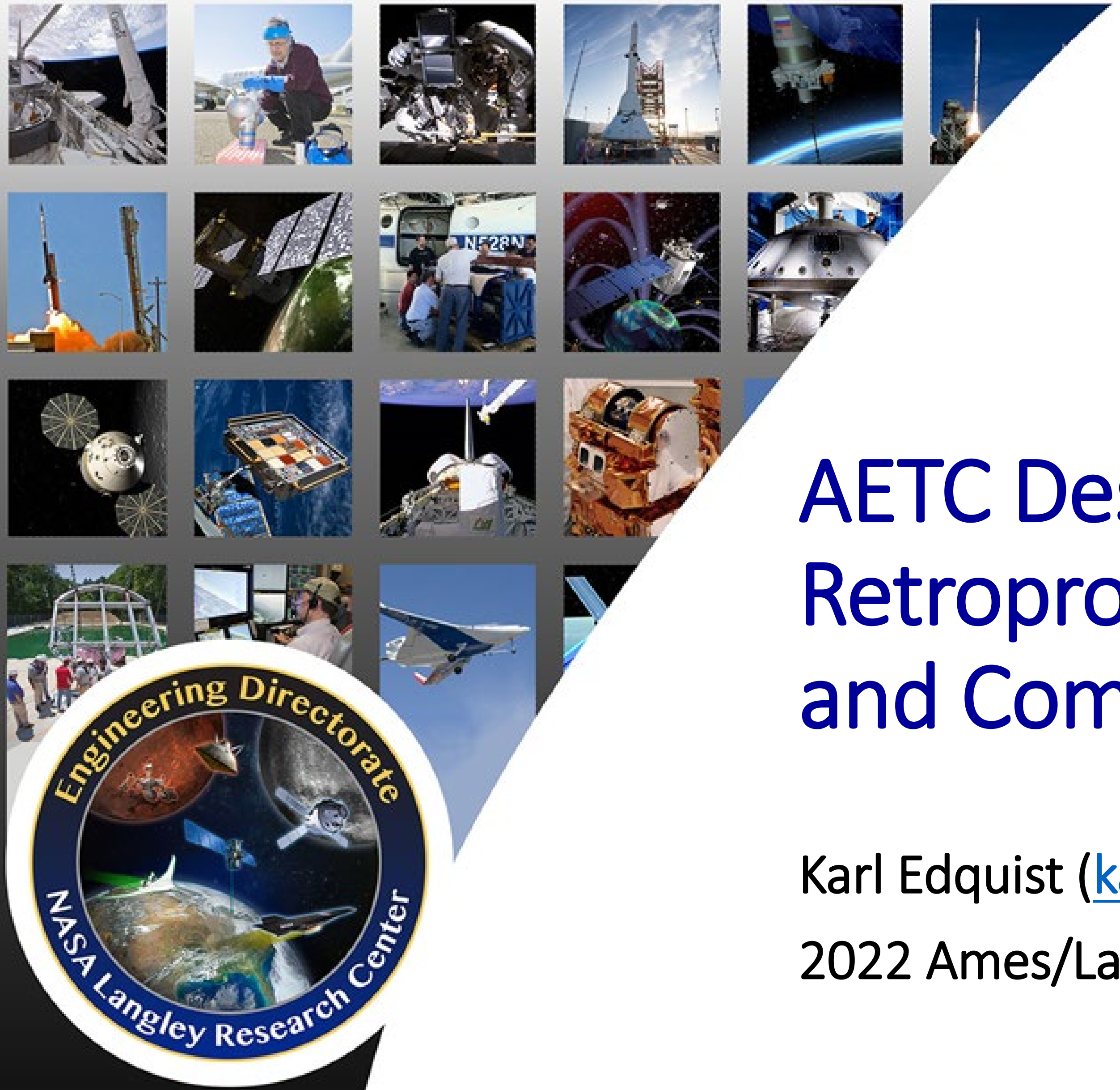


National Aeronautics and Space Administration

AETC Descent Systems Studies (AKA Retropropulsion Wind Tunnel Testing and Computational Flowfield Status)

Karl Edquist (karl.t.edquist@nasa.gov)

2022 Ames/Langley EDL Summer Seminar

11 July 2022

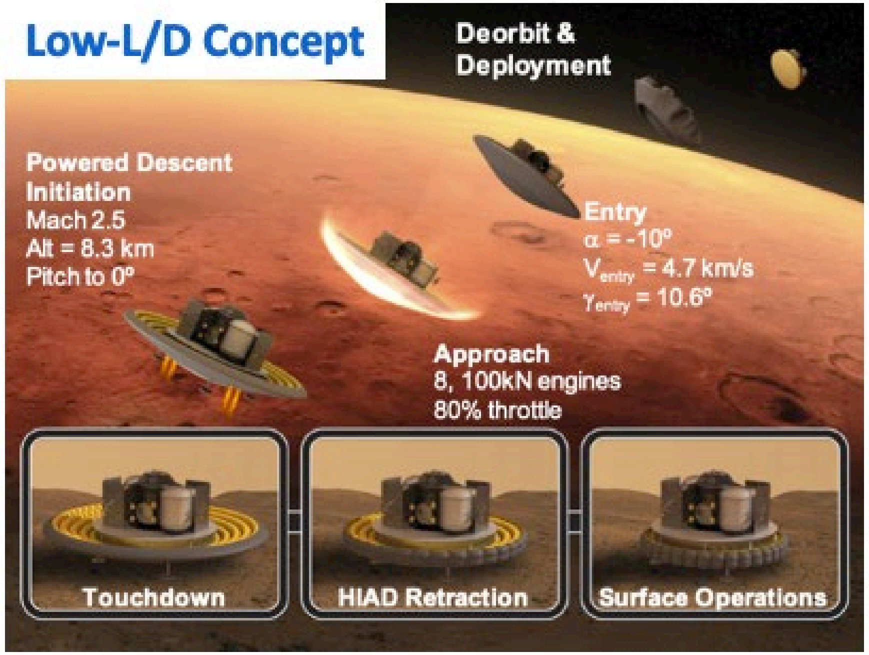
Biography

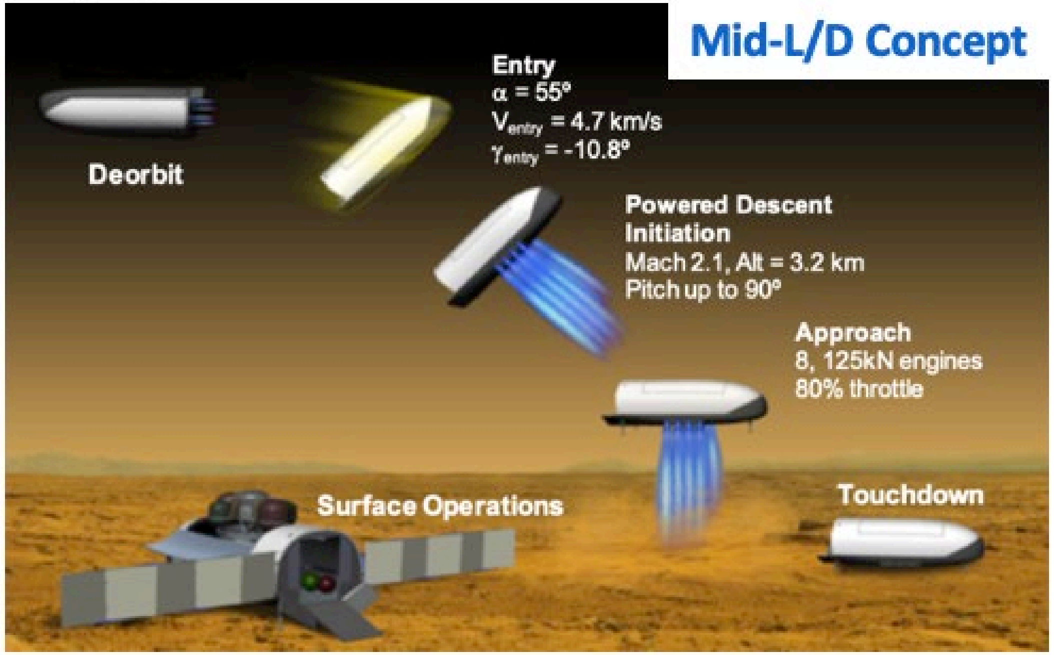
- BS from U. of Colorado and MS from U. of Maryland
- Started at NASA Langley in 2000, duties include aerodynamic/aerothermodynamic analysis/testing for science missions (Science Mission Directorate) and technical ledership of technology development projects (Space Technology Mission Directorate)
- Past science mission roles:
  - Mars Science Laboratory Aerothermal Lead
  - Mars 2020 Aerothermal Lead
  - Mars Phoenix Aerodynamic Lead

- Past technology development project roles:
  - EDL Technology Development Project Supersonic Retropropulsion (SRP) Lead
- Current roles:
  - Dragonfly Deputy EDL Phase Lead
  - Mars Sample Return Sample Retrieval Lander Aerosciences Lead
  - Descent Systems Study (Retropulsion technology development for Mars EDL)

Background & Motivation

- NASA studies show that powered descent starting at supersonic conditions, which has never been done at Mars, is enabling to land human payloads (~20 metric ton payloads) within 50 meters of a target
  - Low-L/D = blunt rigid heatshield surrounded by a Hypersonic Inflatable Aerodynamic Decelerator (HIAD)
  - Mid-L/D = slender rigid aeroshell with body flaps





Edquist, et al, "Model Design and Pre-Test CFD Analysis for a Supersonic Retropropulsion Wind Tunnel Test," AIAA 2020-2230

- Relevant ground test data do not yet exist to determine the computational fluid dynamic (CFD) predictive capabilities for vehicle aerodynamics during powered descent

This presentation discusses the status of testing sub-scale Mars retropropulsion models in the Langley Unitary Plan Wind Tunnel (LUPWT) in 2022

Motivation

- The most challenging aerosciences problem for large-scale Mars entry systems is aerodynamic interference (AI) during powered descent
- NASA's Aerosciences Evaluation and Test Capability (AETC) program established a project to determine whether CFD methods are sufficiently accurate for calculating "challenging" aerosciences problems at "high supersonic" conditions
  - Using the NASA Langley Unitary Plan Wind Tunnel (UPWT)

This presentation discusses the status of an upcoming retropropulsion test in the Langley UPWT and pre-test CFD analysis of Mars retropropulsion concepts

- Current status: The test had been planned to be completed as far back as late 2020, but COVID-19 and facility repair/maintenance delays have pushed the test to start no earlier than Sept. 2022

Outline

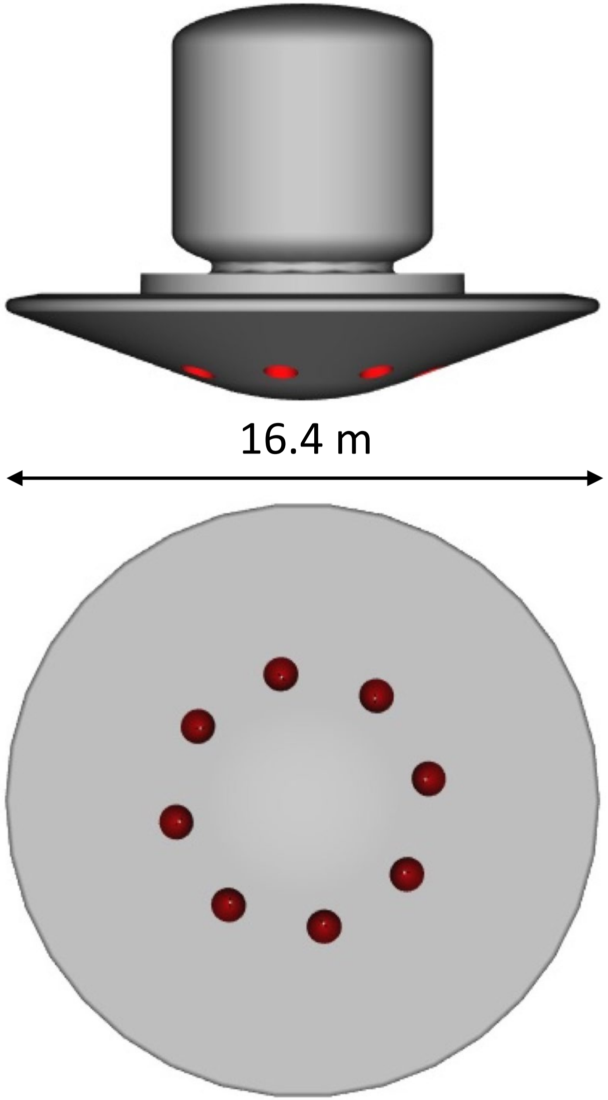
- Reference Vehicles
- Test Facility
- Models & Instrumentation
- CFD Solvers & Sample Results
- Summary & Conclusions

- The wind tunnel test is funded by the Aerosciences Evaluation and Test Capabilities (AETC) office and the CFD is funded by the Space Technology Mission Directorate (STMD) Game Changing Development (GCD) program

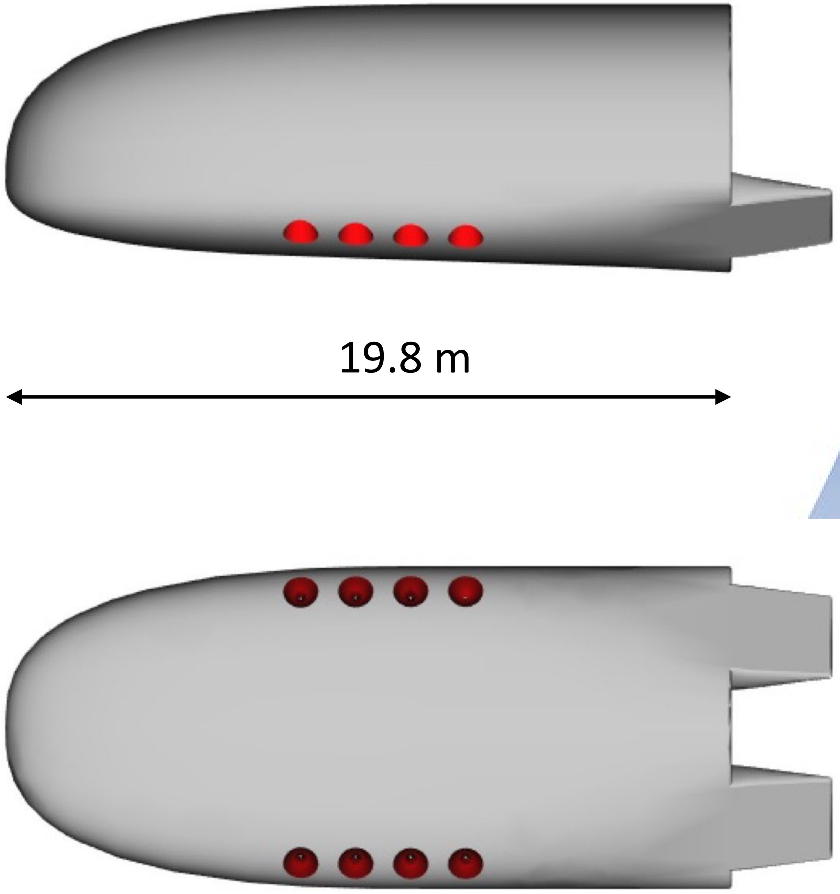
- Presentation is adapted from AIAA Paper 2022-0911 and AIAA Paper 2022-0912

Flight Referenc metric tons at entry)

Low-L/D

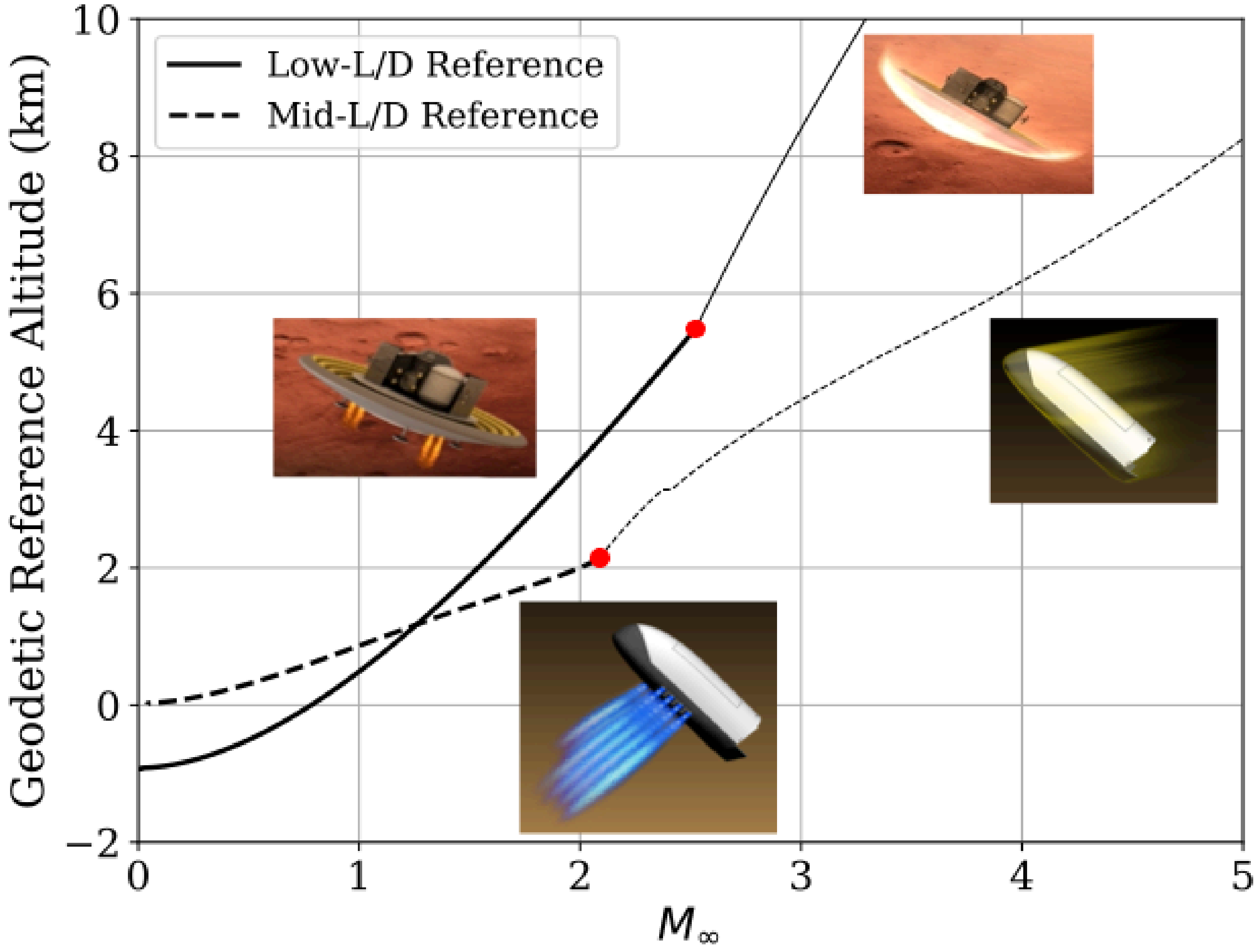


Mid-L/D



Nominal Reference Trajectories

- Eight LO_2/LCH_4 engines, 177:1 area ratio (AR = A_e/A*) nozzles
  - 96 kN engines for Low-L/D (~50 tons at entry), 120 kN for Mid-L/D (~60 tons)

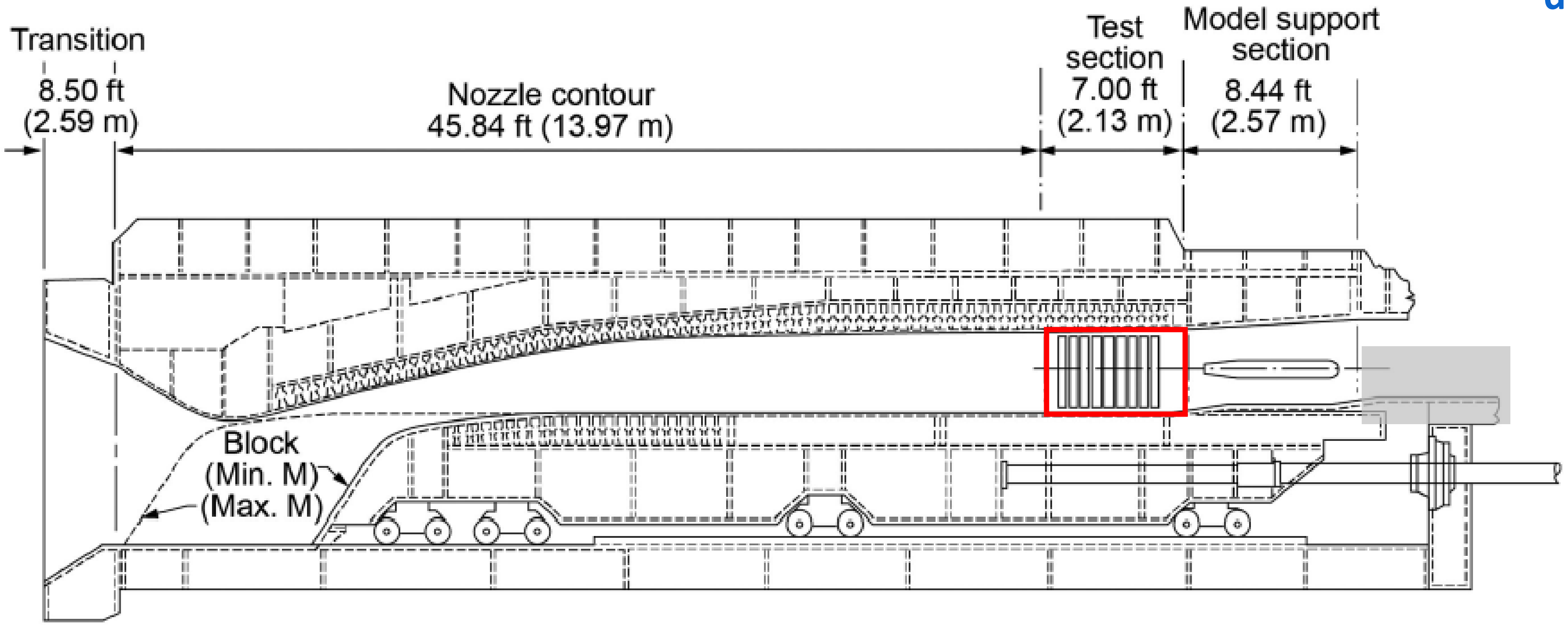


Wind Tunnel Test Objectives

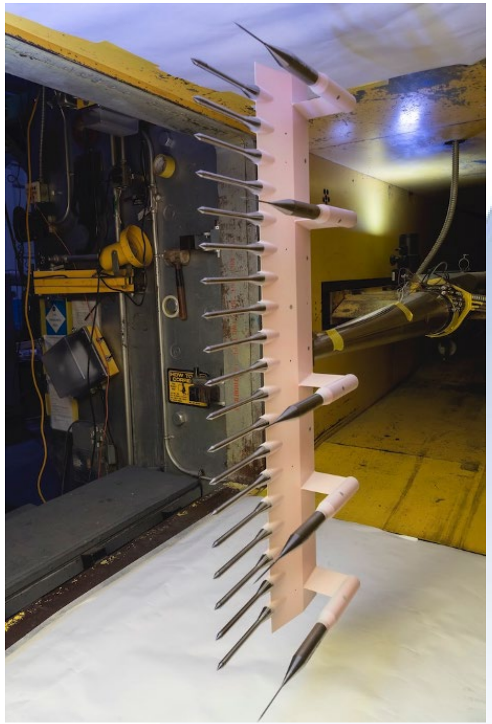
1. **Design and fabricate subscale versions of the two Mars reference powered descent vehicles, to test in the LUPWT**
2. **Test the models over a range of Mach numbers, angles of attack, roll angles, nozzle configurations, and thrust levels that envelope the flight conditions as much as possible**
3. **Complete uncertainty quantification (UQ) analysis of the test data**
4. **Provide data for comparison to CFD results**

LUPWT Test Section 2

- Mach number (2.30 to 4.63) is controlled with an asymmetric sliding-block nozzle, which is used to select the ratio of the nozzle throat area to test section area
- A re-characterization of test section 2 recently was completed to select conditions for the upcoming test
  - The rake data will also be factored into the test data UQ analysis

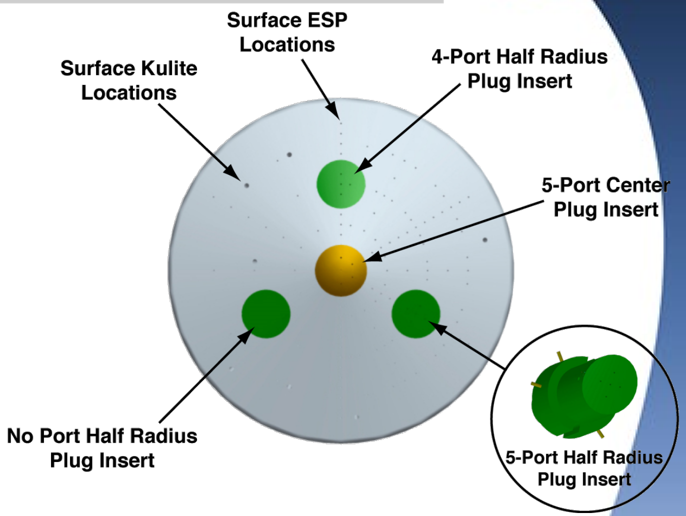


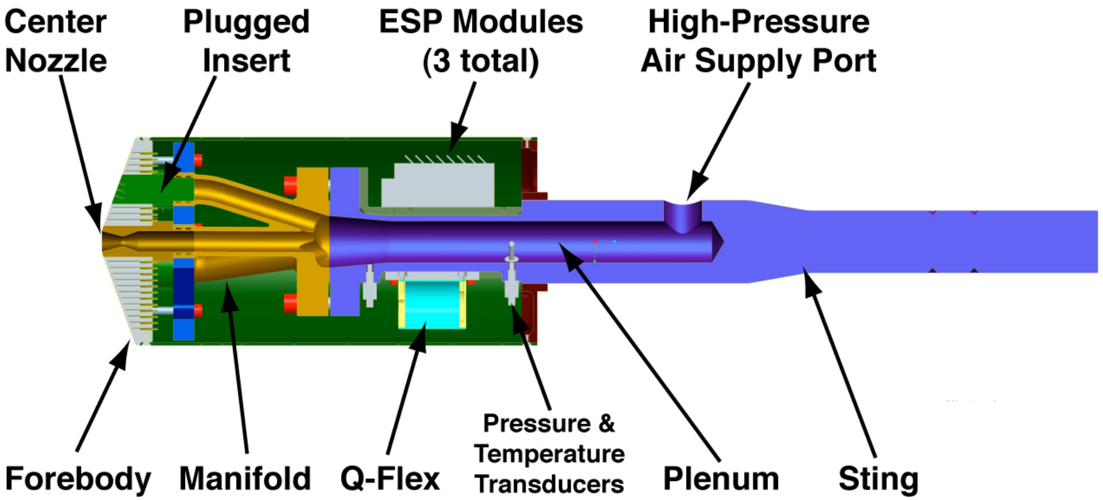
Probe rake used for test section re-calibration (Mach number, dynamic pressure, flow angularity)



2010 Wind Tunnel Test

- Objective: Provide SRP data for CFD validation
- Generic 5” dia. model with 0, 1, 3, 4 cold-gas air nozzles
- Mach = 2.6, 3.5, 4.6
- AoA = 0, ±4, ±8, 12, 16, 20
- Thrust Coefficients: CT = 0.5 to 4+





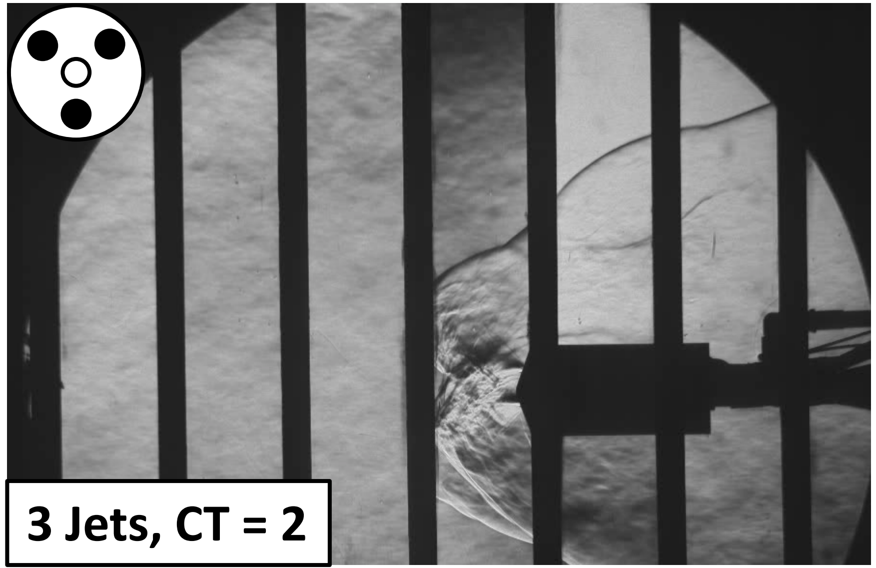
Pressure Instrumentation:
- 118 Forebody Surface (ESP)
- 7 Forebody Surface (Kulites)
- 49 Aftbody Surface (ESP)
- 4 Internal (Kulites)

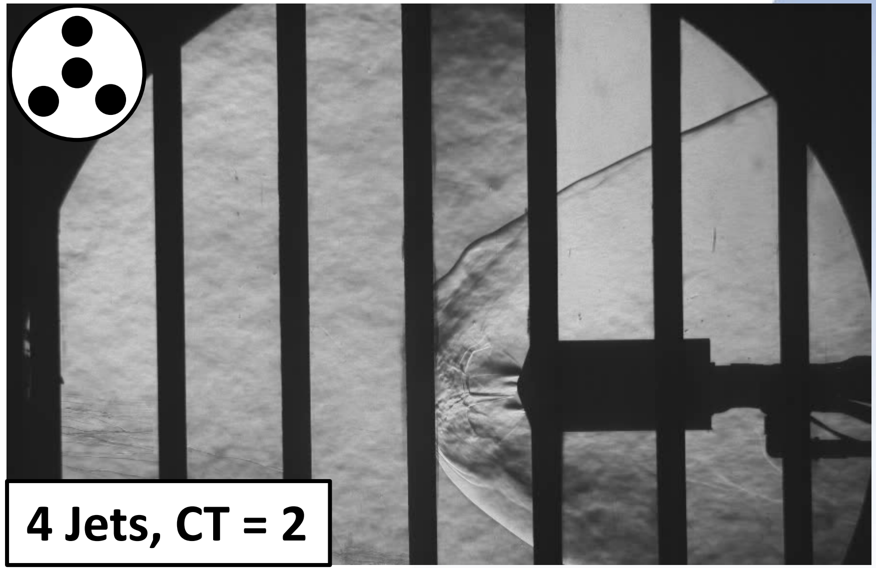
2010 Wind Tunnel Test
Sample Schlieren Videos, Mach 4.6

- **Videos were captured at 6 to 10K frames per second**


No Jets

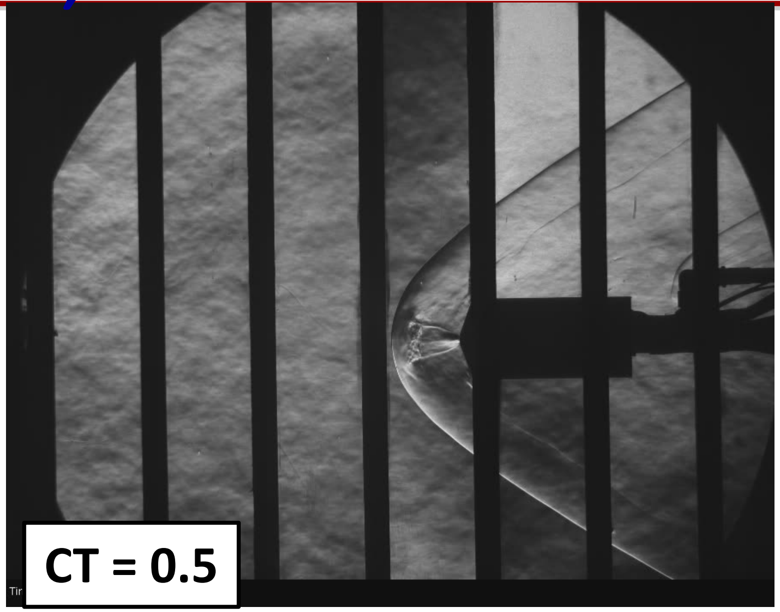

1 Jet, CT = 2

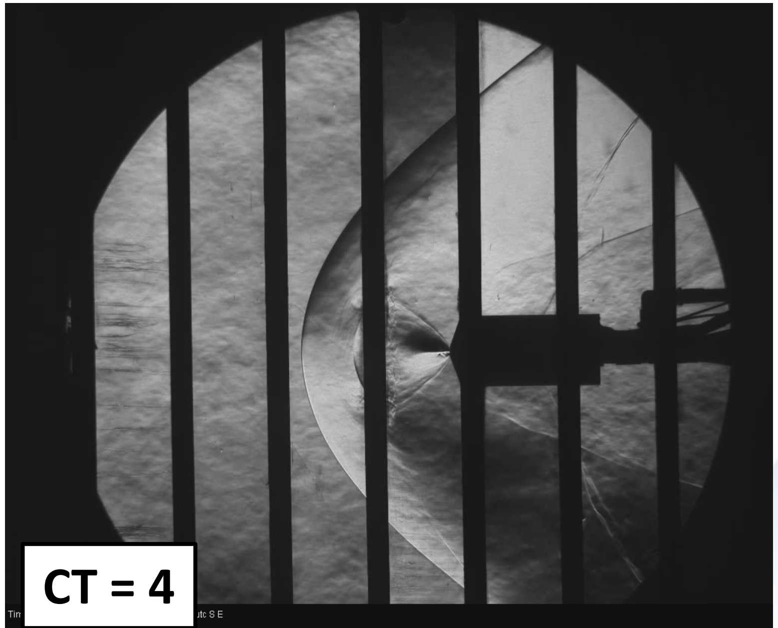

3 Jets, CT = 2


4 Jets, CT = 2

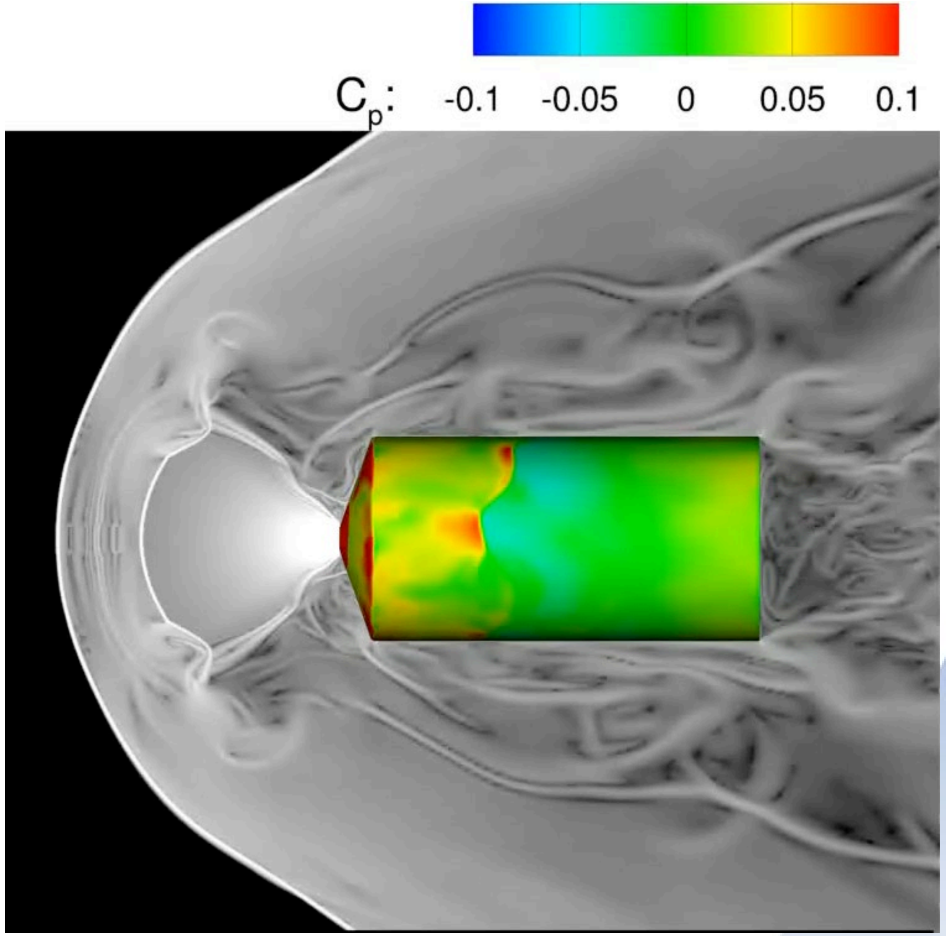
2010 Test, Effect of Thrust Coefficient
1 Jet, Mach = 2.4, AoA = 0

- **Higher thrust pushes out the bow shock and creates a larger jet barrel due to a higher degree of jet under-expansion**
  - **Full-scale vehicle CTs > 10 are needed based on EDL-SA studies**



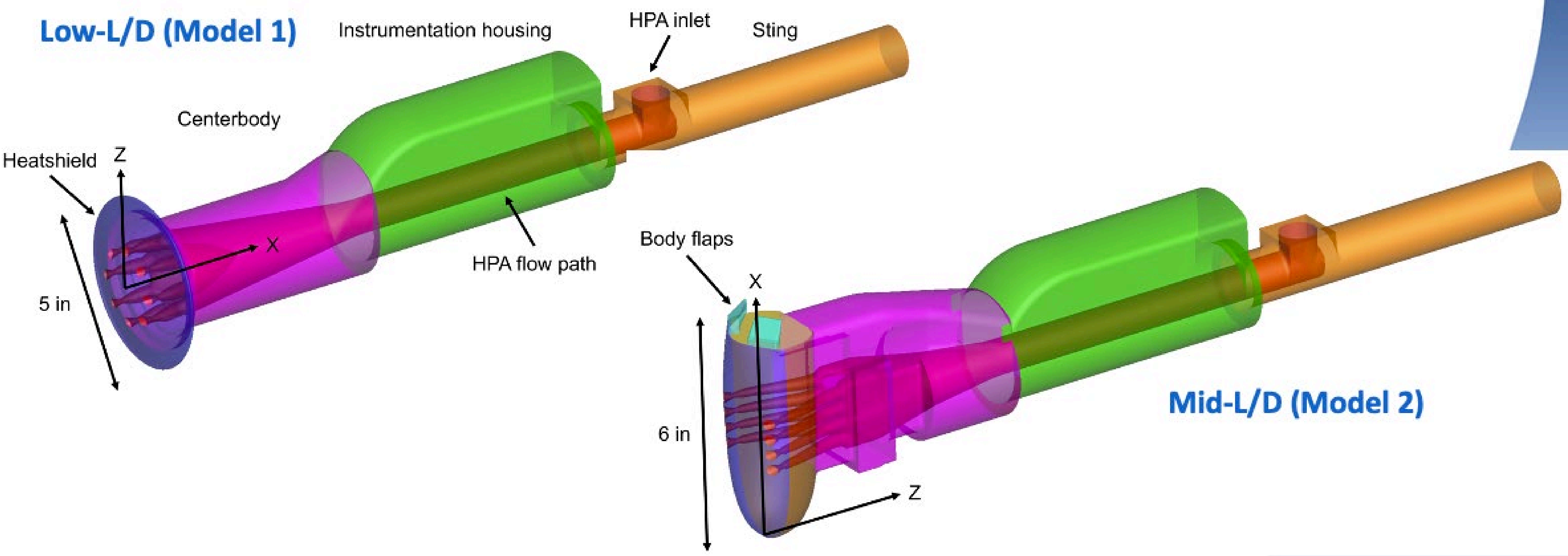


2010 Test, Comparison to CFD



New Wind Tunnel Models

- High-pressure air (HPA) will flow through the model nozzles to simulate retrorockets
- The Low-L/D heatshield will have interchangeable nozzles that vary in size, location, cant angle, and area ratio



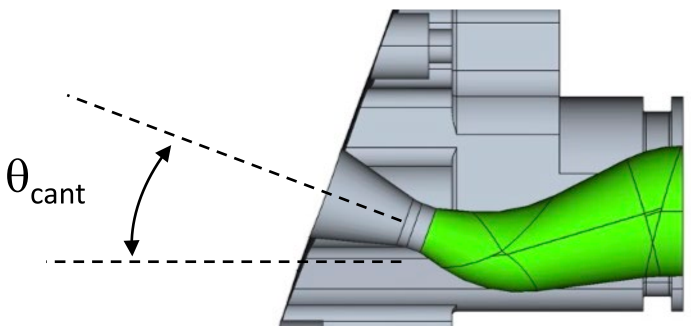
Wind Tunnel Model Scaling

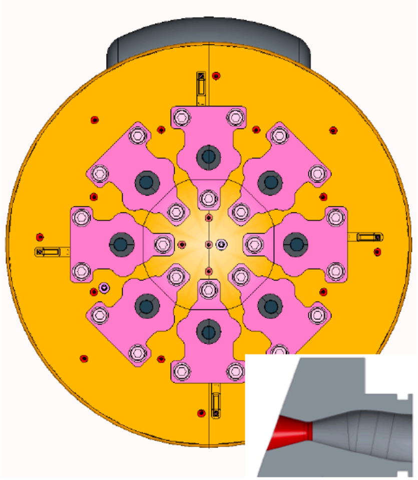
- **Geometric scaling** is used for the model geometries, based on the reference vehicles
- **Jet scaling** is used to tailor the nozzle conditions to approximate the important jet interaction parameters that govern the aero/propulsive interaction flowfield, such as:
  - Thrust coefficient, C_T = Thrust / $(1/2\ \rho_\infty V_\infty^2\ S_{ref})$
  - Ratio of nozzle exit pressure and stagnation pressure, $p_e\ /\ p_{0,2}$
- The wind tunnel models will use HPA to simulate the retro-rockets, so true scaling of the flight reference vehicles is not possible

Since HPA must be used for the nozzles instead of rocket engines, and because air and the combustion products differ thermodynamically, only one jet scaling parameter at a time can be matched to flight

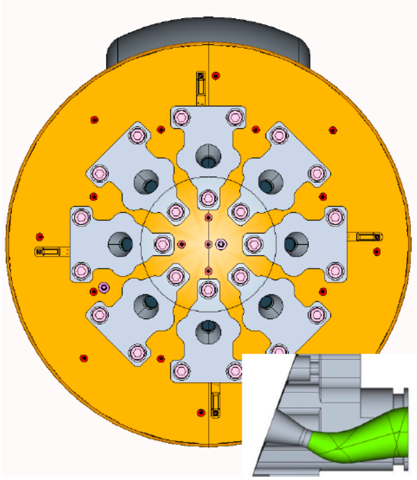
Low-L/D Nozzle Variations

- The Low-L/D heatshield has interchangeable nozzles that are expected to impact test results:
  - Exit area relative to heatshield area
  - Radial distance from nose (R_n/R_b)
  - Cant angle (θ_{cant})
  - Exit-to-throat area ratio (AR), limited by using unheated HPA (T_0 = ~250 deg. F)
  - Spacing (evenly or paired)

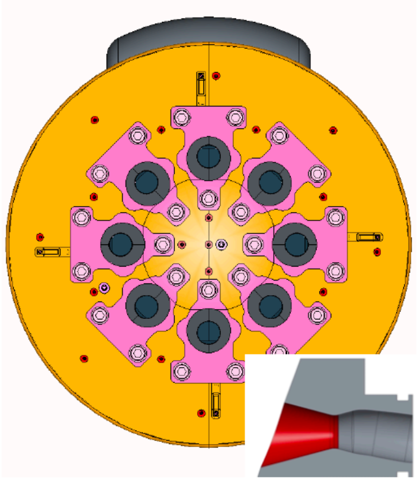




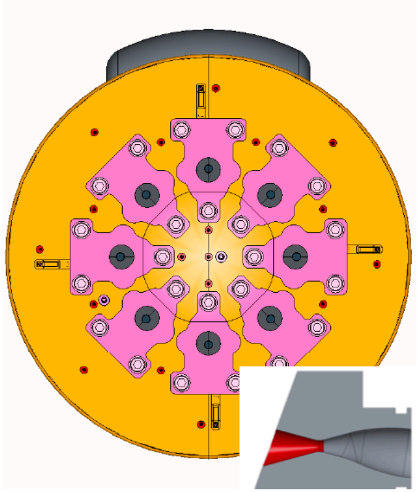
(a) 1A (AR=4, θ_{cant}=0°, R_n/R_b=0.434)



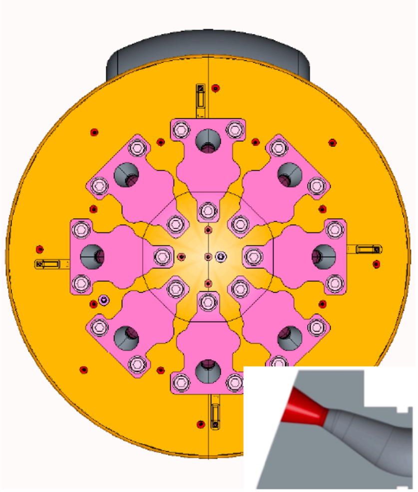
(b) 1B (AR=4, θ_{cant}=20°, R_n/R_b=0.434)



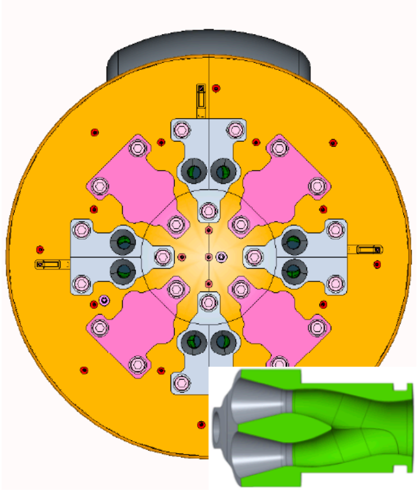
(c) 1C (AR=4, θ_{cant}=0°, R_n/R_b=0.434)



(d) 1D (AR=11, θ_{cant}=0°, R_n/R_b=0.434)



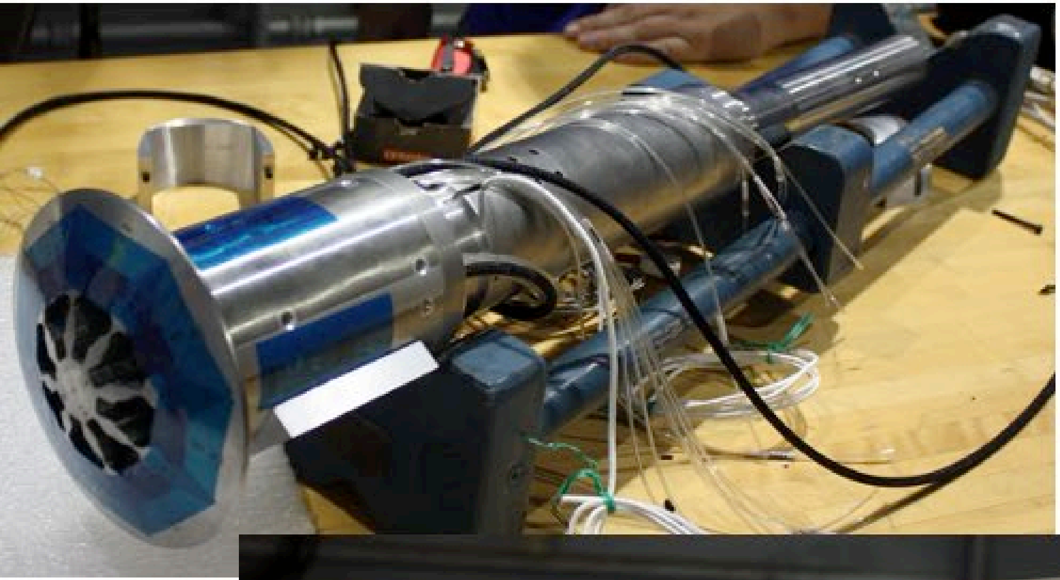
(e) 1E (AR=4, θ_{cant}=20°, R_n/R_b=0.6)

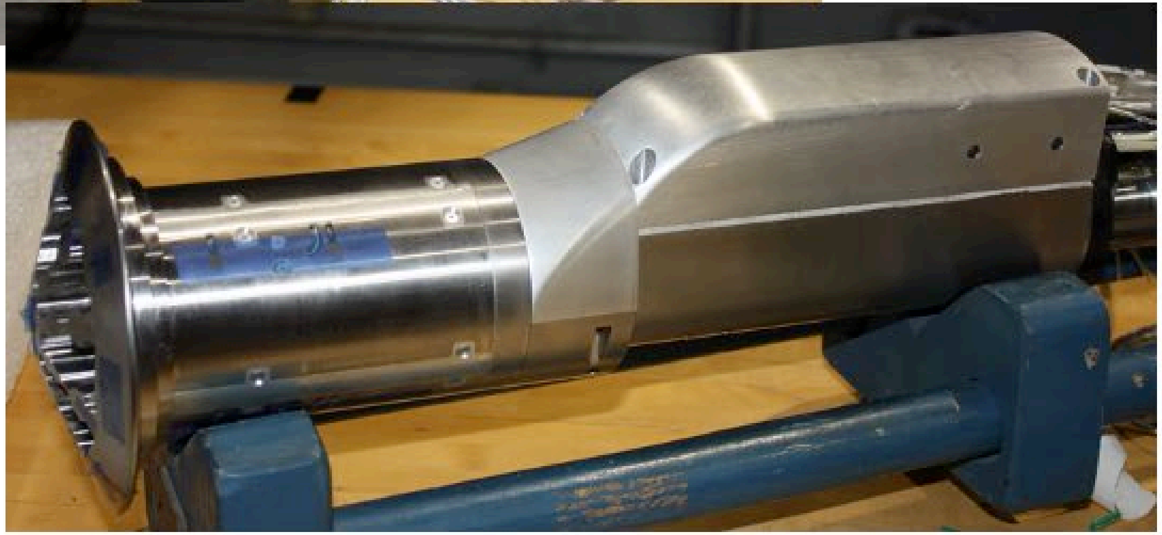


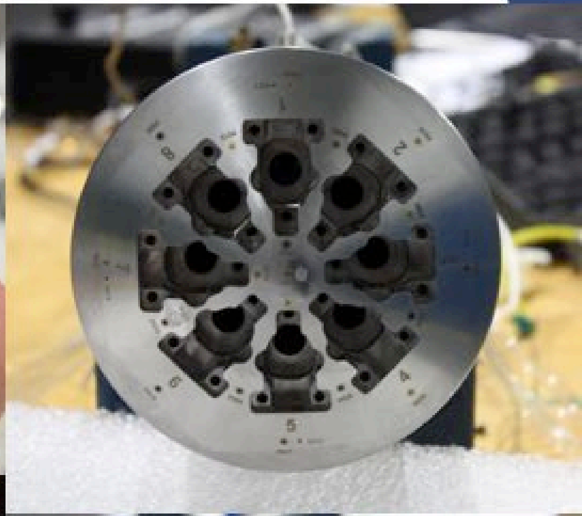
(f) 1F (AR=4, θ_{cant}=5°, R_n/R_b=0.434)

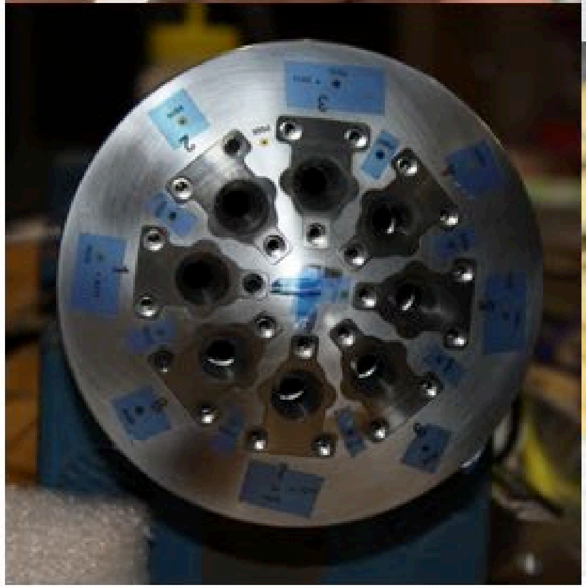
Low-L/D Model Hardware

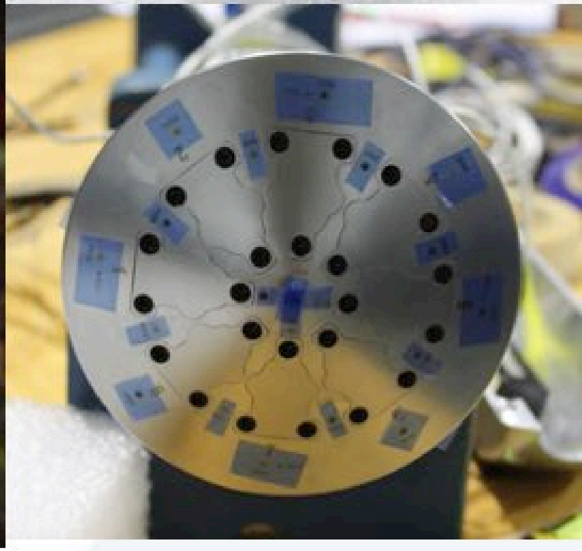
- Both models were inspected at NASA Langley in August 2020



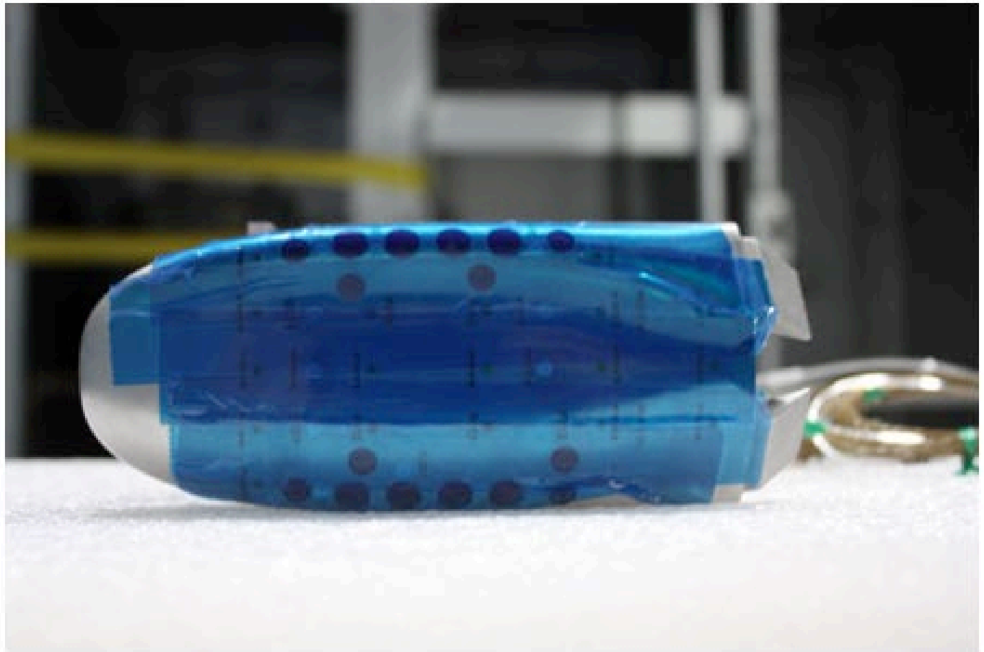


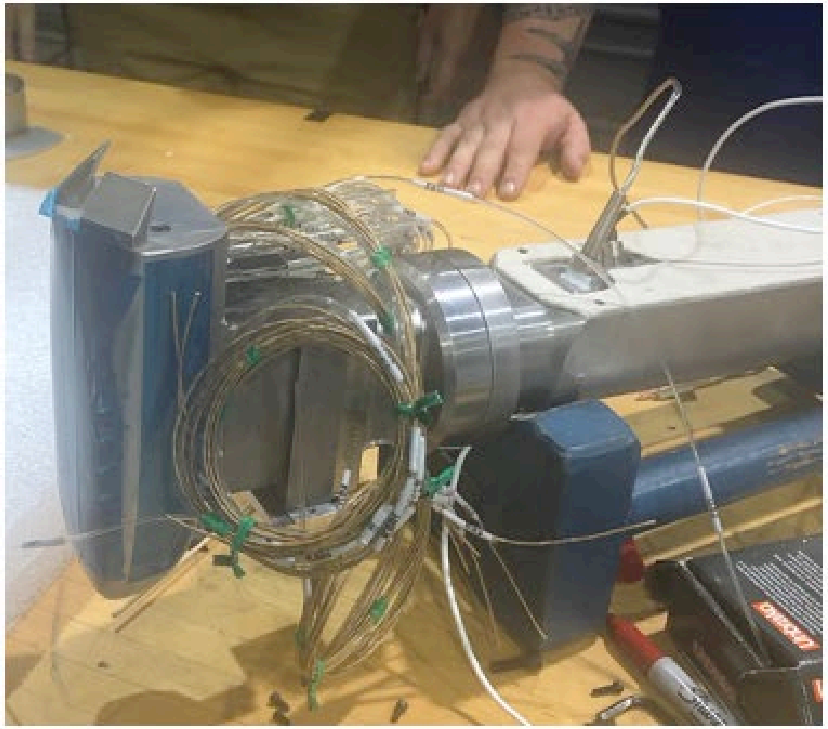






Mid-L/D Model Hardware

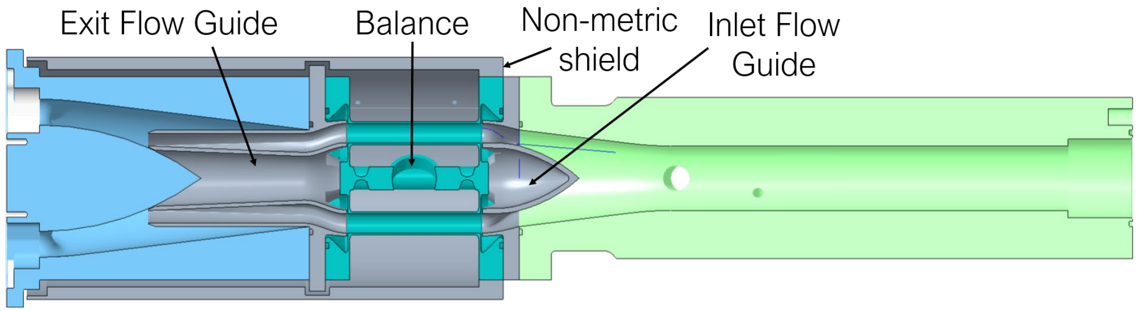




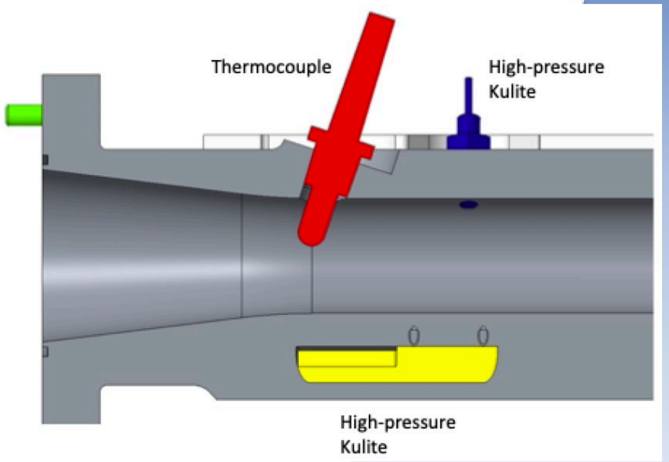
Instrumentation

- **Flow-through six-component force & moment balance (Burns, et al)**
  - **Added after model design & fabrication**
  - **Will be first known such retropropulsion measurements**
- **Discrete pressure (steady and unsteady) on heatshield**
- **Pressure-sensitive paint (PSP) on heatshield**
- **High-speed schlieren video (~10 kHz)**
- **Oil-based nozzle plume seeding for flow visualization (Acharya, et al)**
  - **Added after model design & fabrication**
- **HPA total pressure and temperature**

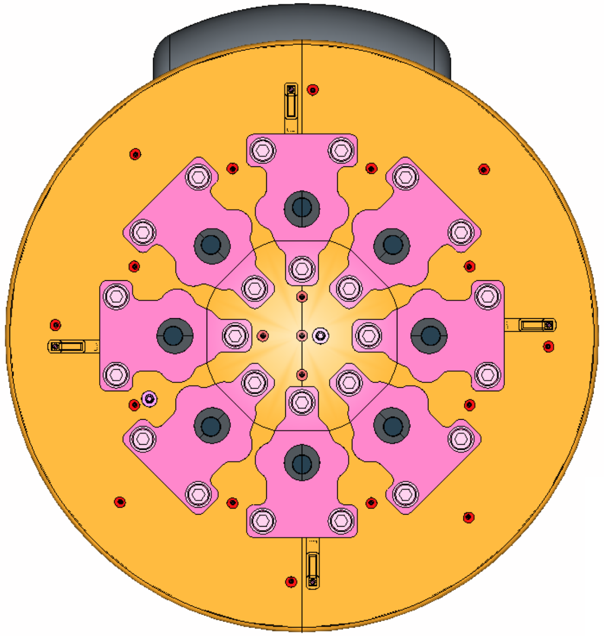
Balance design



HPA measurements



Heatshield pressure



Surface covered in PSP
Steady pressure
High-frequency pressure

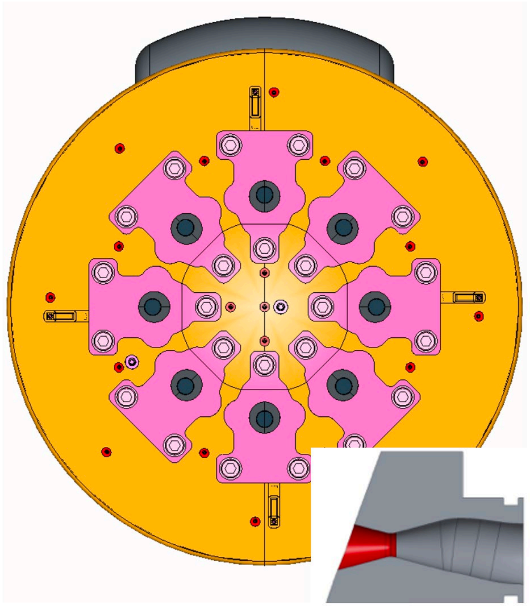
Test Matrix Parameters

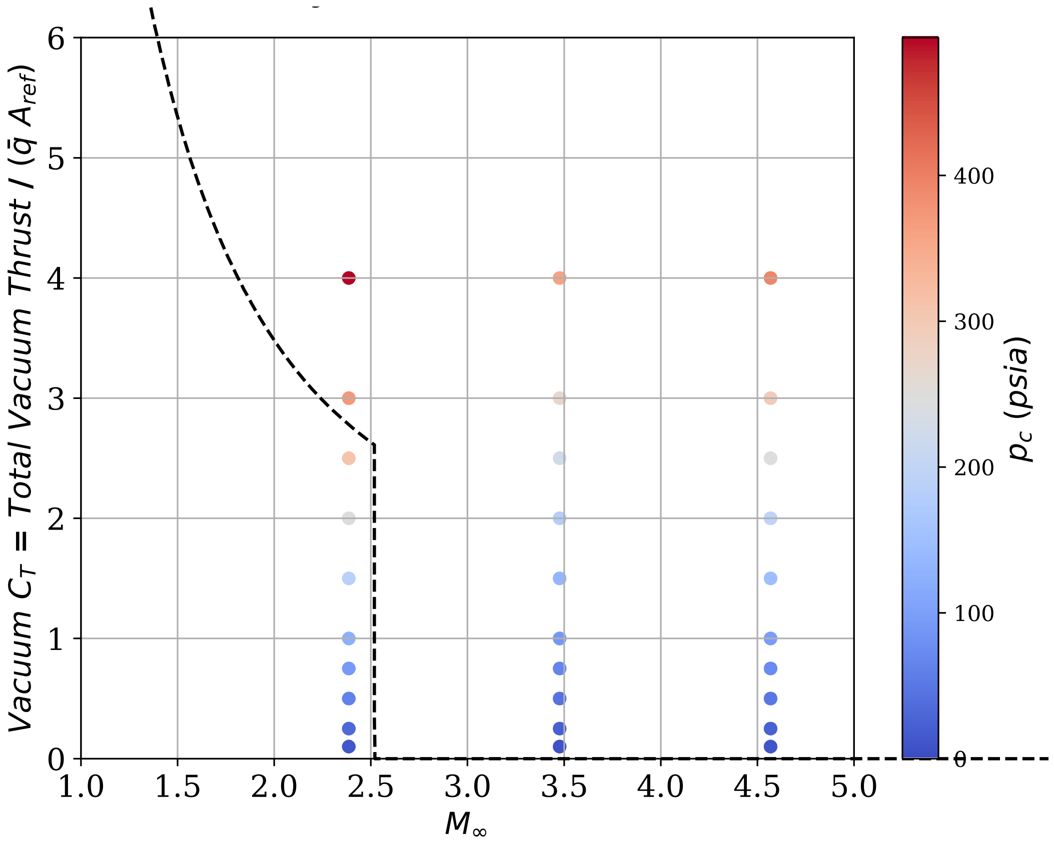
- The number of different values for some parameters will be determined by how much time it takes to make model/tunnel changes and by which measurements are being made, not all of which can be done at the same time

	Low-L/D Model	Mid-L/D Model
Nozzle configurations	1 (plugged), 1A, 1B, 1C, 1D, 1E, 1F,	2 (plugged), 2A
M_∞ and Re_∞/ft	2.4 and 1E6, 3.5 and 1E6, 4.6 and 1.5E6	
HPA total pressure	up to 1500 psia	
HPA total temperature	up to ~250 deg. F	
Angle of attack	-10 to 20 deg	70 to 100 deg
Roll angle	0 and 22.5 or 45 deg	0

Example Test Conditions for Model 1A

- **Each model will be tested at combinations of Mach number (2.4, 3.5, 4.6), angle of attack, roll angle, and HPA total pressure (p_c)**
- **At each condition, p_c will be adjusted to achieve certain vacuum thrust coefficients (C_T) that envelope the nominal reference flight conditions**





C_T = Thrust / ($1/2\rho V^2 S_{ref}$)

CFD Solvers

- **Loci-CHEM (F. Canabal)**
  - **Finite volume, unstructured grids, ~200M grid cells**
  - **Cases to date have been run as unsteady Reynolds-Averaged Navier-Stokes (URANS)**
- **OVERFLOW (R. Childs, L. Halstrom, K. Matsuno)**
  - **Finite difference, overset structured grids with automatic mesh refinement (AMR), ~150-250M grid points**
  - **Cases to date have been run as URANS, will also run Detached Eddy Simulations (DES)**
- **FUN3D (C. Glass, A. Korzun, W. Wood)**
  - **Finite volume, unstructured grids with mesh refinement, ~50M grid points**
  - **Cases to date have been run as DES**

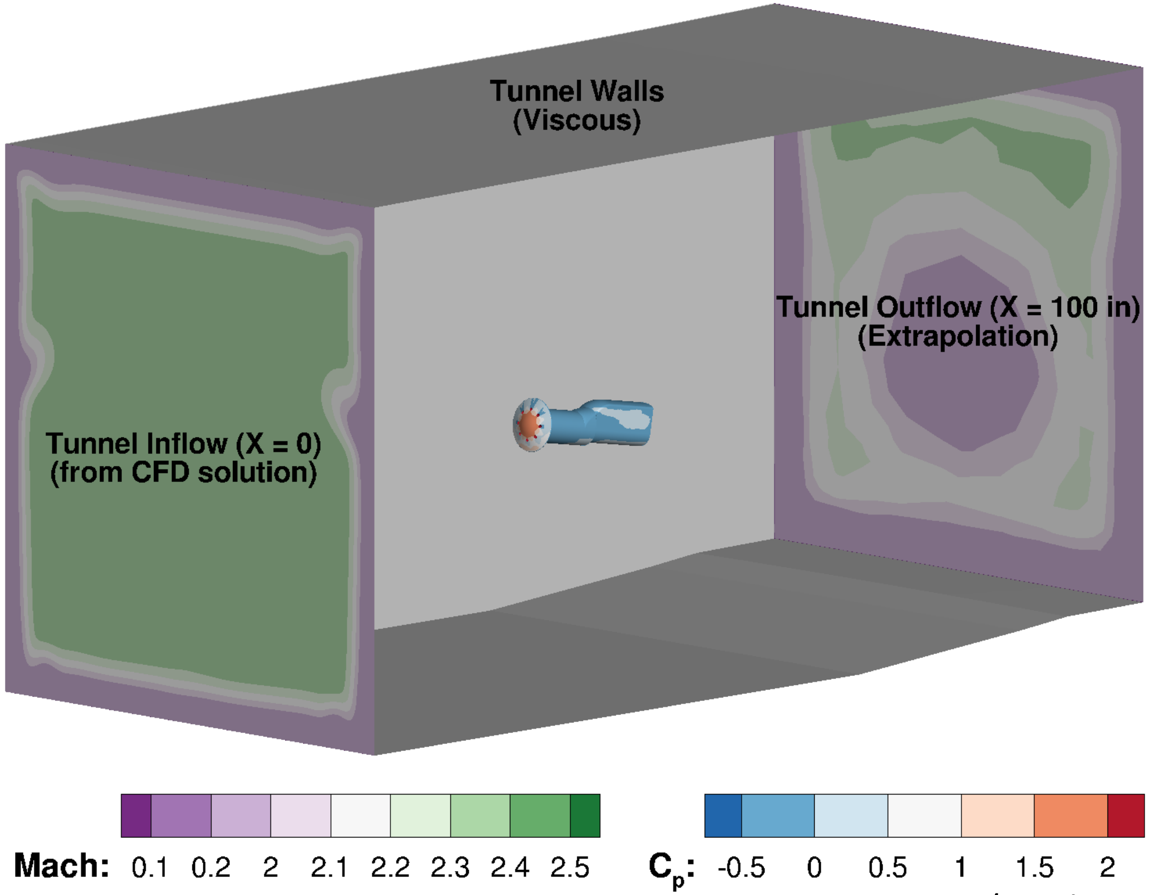
Used in conjunction with retropropulsion wind tunnel testing in 2010/2011

- **Goal prior to test: solutions from at least 2 solvers per condition: 2 non-blowing + 7 blowing models, 3 Mach numbers, 3 thrust coefficients, 3 angles of attack**
- **More than 350 solutions completed to date**

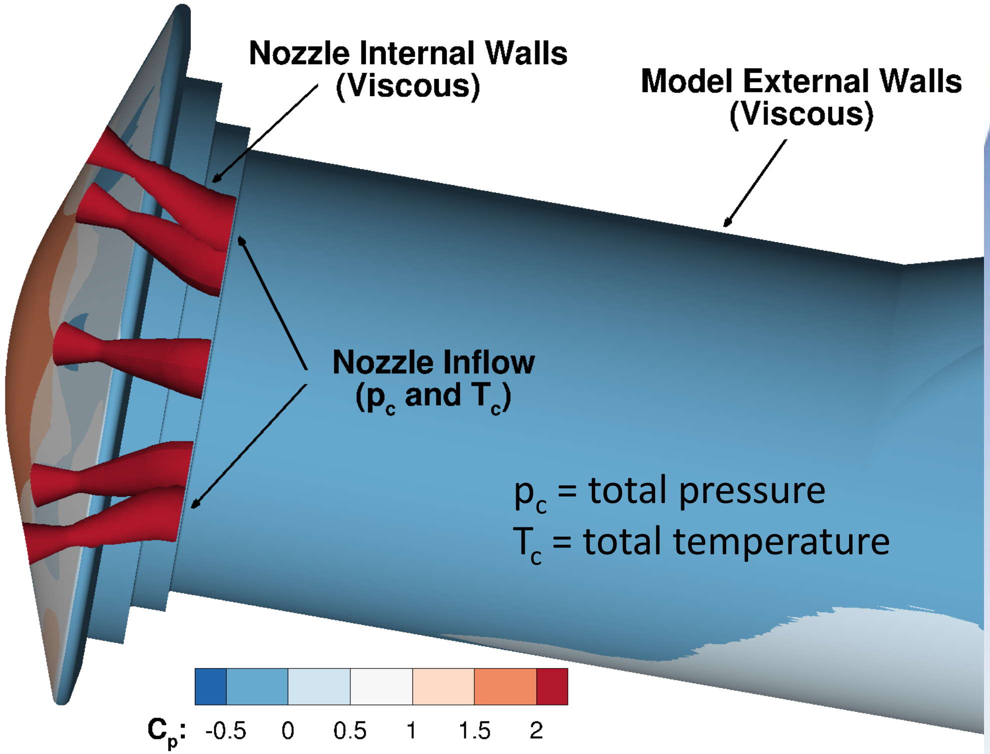
CFD Boundary Conditions

- Tunnel inflow is taken from separate CFD solutions of the tunnel ahead of the test section – non-uniform, vortices at the wall corners, non-zero flow angularity
- Nozzle inflow is applied at total pressure and temperature on the plenum face

Tunnel Boundary Conditions



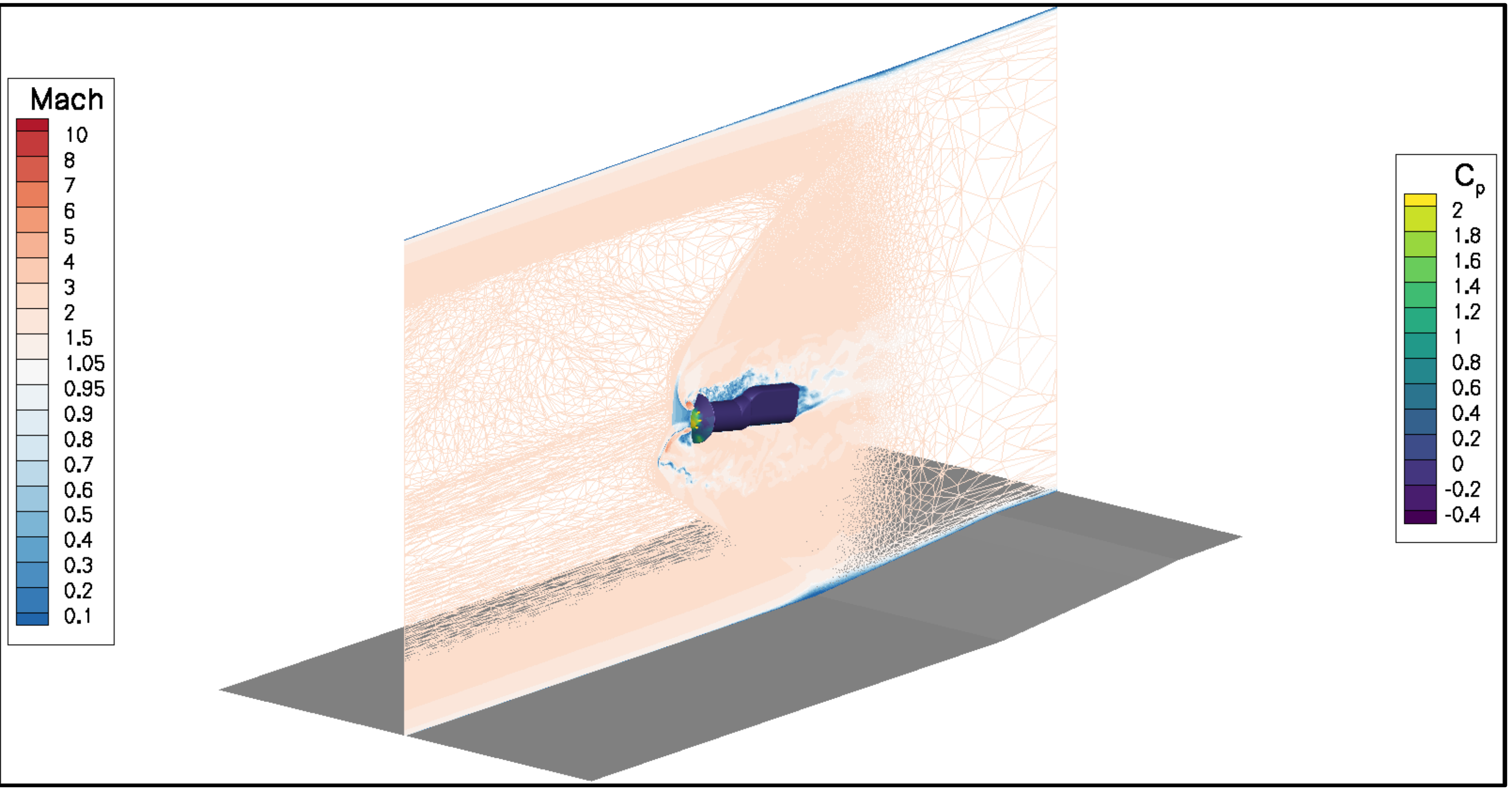
Model Boundary Conditions

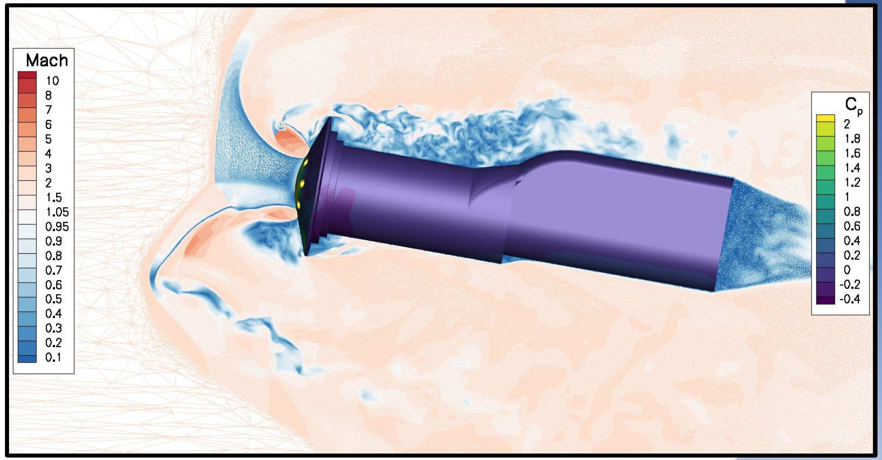


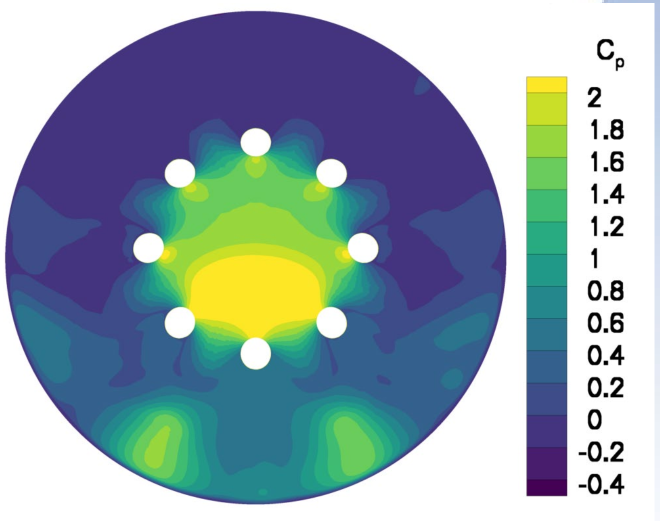
Sample Solution, Model 1A

- Tunnel Mach number = 2.4, model thrust coefficient (C_T) = 1, angle of attack = 10 deg
- Over 350 solutions have been completed to date with three solvers

FUN3D time-averaged Mach number and model surface pressure coefficient on adapted grid



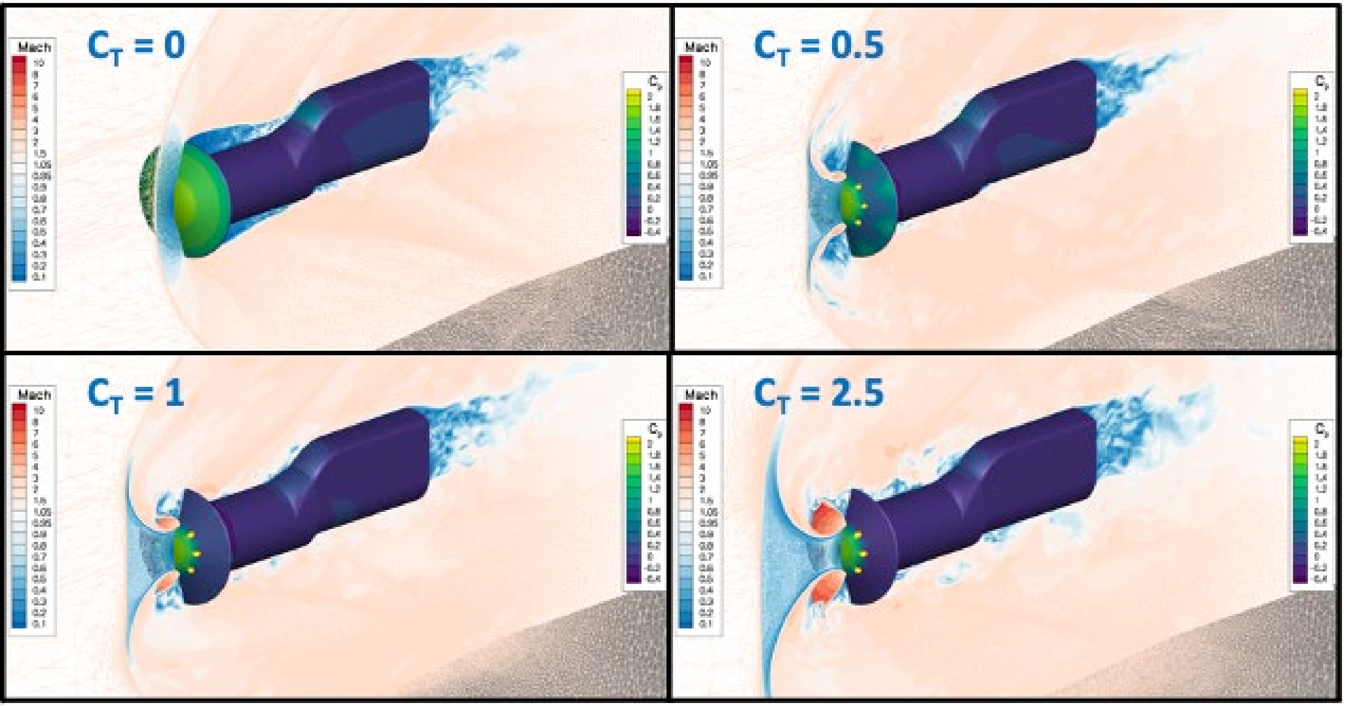


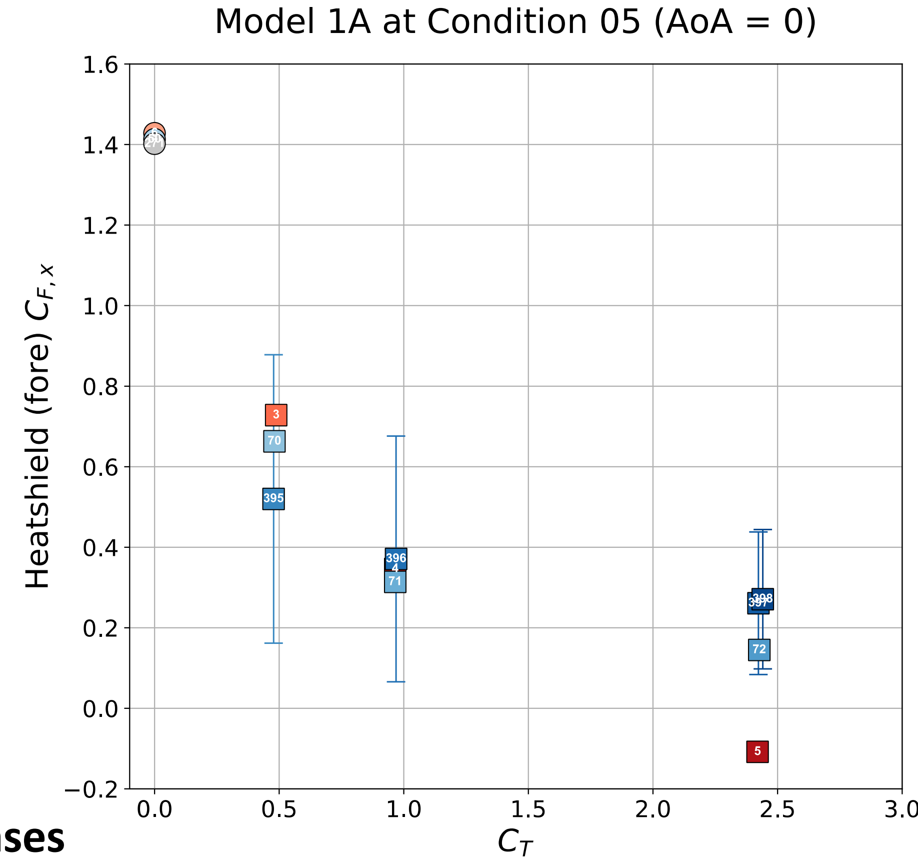


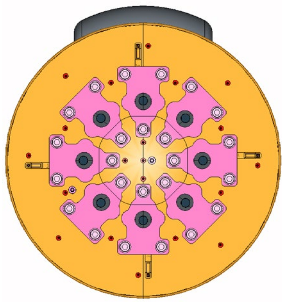
Predicted Effect of Thrust
Model 1A

- **Tunnel Mach number = 2.4, thrust coefficients (C_T) of 0, 0.5, 1, and 2.5**

C_T = Thrust / ($1/2 \rho V^2 S_{ref}$)
AoA = angle of attack
$C_{F,x}$ = aerodynamic axial force coefficient



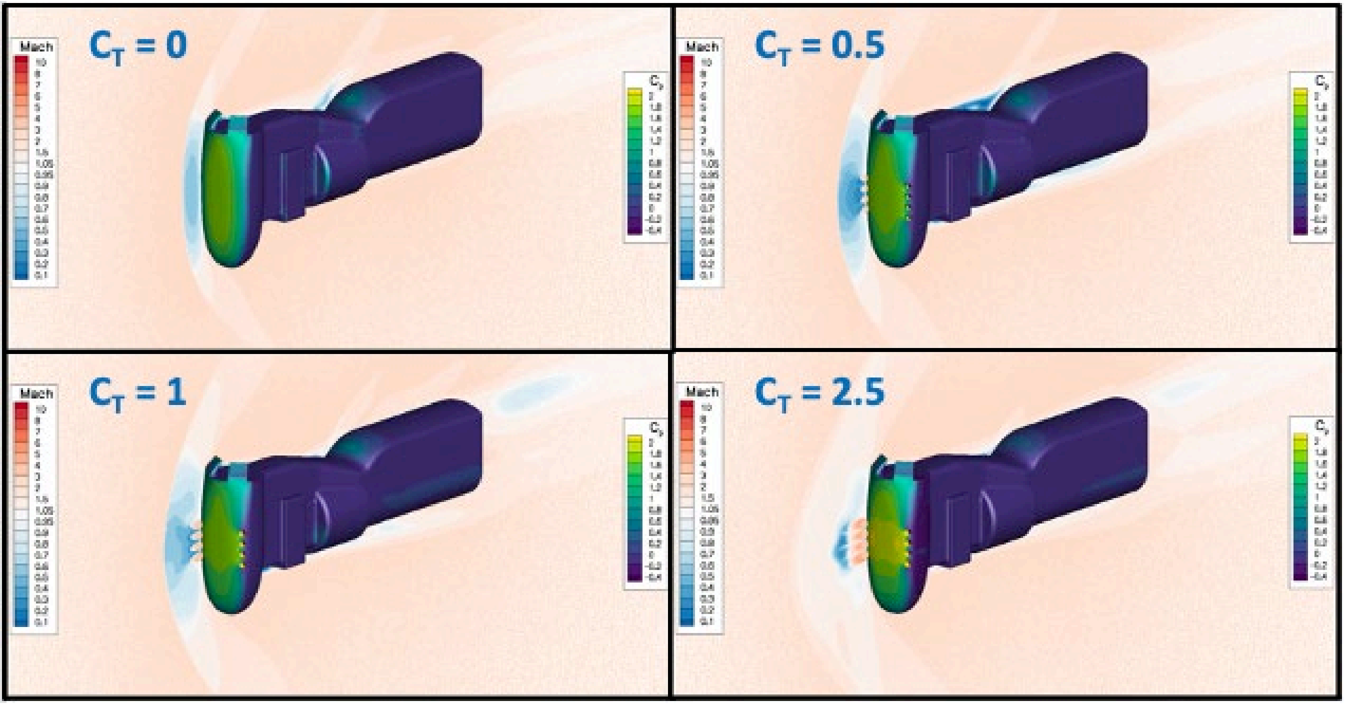


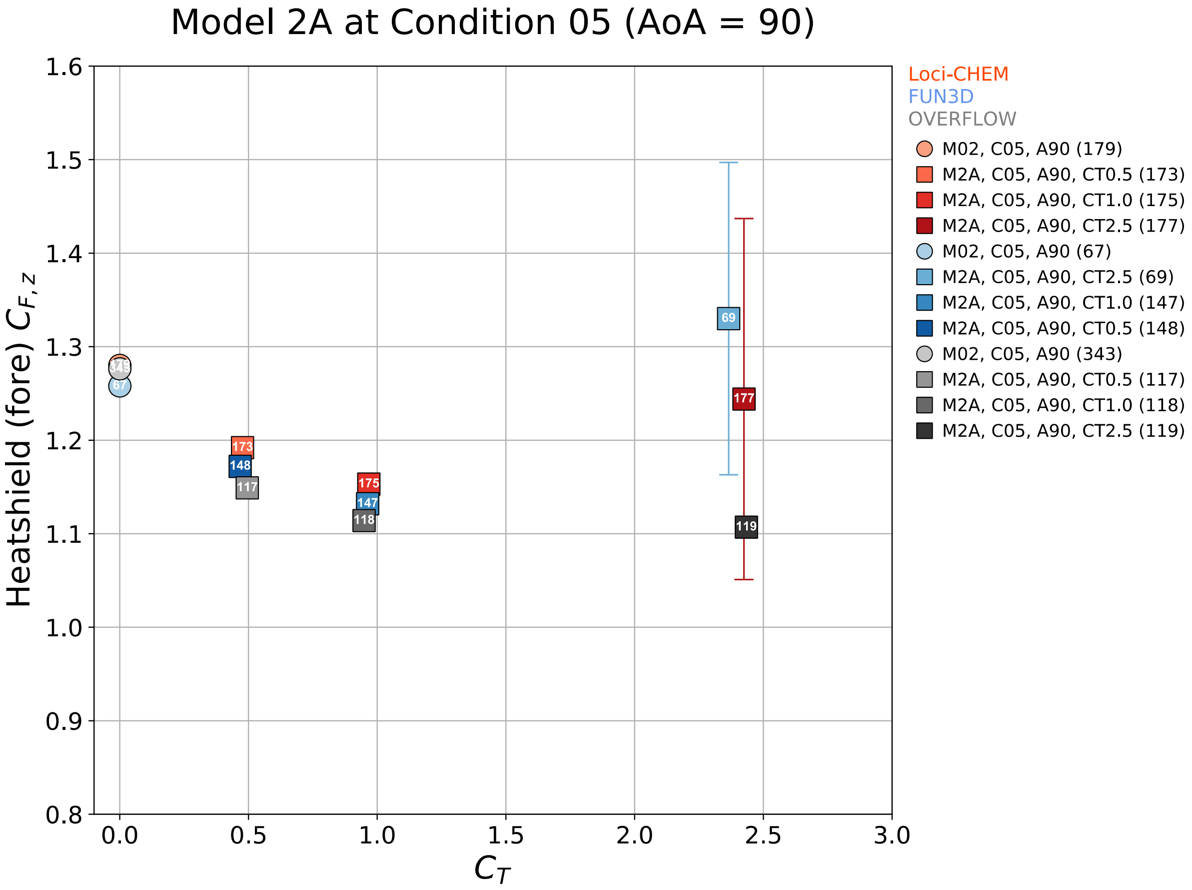


- **With increasing thrust:**
  - **Shock standoff distance increases**
  - **Heatshield aerodynamic axial force coefficient ($C_{F,x}$) decreases**
- **Significant scatter between CFD solvers, possibly due to URANS vs. DES, causes will be investigated further**

Predicted Effect of Thrust Model 2A

- Tunnel Mach number = 2.4, thrust coefficients (C_T) of 0, 0.5, 1, and 2.5

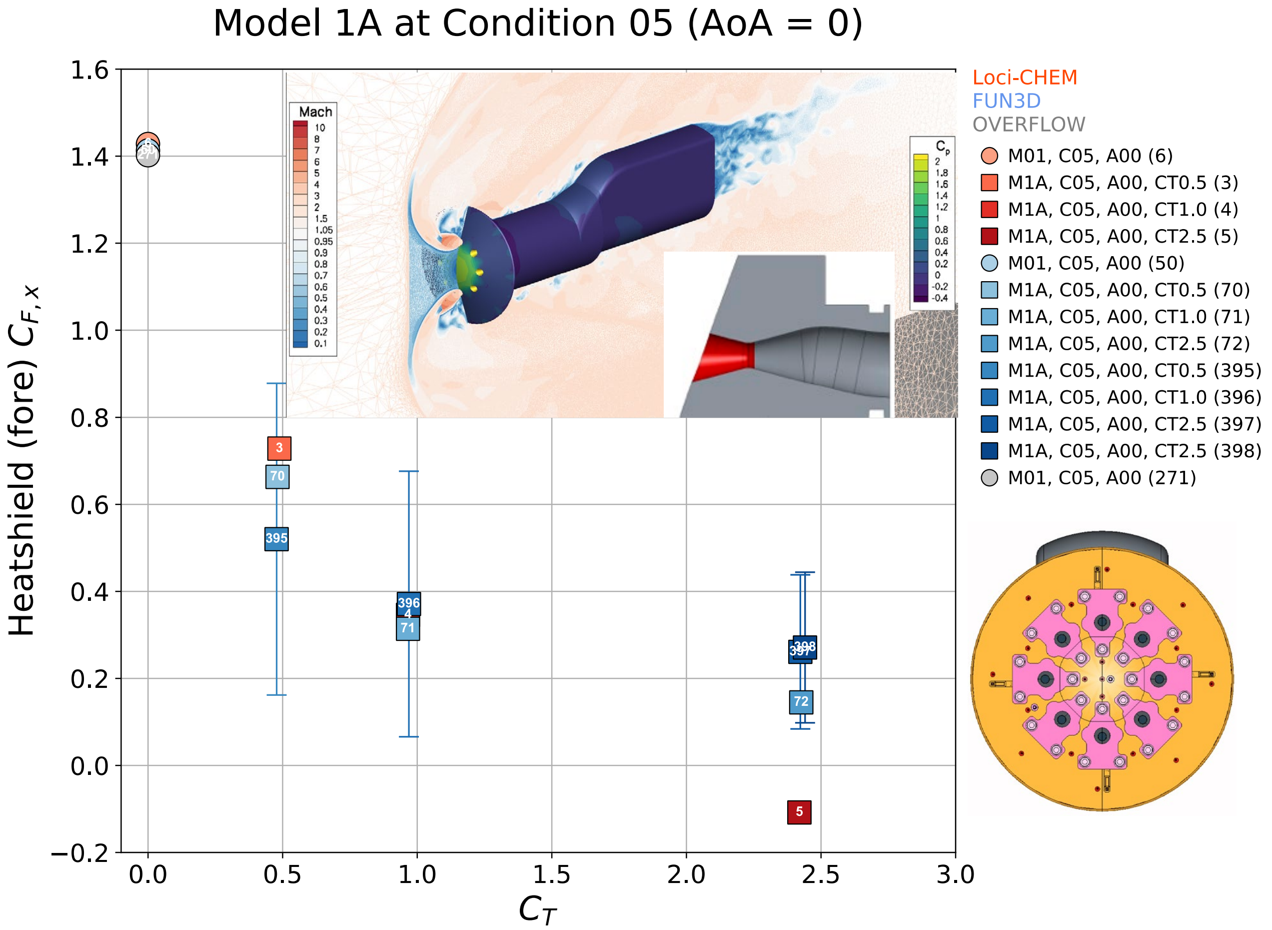


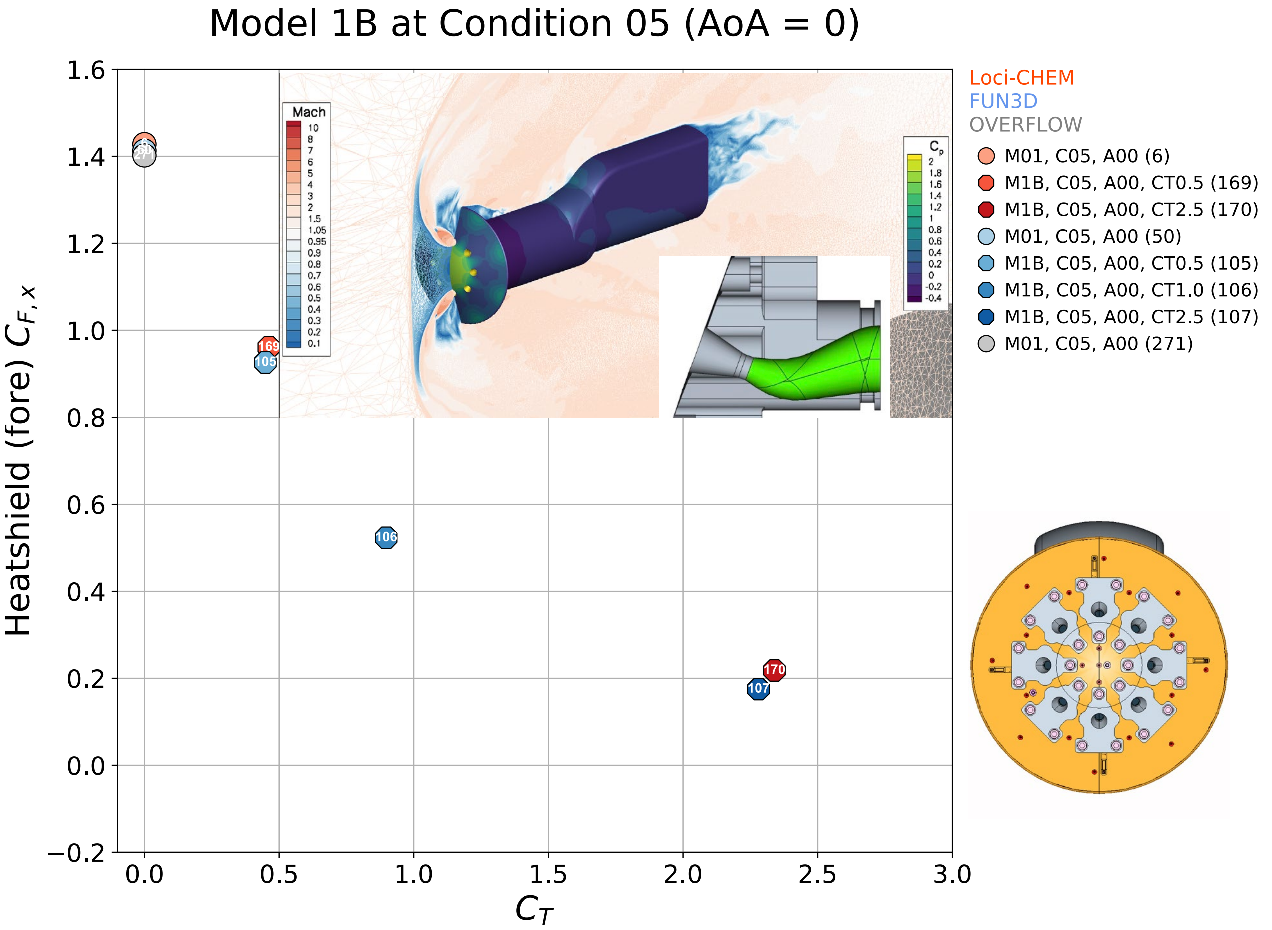


- **With increasing thrust:**
  - Shock standoff distance increases
  - Heatshield $C_{F,z}$ does not not monotonically decrease
- **Significant scatter between CFD solvers at highest C_T**

Predicted Effect of Nozzle Cant Angle Models 1A and 1B

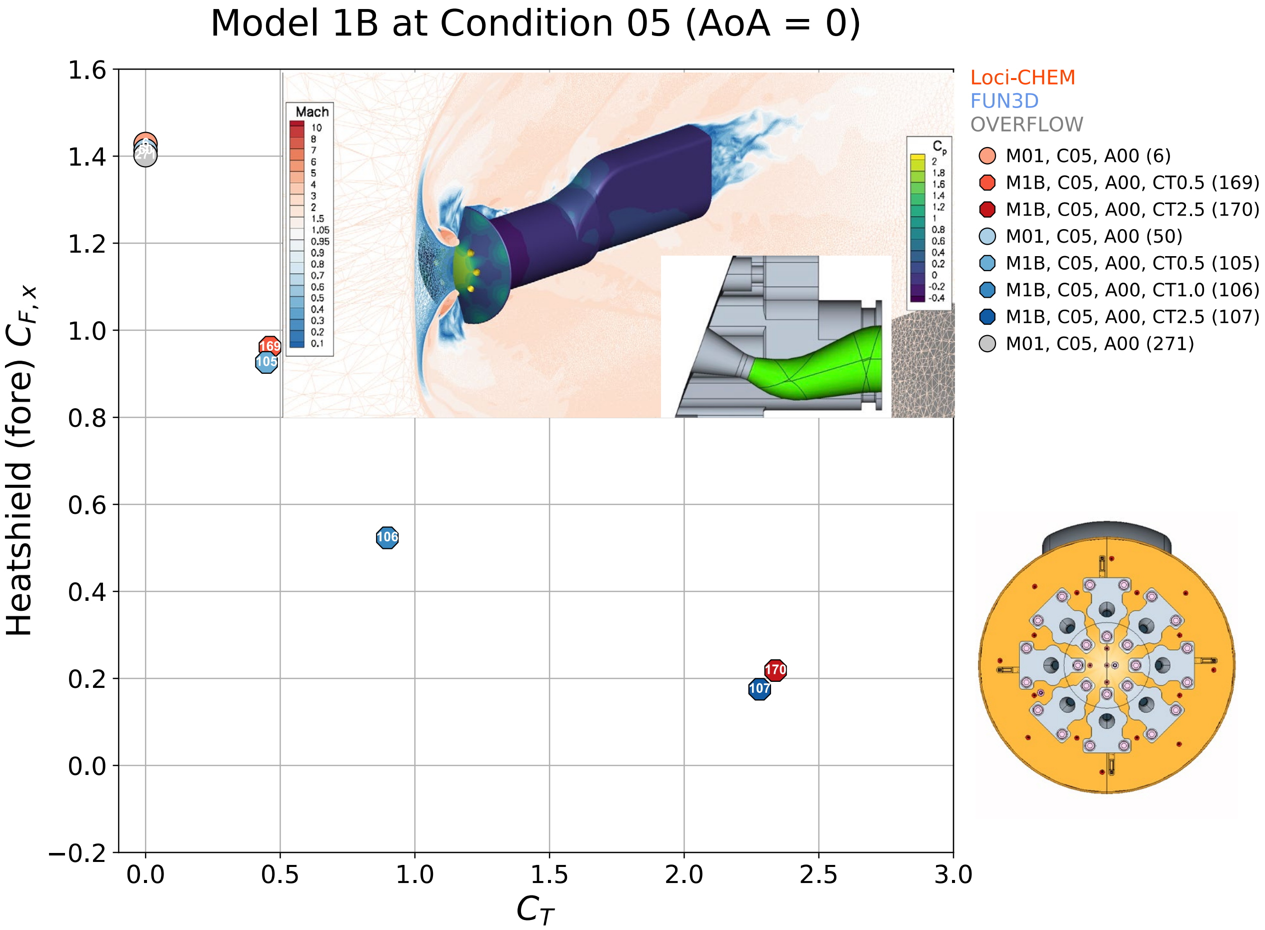
- If nozzles have an outward radial component (cant angle = 20-deg) for a given C_T:
  - **Heatshield aerodynamic axial force coefficient increases due to reduced plume blockage inboard of nozzles**

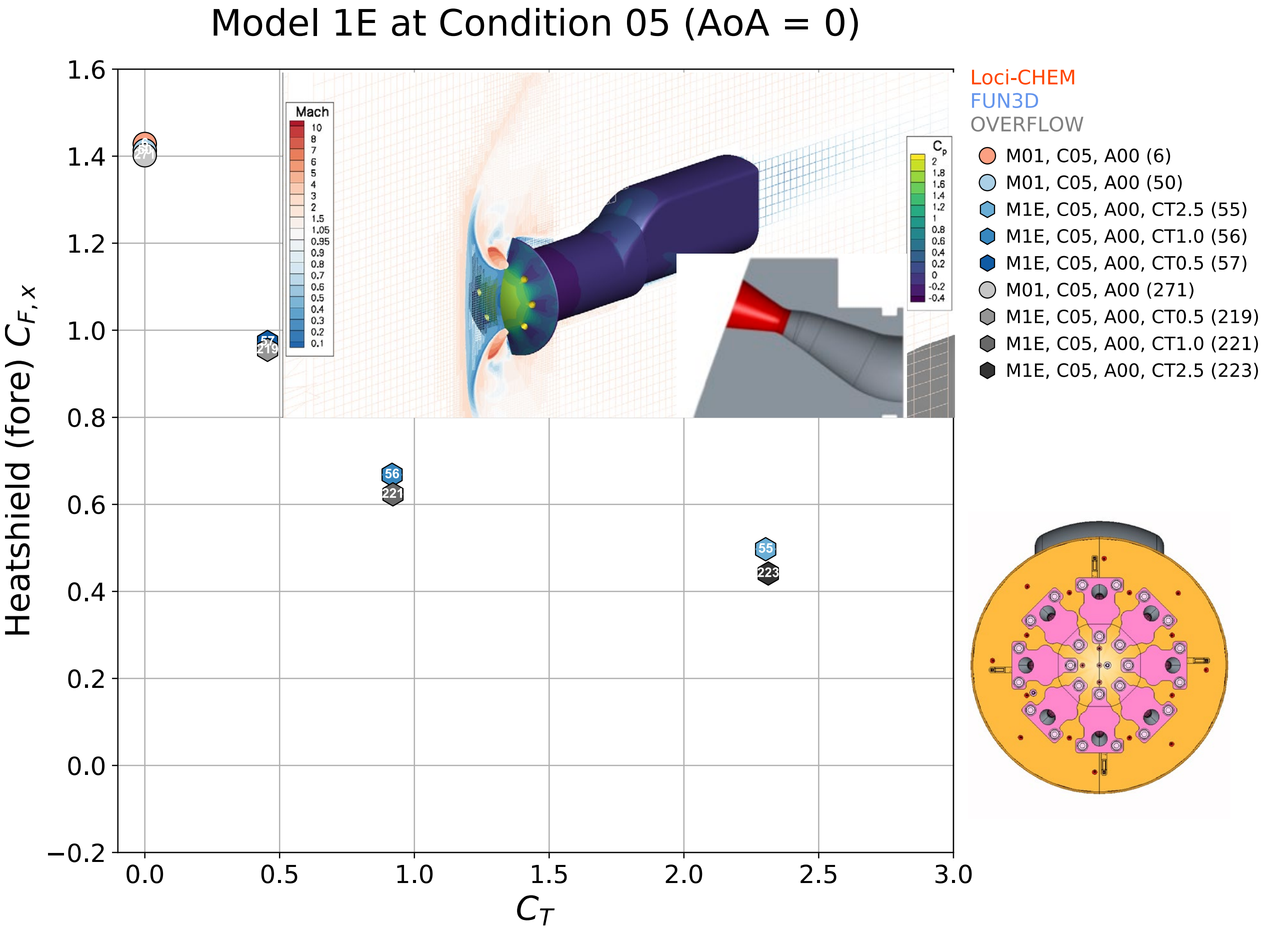




Predicted Effect of Nozzle Radial Location Models 1B and 1E

- **If nozzles are placed closer to the heatshield shoulder (model 1E) for $C_T > 0.5$:**
  - **Heatshield aerodynamic axial force coefficient increases due to larger area of high pressure inboard of nozzles**





Summary

- A test will be run in the NASA Langley Research Center Unitary Plan Wind Tunnel in 2022 in order to investigate aerodynamic interference effects due to simulated (air) retrorocket nozzle plumes at supersonic freestream conditions
- The main test objective is to provide relevant data so that CFD predictive capabilities for retropropulsion can be assessed in a wind tunnel environment
- Two wind tunnel models have been designed and fabricated to be geometrically-scaled versions of the current flight reference vehicles
  - Different nozzle parameters will be explored for the Low-L/D model
- The test data will consist of:
  - Six-component forces & moments from custom flow-through balance
  - Steady and unsteady discrete surface pressures
  - Global steady surface pressure using pressure sensitive paint
  - High-speed schlieren video
  - New plume seeding technique
- To date, over 350 CFD solutions have been completed at planned test conditions, with trends matching expectations for two models with eight jets: blunt and slender
- The test will be followed by extensive uncertainty quantification and comparisons between the data and CFD predictions, both of which will be documented in the open literature

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