Conjugate Heat Transfer Thermal Analysis: Computational Fluid Dynamics (CFD) Correlation of the Thermal Development Test Module (DTM) for Dragonfly Lander

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Agenda

This presentation aims to discuss the thermal CFD correlation and testing efforts for the Thermal Development Test Module (DTM), a full-scale thermal testing article of Dragonfly lander, to validate its thermal control design and performance

- **Dragonfly Mission**
  - Titan Thermal Environment
  - Dragonfly Thermal Design Requirements
  - Dragonfly Thermal Control Design
- **DTM**
  - Objectives
  - Titan Chamber Testing
  - CFD Correlation Effort
- **CFD Modeling**
  - Current DTM CFD Model
  - Cold-Duct Trim CFD
- **Future Work & Conclusions**

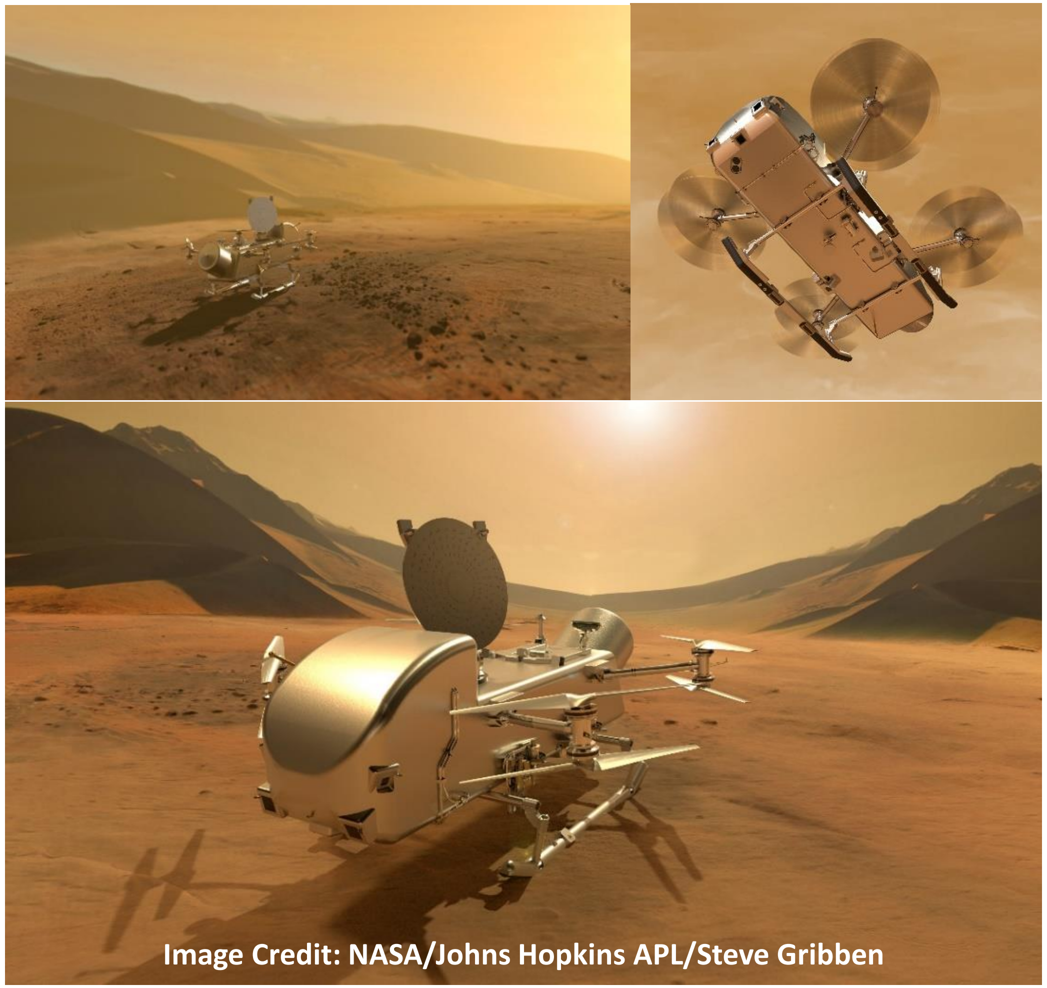
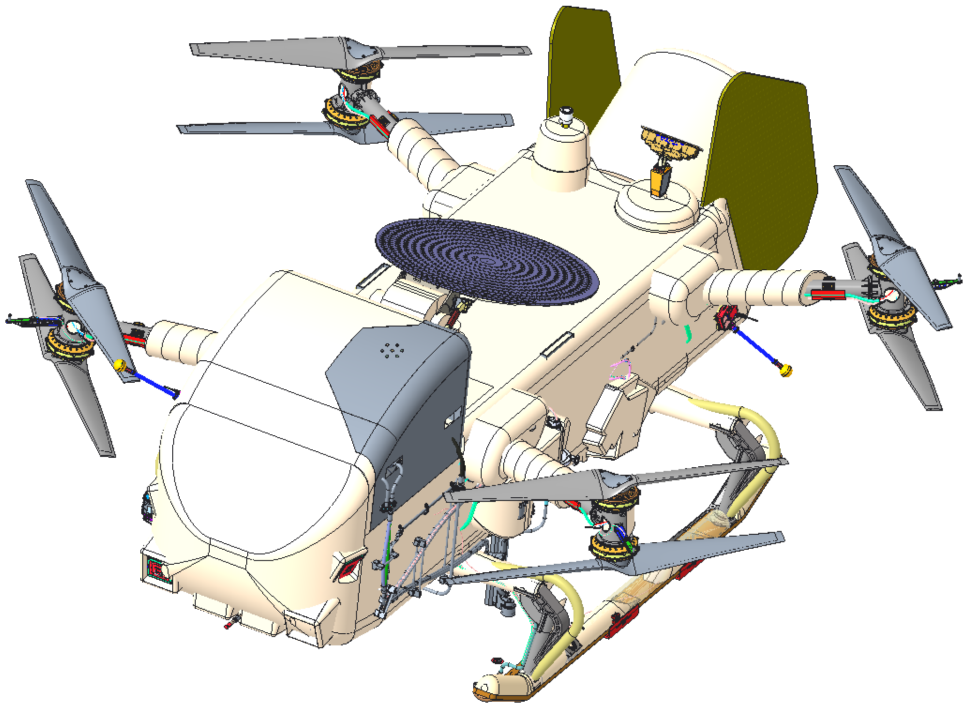


Image Credit: NASA/Johns Hopkins APL/Steve Gribben

Dragonfly Mission

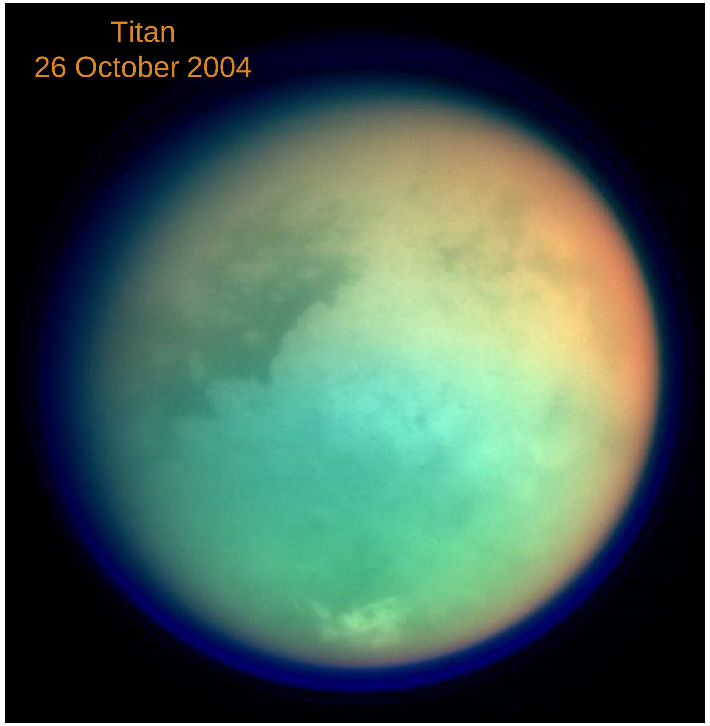
- Rotorcraft designed to fly and explore Saturn's moon, **Titan**
- Multi-year (~3 year) science mission duration
- Part of NASA's New Frontiers Program
- Mission aims to gather scientific data on Titan's pre-biological chemistry and surface properties
- Focus on survivability over a long duration
- Thermal design challenges & requirements
  - Titan atmosphere presents unique thermal challenges compared to scenarios on Earth
  - Heat transfer analysis critical to ensure survivability and success across the entire scientific mission on Titan
  - Ensure operational components maintain safe temperatures for the entire duration of mission



Dragonfly Flight Lander

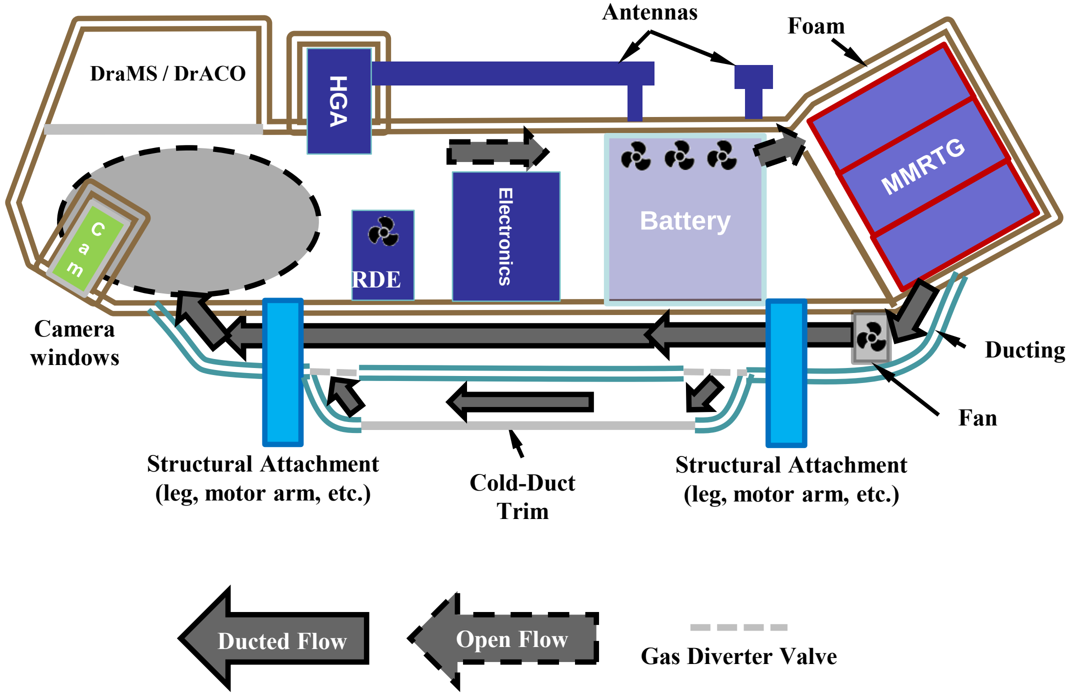
Titan Thermal Environment

- Surface Atmospheric Temperature: **94K ~ –180° C**
  - Temperature is fairly stable with little diurnal/seasonal variation
  - Mostly nitrogen atmosphere with small chance of methane rain
  - Atmospheric wind conditions are typically < 1 m/s
- Surface Gravity: **0.14g ~ 1.352 m/s^2**
  - 1/7th Earth gravity
- Surface Atmospheric Pressure: **146 kPa ~ 1.5 atm.**
  - ~1.5 times Earth atmospheric pressure (101 kPa ~ 1.0 atm.)
- Surface Atmospheric Density: **5.44 kg/m^3**
  - ~4.5 times Earth atmospheric density (1.225 kg/m^3)
- Thick, cold atmosphere poses unique thermal challenge
  - Relatively thick atmosphere results in significant convection
  - Convective heat transfer performance at such conditions not observed on Earth



Dragonfly Lander Thermal System

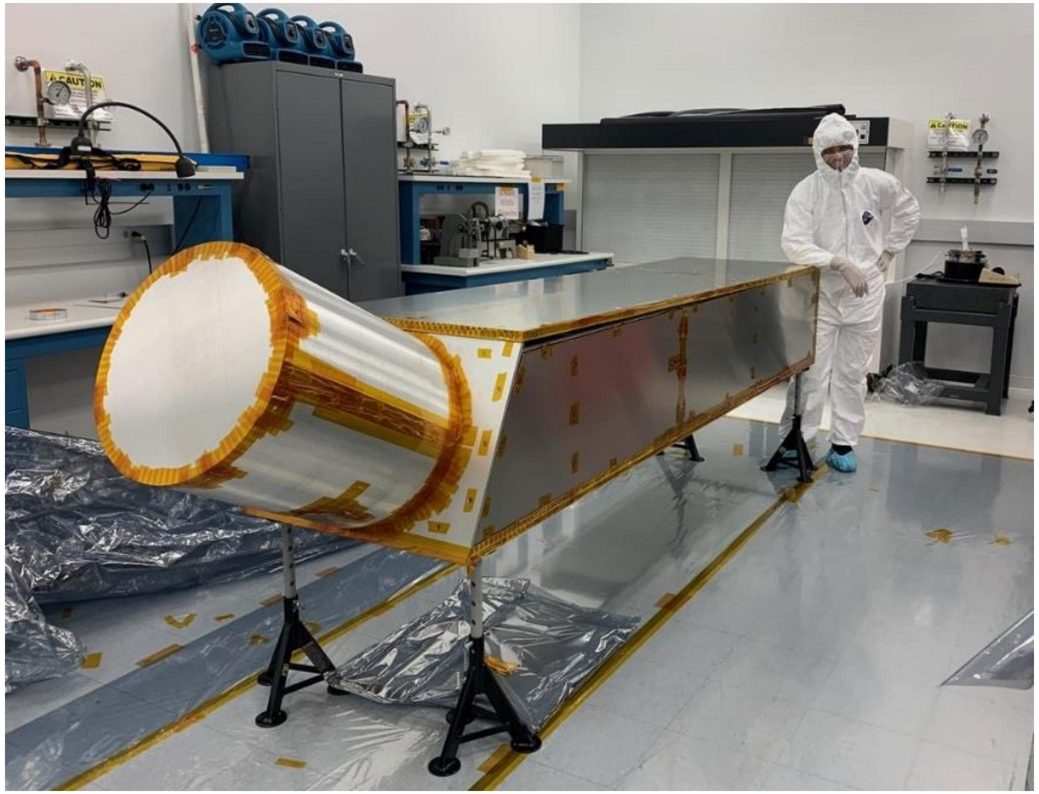
- The Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) is the heart of Dragonfly
  - Powers the Lander and the Flight System
  - Radioactive power source generates ~ 2 kW of precious "waste" heat
  - Battery and other electronics also produce excess heat during operation
- Fan with ducting distributes MMRTG heat to the rest of the Lander
  - Convection takes heat away from the MMRTG to control its fin root temperature
  - The heat distributed throughout the Lander keeps internal components warm in the Titan's cold environment



- Lander temperatures are controlled with cold-duct trim while on Titan surface
  - The battery has tight temperature limits, which constrains the Lander thermal performance
  - The MMRTG temperature must be controlled within a tight tolerance to maximize its electrical power generation
  - Diverter valves, located fore and aft of the Lander cold-duct, shunt warm outflow gas from the MMRTG through the bypass duct which cycles back into the Lander cavity
  - Combined thermal fan and cold-duct system used to maintain Lander internal temperature in response to changes in external and internal conditions

Thermal Development Test Module (DTM)

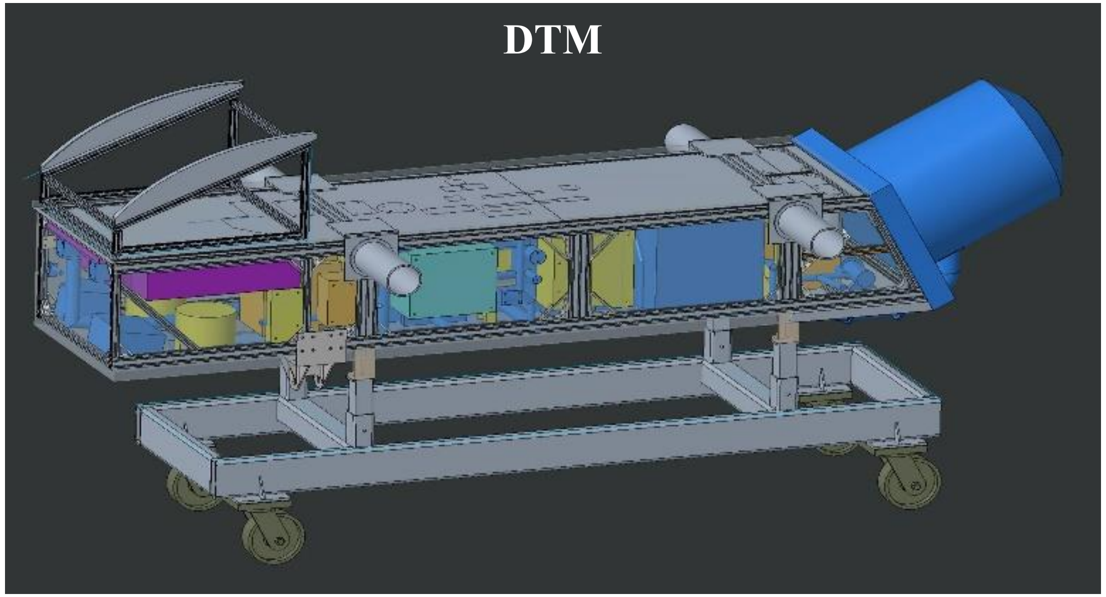
- DTM is a full-scale flight-like platform which will provide verification of component thermal performance, internal flow, and heat leaks
  - Aluminum honeycomb panel outer body
  - 80-20 internal structure
  - Foam attachment (Polystyrene)
  - Fan and ducting
  - Cold-duct trim and valves
  - Heater with fins for MMRTG representative
  - Simulated battery, RDE, and other modular boxes inside consisting of sheet metal or 3D-printed Ultem 9085 parts
  - DraMS representative, harness representatives, and nose will be added for next phase test



DTM Assembly with Outer Honeycomb Panels Visible (courtesy Johns Hopkins APL)

Thermal Development Test Module (DTM)

- DTM Experimental Test Goals
  - Full-scale correlation using a CFD modeling approach
  - Pressure test and fan power verification
  - Heat leak verifications
  - Thermal cold-duct trim performance
  - Demonstrate foam and sealing methods
  - Lander temperature and air flow verification
- DTM CFD Model - ANSYS Fluent
  - Model parameters adjustable for Titan conditions
  - Verification of lander temperatures, pressures, thermal properties, and air flow
  - Provide fidelity and lessons for full-Lander CFD model



Titan Chamber Validation Testing

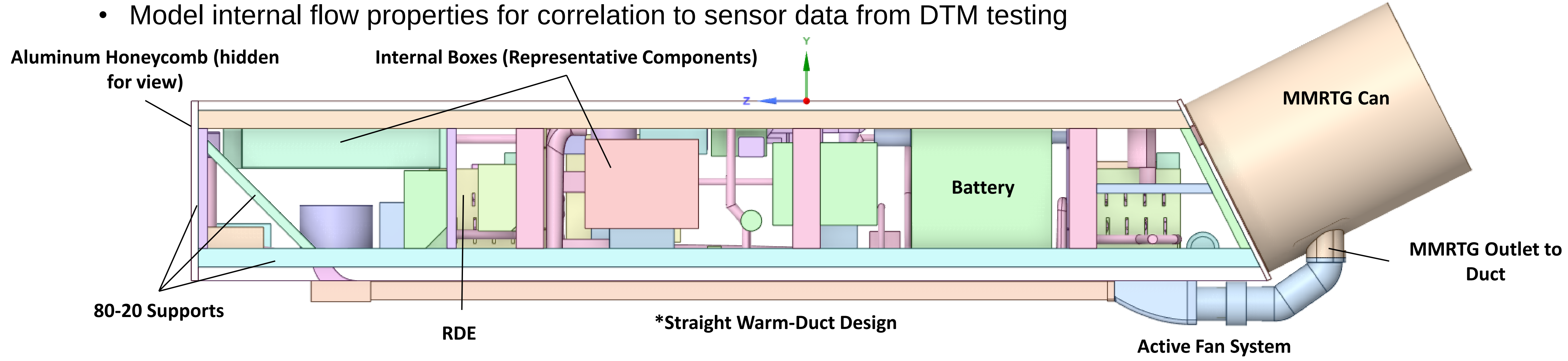
- Titan Chamber Specifications
  - Internal working dimensions: 15 ft. x 15 ft. x 15 ft.
  - Operating temperatures: –180° C to + 150° C
  - Operating pressures: 0.3 – 1.0 atm.
  - Nitrogen (N_2) operating environment
- DTM will be tested in the Titan Chamber starting in September 2023
- Titan Chamber will allow for the entire flight Lander to be tested in cryogenic Titan-simulated environment
  - 0.5 atm. on Earth provides equivalent natural convection as on Titan
  - Titan Chamber DTM tests will be run concurrently with the CFD modeling for correlation and validation purposes

Titan Chamber (courtesy Johns Hopkins APL)

Titan Chamber Internal View (courtesy Johns Hopkins APL)

DTM CAD Setup

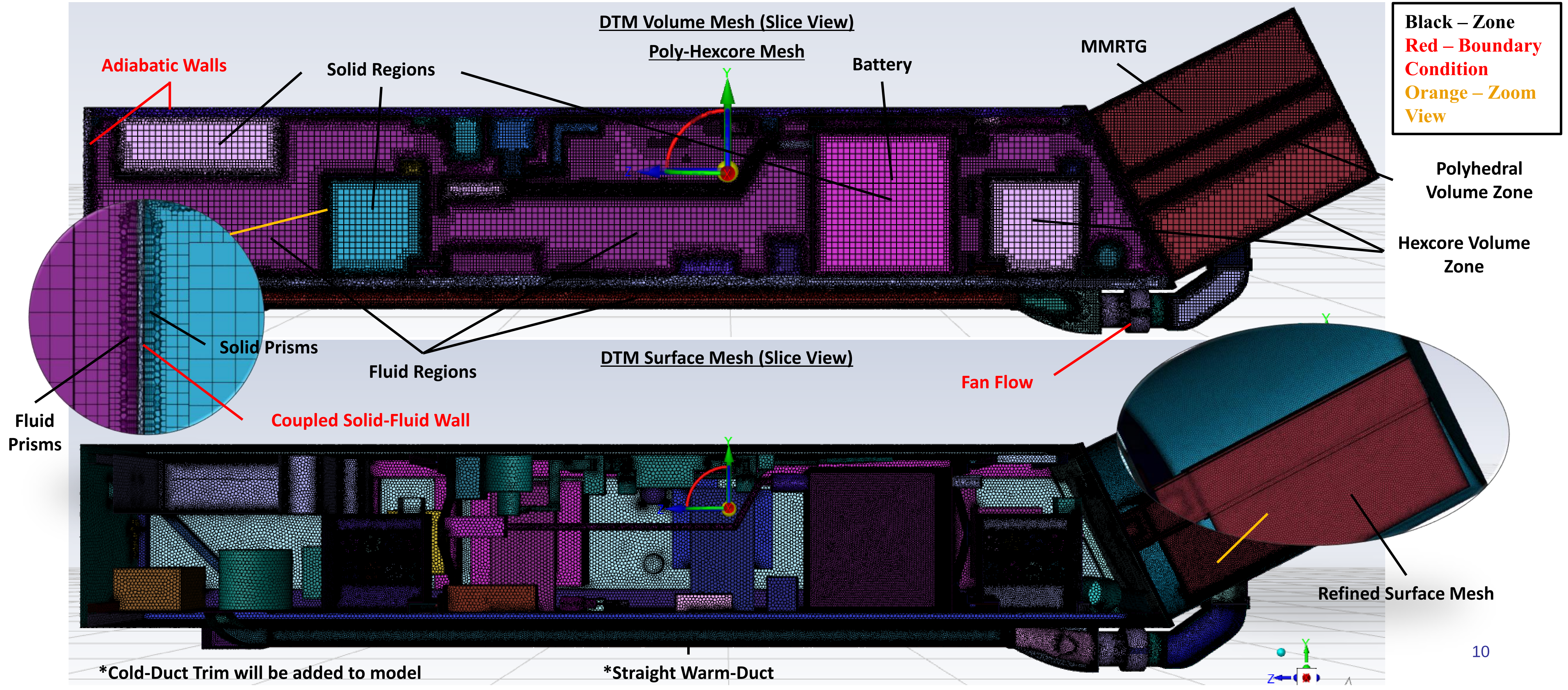
- **ANSYS SpaceClaim and Fluent used for CFD workflow**
  - Geometry cleanup upon delivery of each DTM model update
    - Close gaps, fix holes, simplify components, establish boundary conditions
  - Make DTM model modular to replace/remove assets as needed based on status from the development team
  - Extract internal volumes to properly model solid conduction and internal fluid flow for component convection
  - Share topology among solid-fluid boundaries to enable conformal mesh and coupled-wall thermal solution
  - Multi-objective process
    - Model thermal heat leaks via conduction and convection to inform overall thermal performance
    - Model internal flow properties for correlation to sensor data from DTM testing



*Cold-Duct Trim will be added to model

DTM CFD Mesh

- ANSYS Fluent poly-hexcore meshing scheme used with prism growth on solid-fluid layer coupled interface
- ~24 million cells for internal DTM zones and all solid volumes



DTM CFD Setup

- Boundary Conditions
  - Initial case considers all outer boundaries of DTM to be adiabatic
  - Eventually add ambient fluid zone surrounding DTM and enable coupled-wall thermal solid-fluid convective transfer to ambient zone
  - Model Titan Chamber ambient conditions for further testing scenarios
- Modeling
  - Turbulence model: k-ω-SST
  - Energy equation enabled for thermal solution
  - Ideal gas assumption
- DTM Zone Breakdown
  - Internal bodies modeled as solid zones with conduction and coupled-wall thermal solid-fluid convective transfer enabled
  - Internal cavities of DTM modeled as fluid zones to determine internal flow conditions
    - Desired pressure drop, internal temperatures, flow rates, fan power, convective coefficients, heat flux across all boundaries

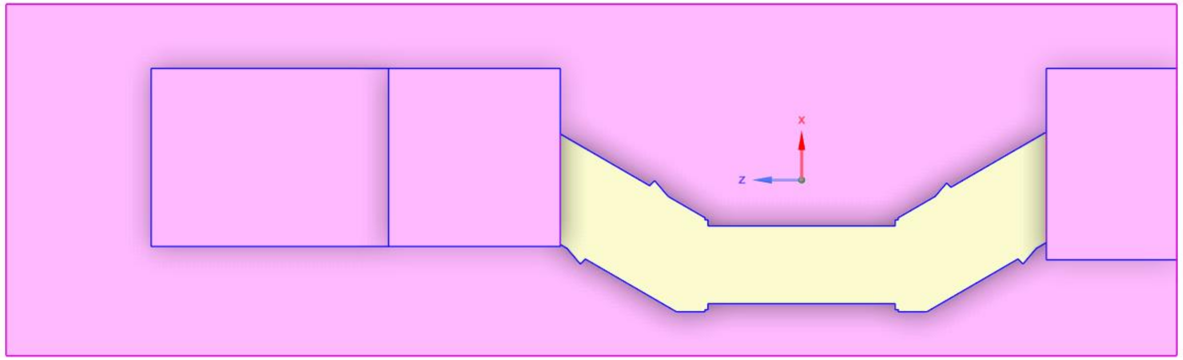
DTM CFD Correlation Effort

- Thermal overview to be obtained through CFD correlations offers insights
  - Air flow rates and pressure drops
  - Convective flow properties
  - Heat transfer rates
  - Internal temperatures
- Critical for the subsequent design and testing phases
  - Provide insights to the Dragonfly Lander team on effective thermal design optimization considerations
  - Model results to provide verification of testing and performance
- DTM experimental test correlation
  - DTM will be tested in both ambient Earth conditions and the Titan Chamber
  - CFD modelling will be used for all future validation efforts
  - Compare analytical data with experimental data to determine accuracy and consistencies
  - Update the team to necessary changes to either the model or testing plan moving forward

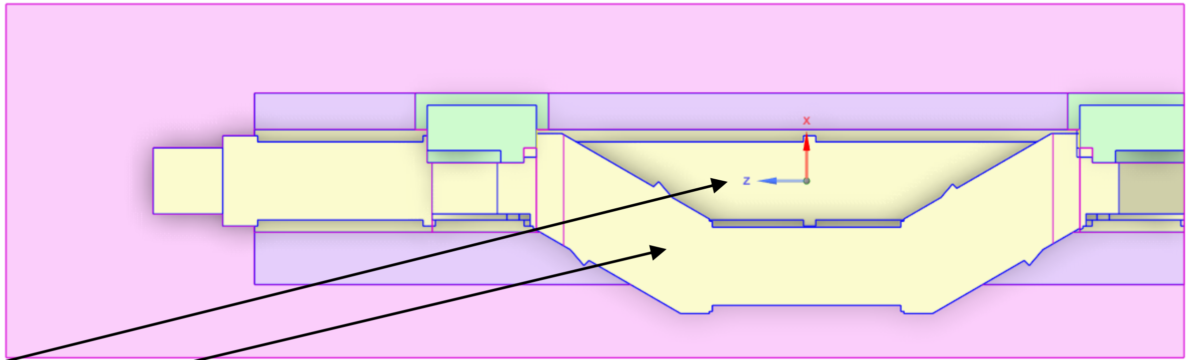
Status: CFD is currently within the preliminary development stage, and runs are presently underway with the current iteration of DTM model

Cold-Duct Trim CFD

- DTM will deploy a warm-cold-duct combination with fan-forced flow and an actively-controlled flapper to divide airflow
- Upper warm-duct will have foam insulation; lower cold-duct will have no foam and be exposed to cold Titan temperatures
- **Objective:** Determine heat rejection from the DTM cold-duct: Currently using 3D-printed Ultem 9085
  - Standalone duct-only case excluding DTM or lander volume
  - Assumptions made for duct inlet and surrounding conditions based on prior CFD cases at Titan conditions
  - Preliminary CFD to understand the thermal effectiveness of the duct design to validate with DTM testing



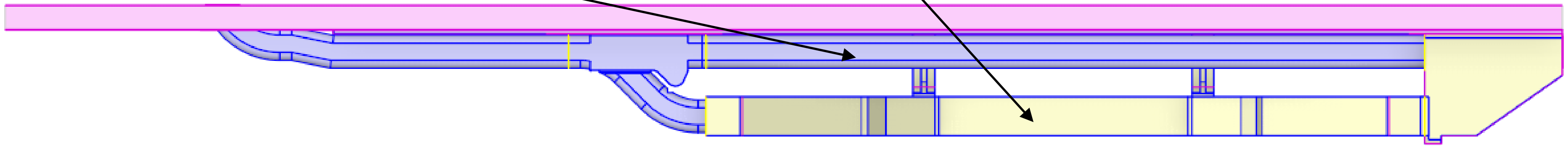
Cold Duct DTM Design (Foam Insulation Shown)



Cold Duct DTM Design (Foam Insulation Hidden)

Cold Duct (Ultem 9085)

Warm Duct (Ultem 9085)



Cold Duct DTM Design (Foam Insulation Hidden)

Status: Modeling is in progress; cold-duct will be added to the DTM model

DTM Future Testing and Correlation

- Extensive Titan Chamber thermal testing scheduled for DTM to answer a multitude of questions regarding the lander thermal design
  - Cold-duct trim heat rejection capacity
  - Lander insulation and sealing: Installation and repeatability
  - Lander airflow, pressure drop, and fan power
  - Heat leaks
- DTM CFD Correlation
  - Update CAD with design changes and more components
  - Incorporate the cold-duct trim and external foam
  - Add surrounding ambient fluid zone for Titan Test Chamber
  - Meshing sensitivity study to determine the optimum refinement level
  - Pre-test runs to predict the temperature, airflow, and pressure to guide the test setup
  - After-test correlation to validate CFD fidelity and inform the full-Lander model

Conclusions

- CFD analysis is critical to predict the Dragonfly Lander thermal performance on Titan surface
  - Dragonfly Lander is different from typical spacecraft due to Titan’s convection-dominating thermal environment
- Extensive cold-duct trim modeling and testing ahead
  - Cold-duct trim is essential for Lander thermal control
  - Testing needs to occur at the DTM full-scale level
- DTM thermal models will be validated by upcoming Titan Chamber testing to inform the full-Lander CFD analysis
  - Test early to learn critical lessons and facilitate decision making
  - Uncertainty in the heat leaks will be minimized with continued testing and DTM simulation

Thank You

Questions?

DRAGONFLY

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