gamma-ray and Neutron Spectrometer
  - APL, LLNL – *MESSENGER* GRNS, *Psyche* GRNS
- **DraGMet**: Geophysics & Meteorology Package
  - APL sensor suite + JAXA *Lunar-A* seismometer
- **DragonCam**: Camera Suite
  - MSSS – *OSIRIS-REx* ECAM, *MSL* Mastcam, *Mars 2020* descent camera

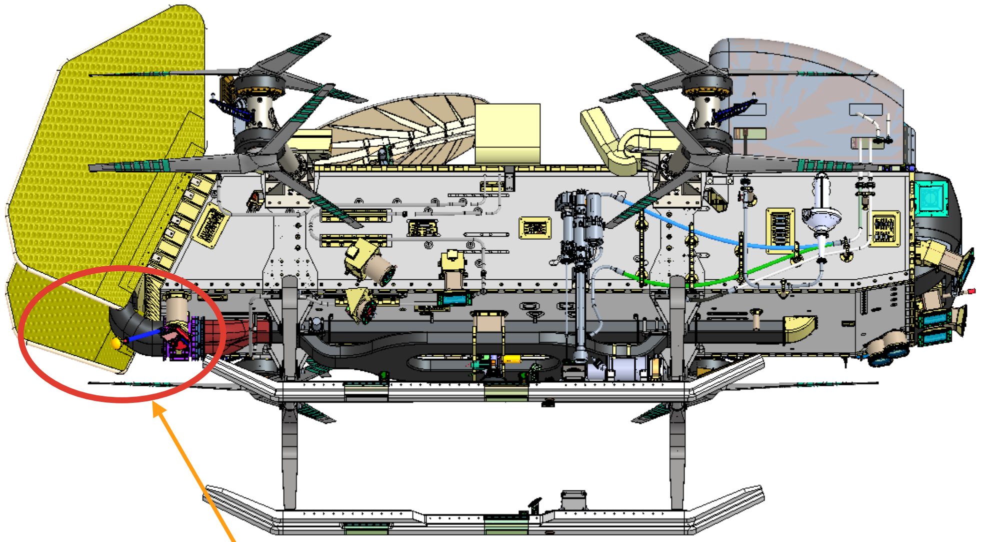


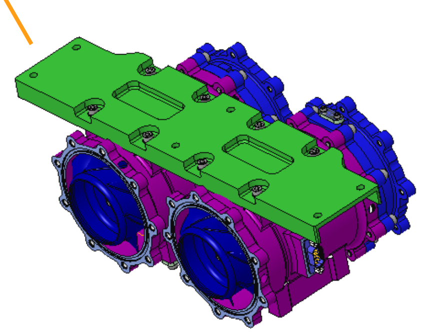
1.6 m tall
3.8 m wide
4 m long

Thermal Hardware

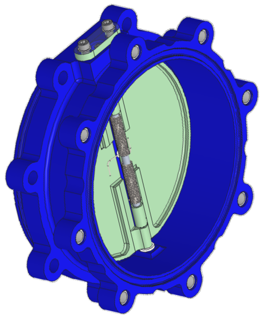
Lander Fan Assembly

- **The fan assembly is used to circulate the air and distribute the heat from MMRTG to the lander body**
  - Includes 2 fans and 2 check valves with redundancy
  - Nominal flow rate on Titan surface: 50 CFM, max flowrate 60 CFM, plus 25% margin
- **MMRTG fin root temperature during Titan surface hibernations is controlled by adjusting the lander fan speed (mass flow rate)**
  - A reduction of 1 CFM flow rate leads to a 1.3 °C rise in average fin root temperature, estimated nominal fan flow rate during Titan surface hibernation ~50CFM





Fan Package



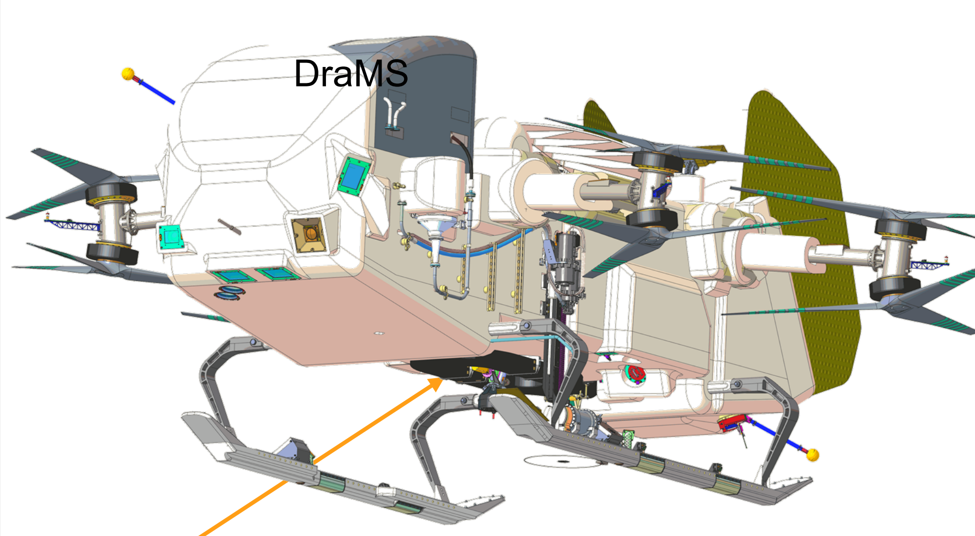
Check Valve

Thermal Hardware

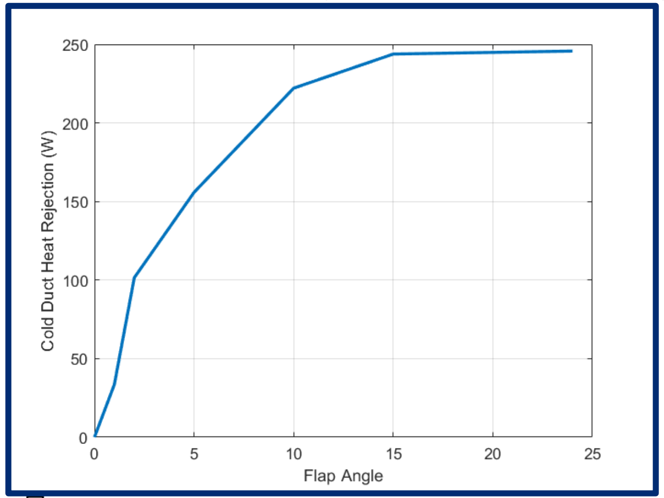
Cold Duct Trim

Split Cold Duct Thermal Trim capable of 1000 W heat rejection from the lander to Titan ambient environment

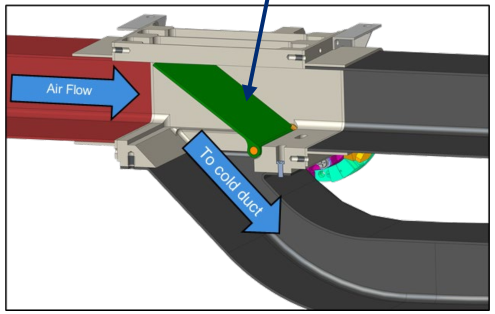
- Designed to accommodate Titan surface hot cases including DraMS operations
- Use the Thermal Trim Device (TTD) forward and aft diverters to control air flow to the cold duct for heat rejection to ambient environment
- DTM Testing Phase 1.3 validated the prototype split cold duct heat rejection capability and prototype TTD control



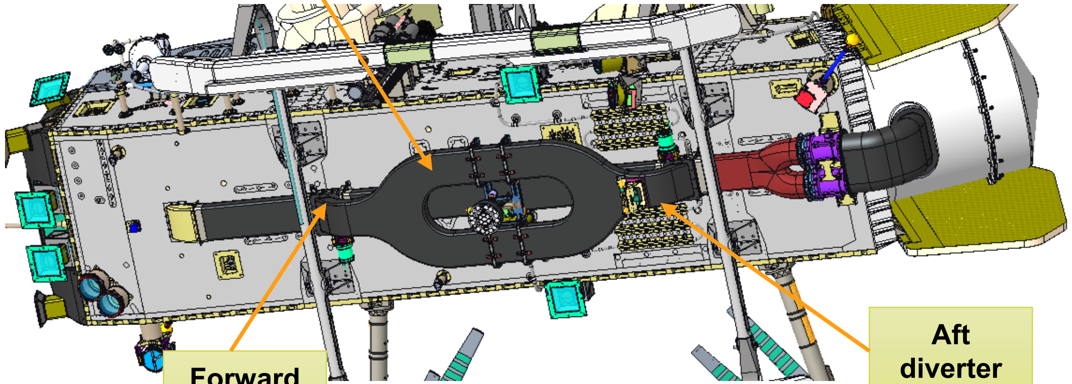
DTM Cold duct heat rejection vs. diverter angles



TTD Diverter



Split cold duct trim (outside the foam)



Forward diverter

Aft diverter