

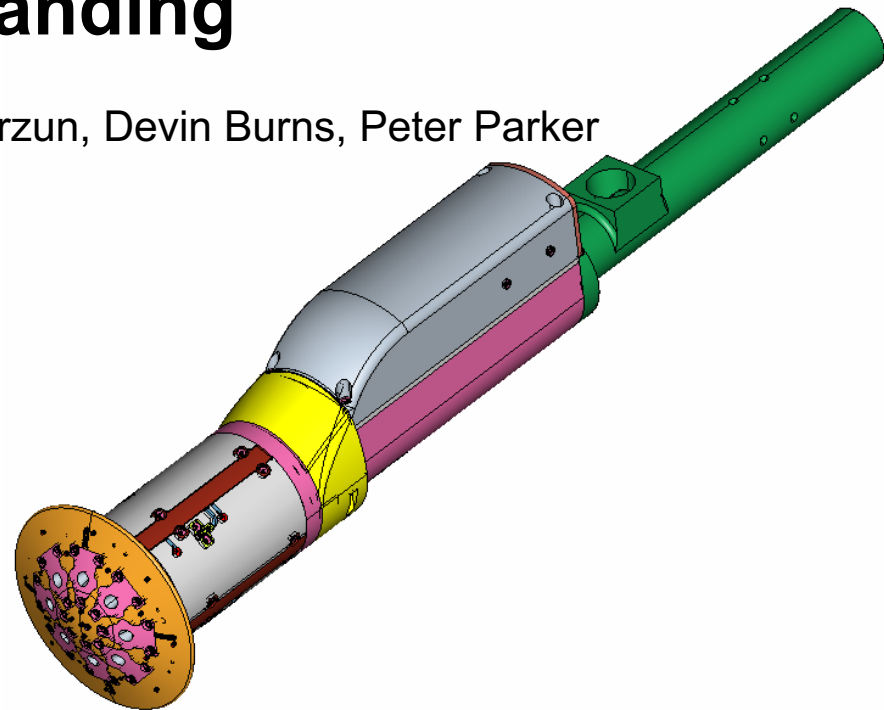


New Developments in Retropropulsion Testing for Mars Entry, Descent and Landing

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Airbreathing Propulsion, Exhaust Plume
and Signatures, and Energetic Systems Hazards
7-11 December 2020

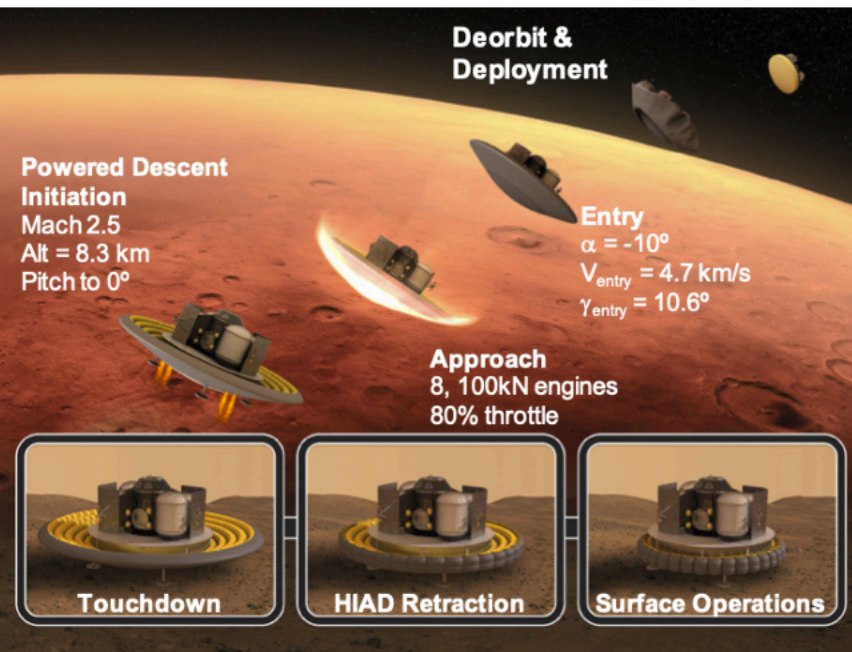


Background

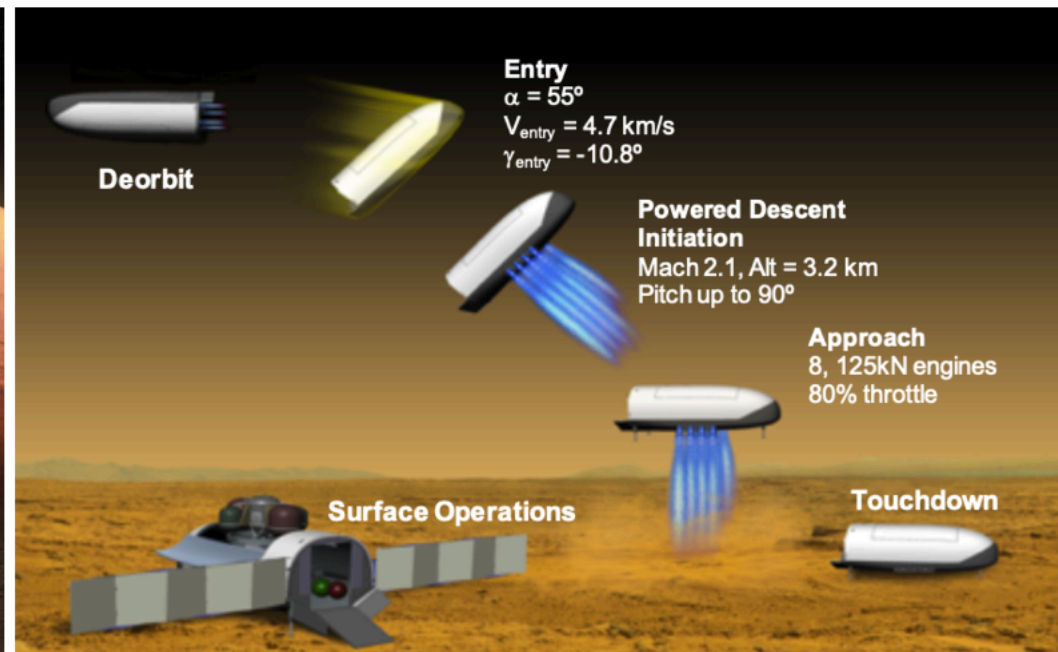


- NASA studies over the last several years show that powered descent starting at supersonic conditions, which has never been done at Mars, is enabling to land human payloads (~20 metric ton payloads) within 50 meters of a target
- Low-L/D = blunt rigid heatshield surrounded by a Hypersonic Inflatable Aerodynamic Decelerator (HIAD), hypersonic lift-to-drag ratio (L/D) of ~0.24
- Mid-L/D = slender rigid aeroshell with body flaps, hypersonic L/D of ~0.54

Low-L/D Entry Concept



Mid-L/D Entry Concept

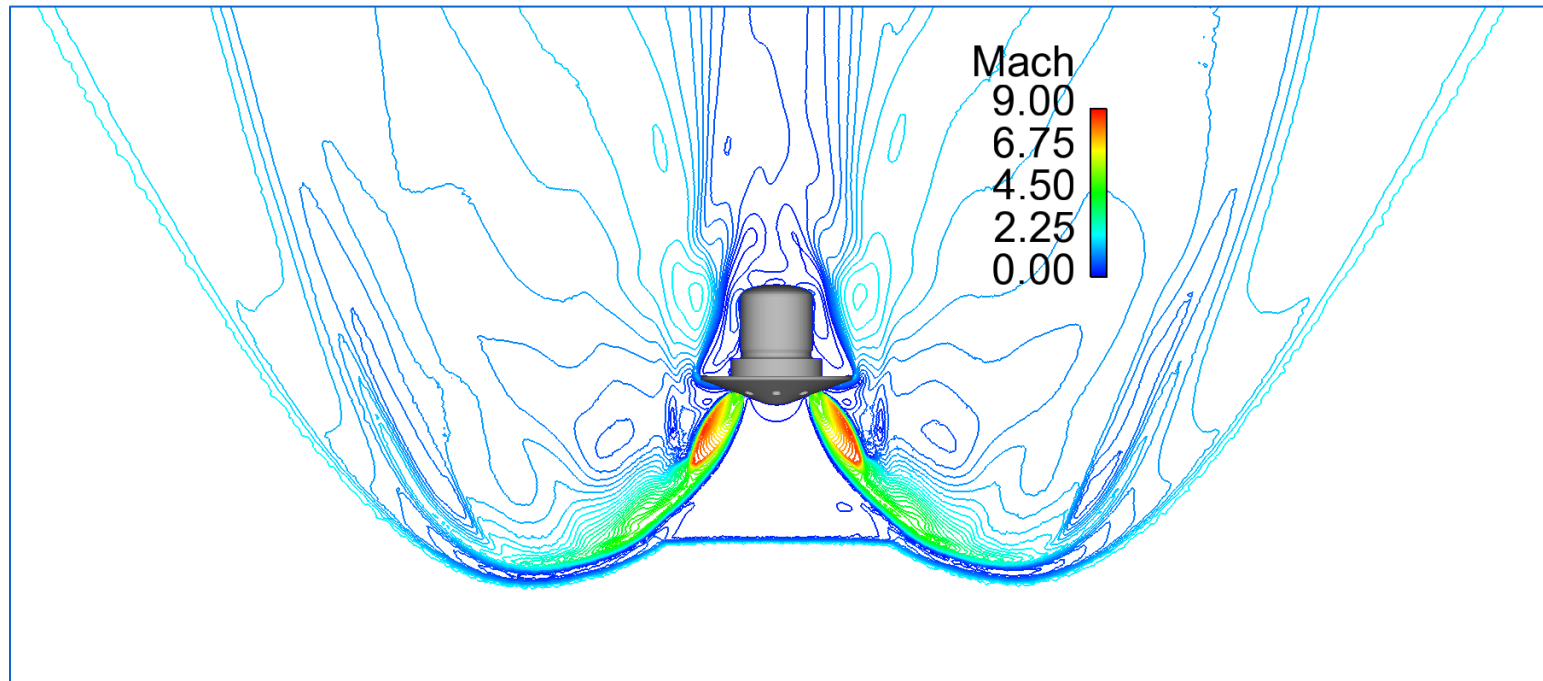


A. Korzun, AIAA-2020-1510

CFD Simulation at Flight Conditions



Loci-CHEM Reynolds-Averaged Simulation, Mach 2.7, 8 100-kN LOX/LCH₄ Engines



F. Canabal, NASA MSFC

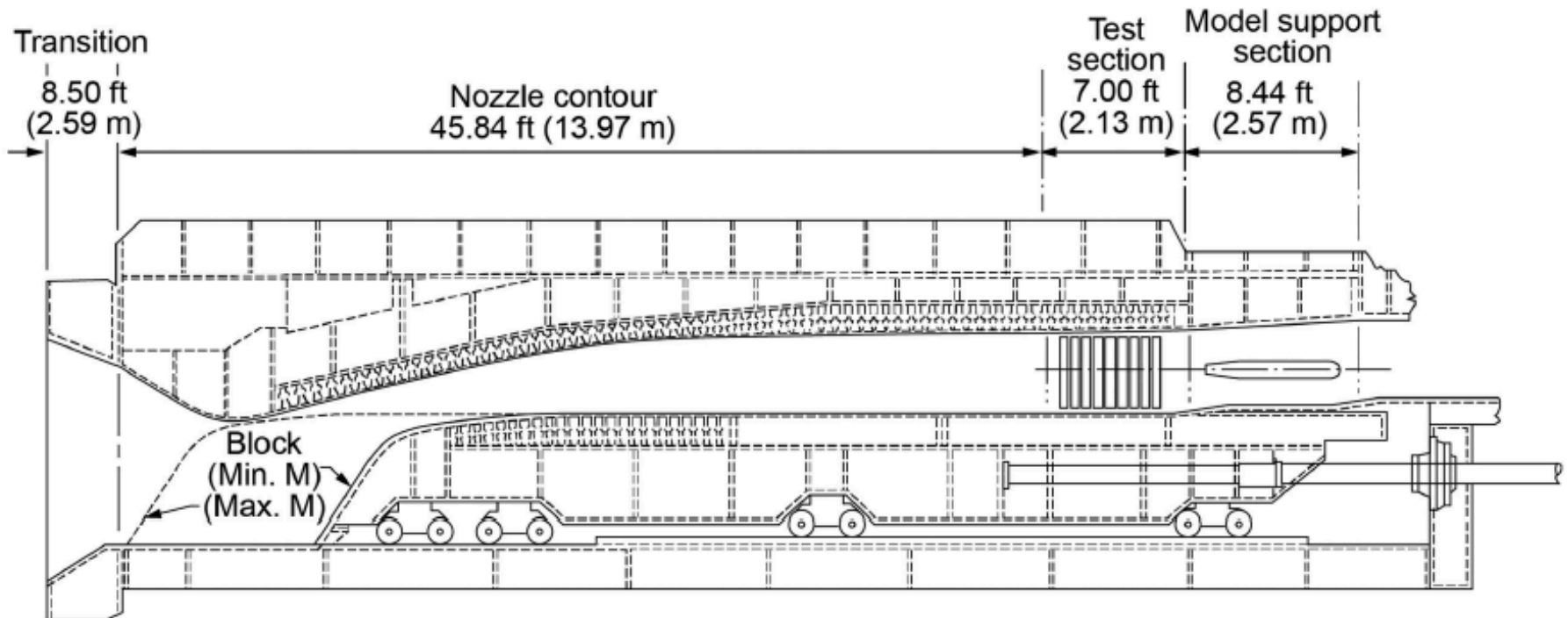
CFD models need to be calibrated with relevant powered descent aerodynamics test data, in order to inform uncertainties for predictions at flight scale

- **Summary of Upcoming Wind Tunnel Test & CFD**
- **Status of Developing New Testing Methods**
 - Flow-Through Balance
 - Heated Ethane
- **Summary & Conclusions**

Langley UPWT Test Section 2



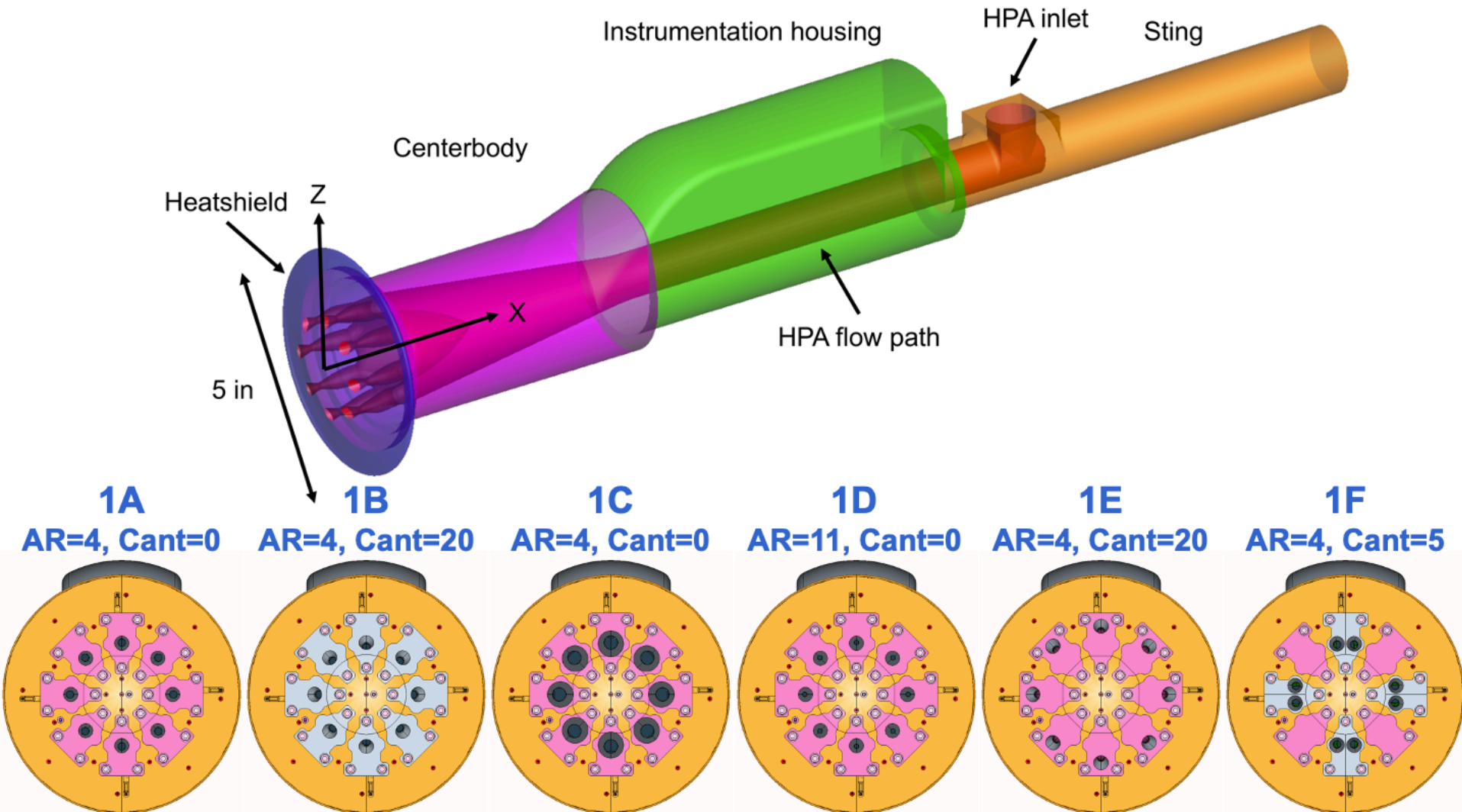
- **A retropropulsion test in the UPWT will start in December/January**
 - Mach number (2.30 to 4.63) is controlled with a sliding-block nozzle, which is used to select the ratio of the nozzle throat area to test section area
- **The main test objective is to estimate interference forces & moments with pressure-sensitive paint (PSP) while simulated retro-rockets are blowing high pressure air (HPA)...and to provide the data for CFD analysis**



Low-L/D Model



- The heatshield will have interchangeable nozzles that vary in size, location, cant angle (deg), and area ratio (AR) to simulate possible flight configurations



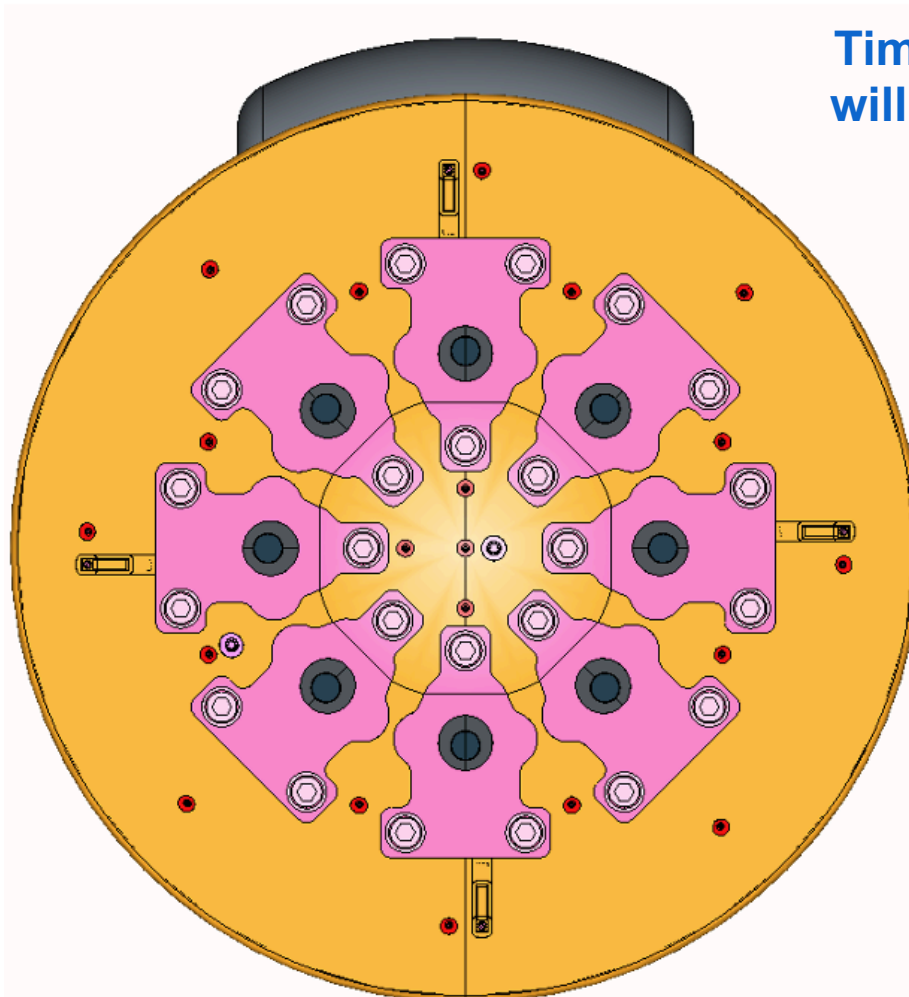
Low-L/D Model Instrumentation



Surface covered in PSP

Steady pressure ●

High-frequency pressure 



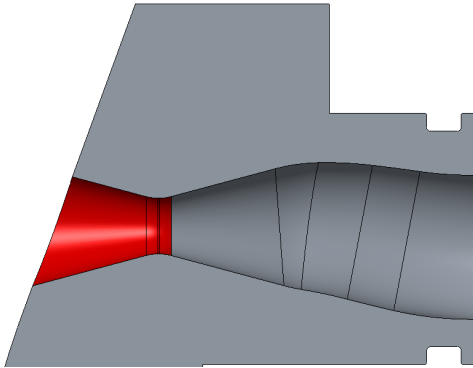
Time-averaged force & moments
will be derived from the PSP

Low-L/D Nozzle Inserts

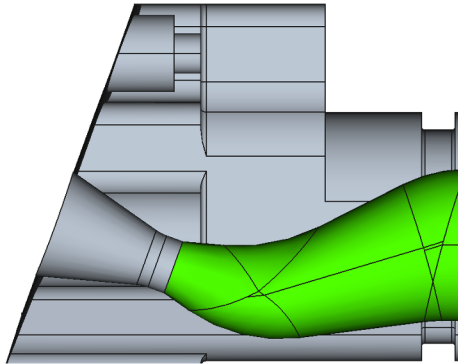


- Conical 15-deg nozzles with $AR = 4$ will be used for all but one model

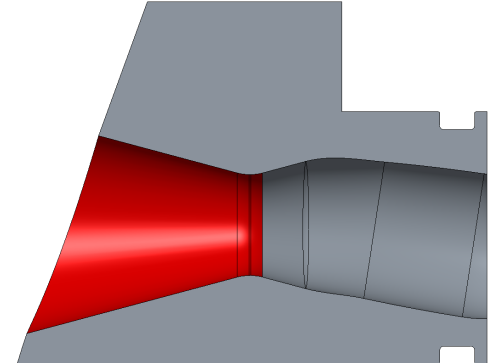
1A, $AR = 4$, Cant = 0



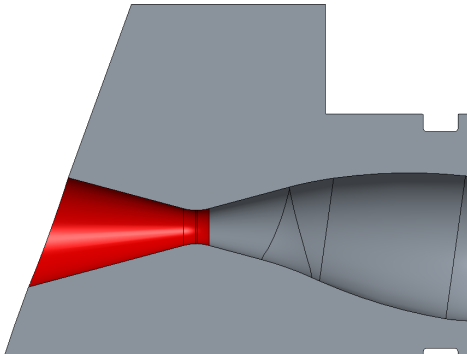
1B, $AR = 4$, Cant = 20



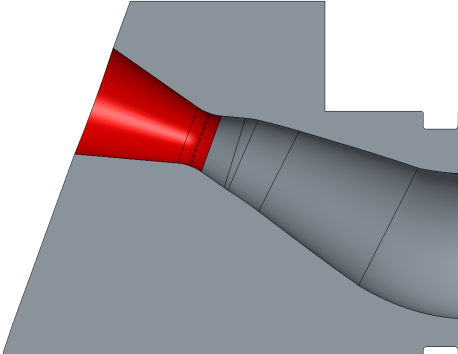
1C, $AR = 4$, Cant = 0



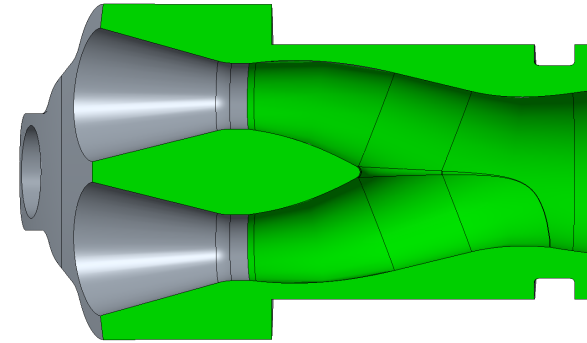
1D, $AR = 11$, Cant = 0



1E, $AR = 4$, Cant = 20



1F, $AR = 4$, Cant = 0



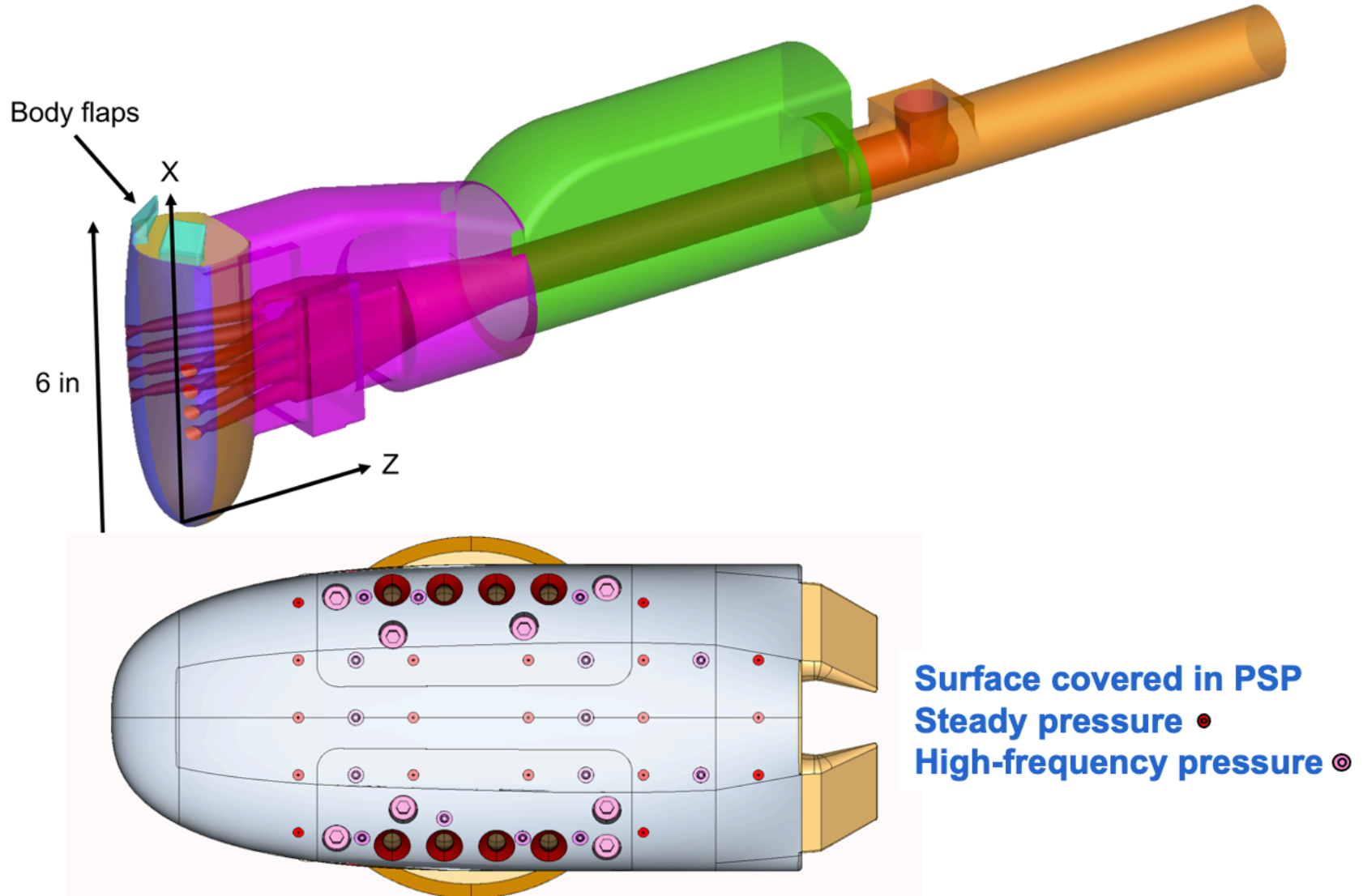
$$AR = 4 \rightarrow M_e = 2.94$$

$$AR = 11 \rightarrow M_e = 4.03$$

Mid-L/D Model & Instrumentation



- The model will have one set of nozzles (AR = 4)



Wind Tunnel Model Scaling



- **Geometric scaling** is used for the model outer mold lines, based on the reference vehicles
- **Jet scaling** is used to tailor the nozzle conditions to approximate the jet interaction parameters that govern the aero/propulsive interaction flowfield, such as:
 - Thrust coefficient, $C_T = \text{Thrust} / (1/2 \rho_\infty V_\infty^2 S_{\text{ref}})$
 - Ratio of nozzle exit pressure and post-shock stagnation pressure, $p_e / p_{0,2}$
- The wind tunnel models will use HPA to simulate the retro-rockets, so full 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

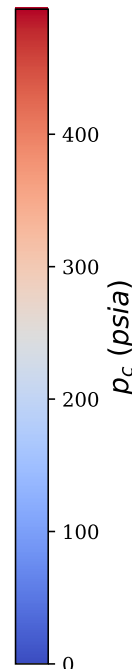
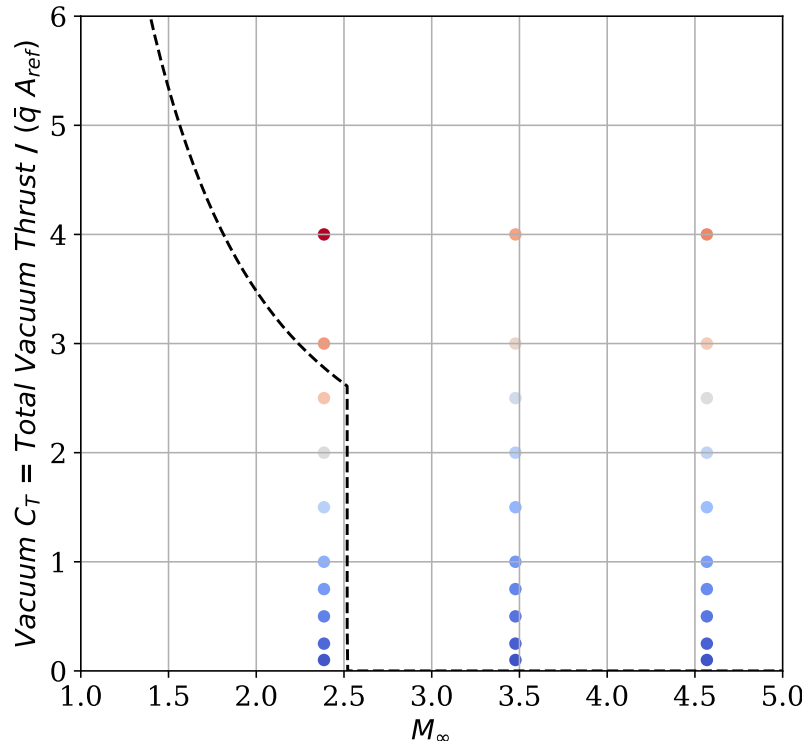
Example Jet Scaling for Model 1A



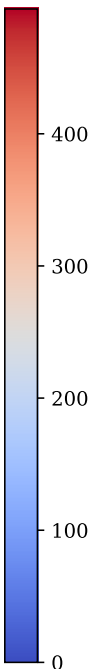
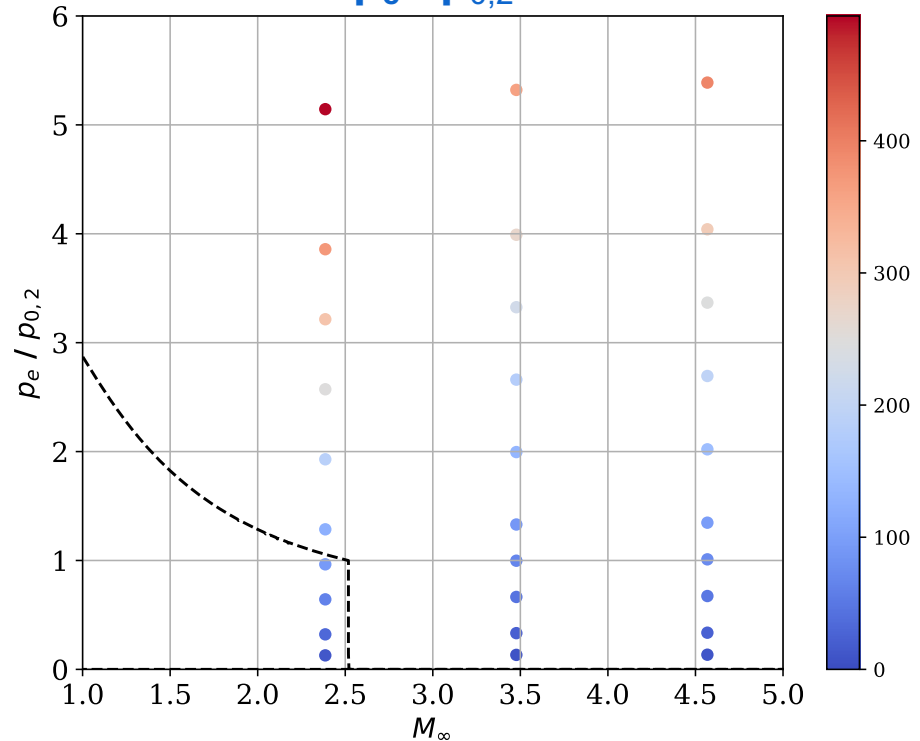
- Each model will be tested at combinations of Mach number (2.4, 3.5, 4.6), angle of attack, roll angle, and HPA pressure (p_c)
- At each condition, p_c will be adjusted to achieve certain vacuum thrust coefficients (C_T) and nozzle pressure ratios ($p_e/p_{0,2}$) that envelope the reference flight conditions

* Max. p_c will be limited by tunnel interference/blockage

Thrust Coefficient



$p_e / p_{0,2}$



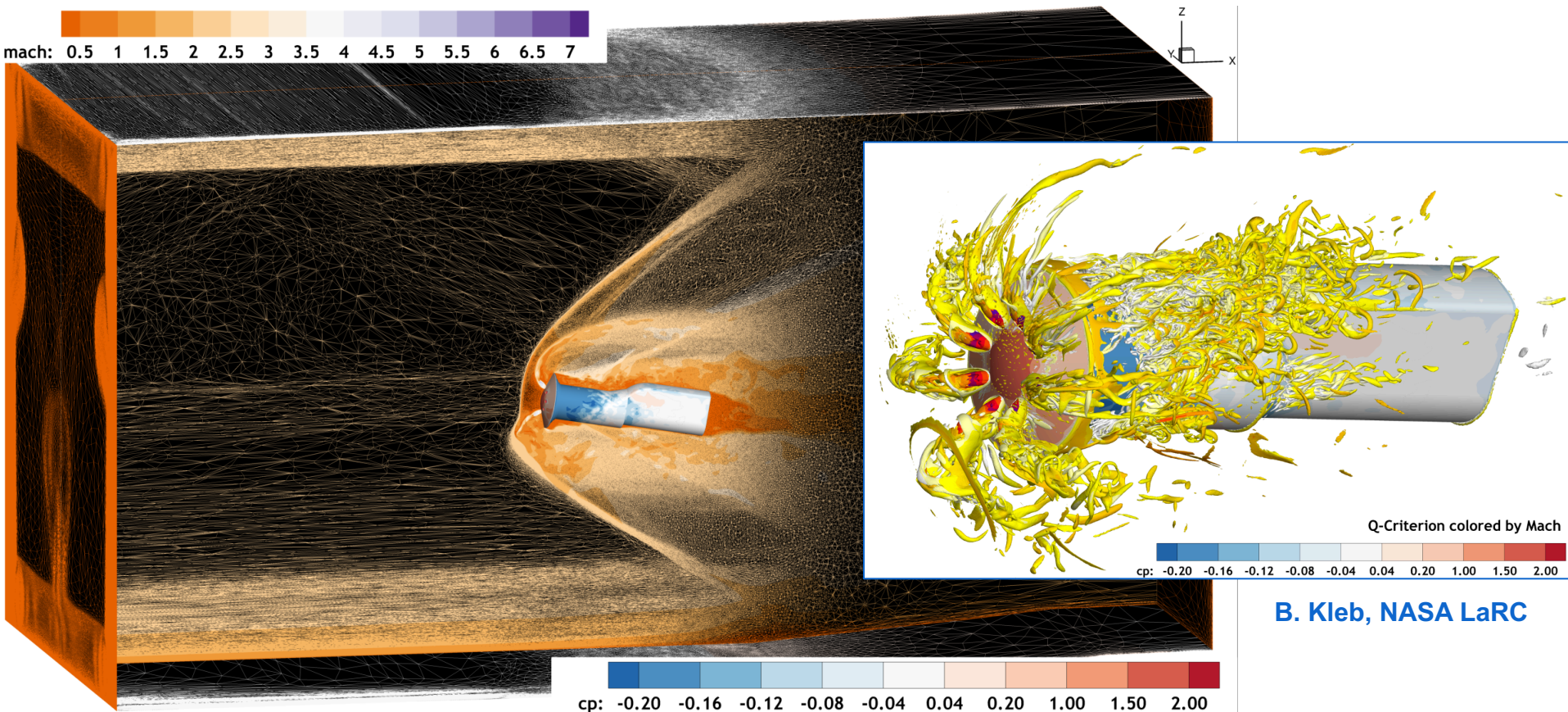
Sample CFD Results, Model 1B

Mach = 2.4, $C_T = 0.5$



- The UPWT test section has non-uniform flow, which means the tunnel walls must be modeled
- CFD results are reported as time-averaged +/- standard deviation

FUN3D Detached Eddy Simulation (50M Points, 50K Time-Averaged Iterations)



B. Kleb, NASA LaRC

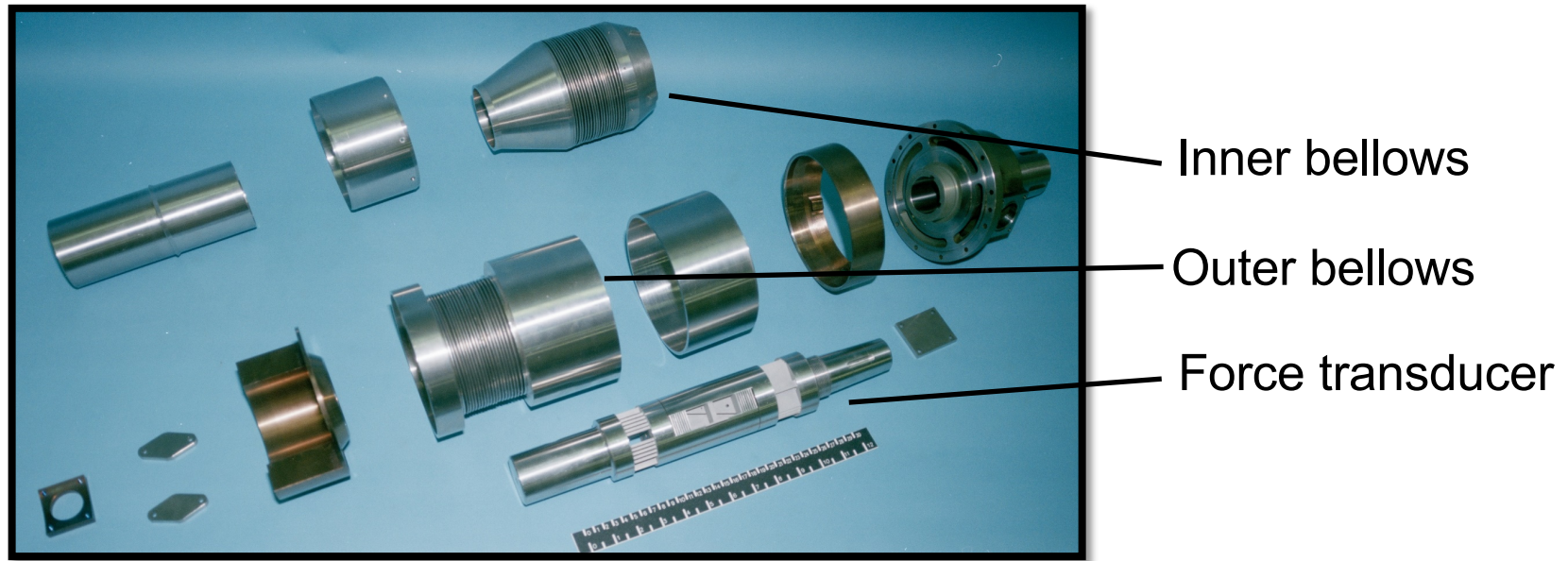
- **Direct six-component force & moment measurements**
 - Ideally, the upcoming test would include direct measurements of aerodynamic interference forces & moments using a flow-through 6-component balance
 - However, the current NASA inventory of flow-through balances (< 5 such balances currently) is not applicable due to insufficient load ranges and a missing or uncalibrated axial force channel
 - An effort to develop a **new flow-through balance prototype** is underway at NASA Langley
- **Better combustion product simulants**
 - The upcoming test will use the standard HPA plumes, but air (and others such as N_2 , helium) are poor simulants of combustion products from LO_2/LCH_4 engines envisioned for Mars EDL
 - NASA Stennis has developed portable hardware to deliver **heated ethane** to sub-scale test articles to better simulate combustion product expansion, will investigate if it can be applied to wind tunnel testing

Better testing methods for retropropulsion aerodynamic interference are needed in the future in order to enhance the test data quality needed to validate CFD methods and build flight aerodynamics models

Force & Moment Transducer Design Involving Fluids



- **Force transducers with fluid flow fall into two categories:**
 - Flow around transducers – lower pressure, higher flow rate
 - Flow through transducers – higher pressure, lower flow rate
- **Flow around transducers typically employ bellows, which are complex to install and maintain and can lead to hysteresis effects**

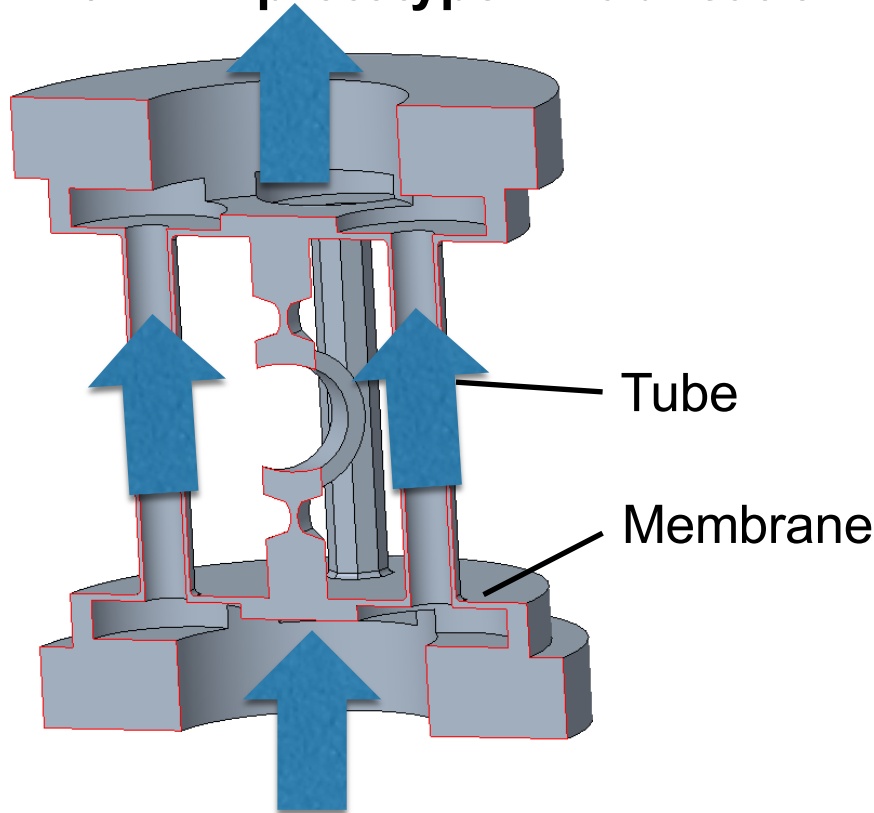


Disassembled View of Heritage NASA Flow Around Design

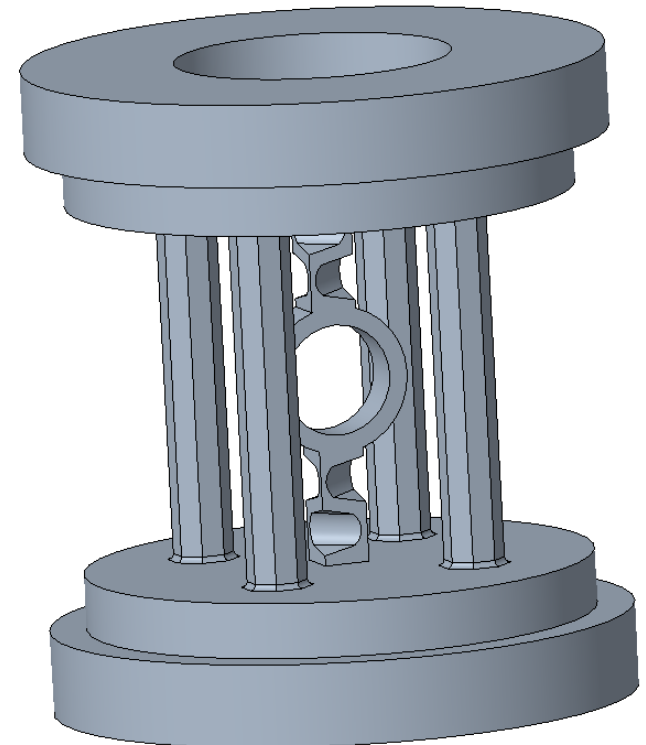
Flow Through Transducer Prototype



- Bellows replaced with structural tubes
- Membranes provide compliance similar to bellows
- Integrates into existing model hardware
- Additive Ti-6Al-4V prototype in fabrication



Section view depicting flow path through transducer.



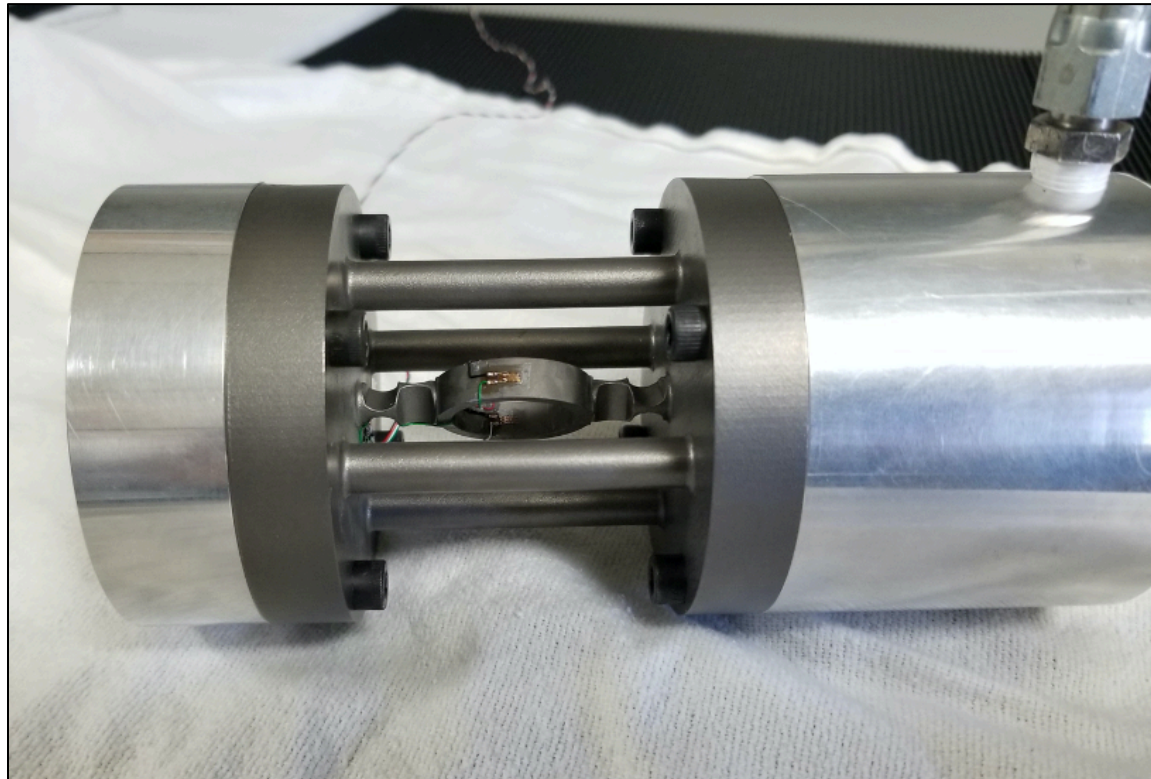
Transducer concept for Mars EDL testing

Transducer Status



- **Prototype was fabricated and passed pressurization testing in November**
- **Testing will continue for the next few weeks, after which production balance can be fabricated**

Flow-Through Balance Prototype



Heated Ethane Plume Simulant



- **Air and other inert gases are poor analogs for rocket exhaust plumes e. g. LOX/GH2 or LOX/LCH4 engines**
 - Poor match of specific heat ratio
- **NASA Stennis proposed to use heated ethane (C_2H_6) for sub-scale rocket testing, rather than inaccurate cold-flow or expensive hot-fire tests**
 - Analysis showed that heated ethane can match the expansion of rocket combustion products, by adjusting total temperature (specific heat ratio)
- **Possible second use case: heated ethane for future retropropulsion wind tunnel tests to better match similitude parameters**

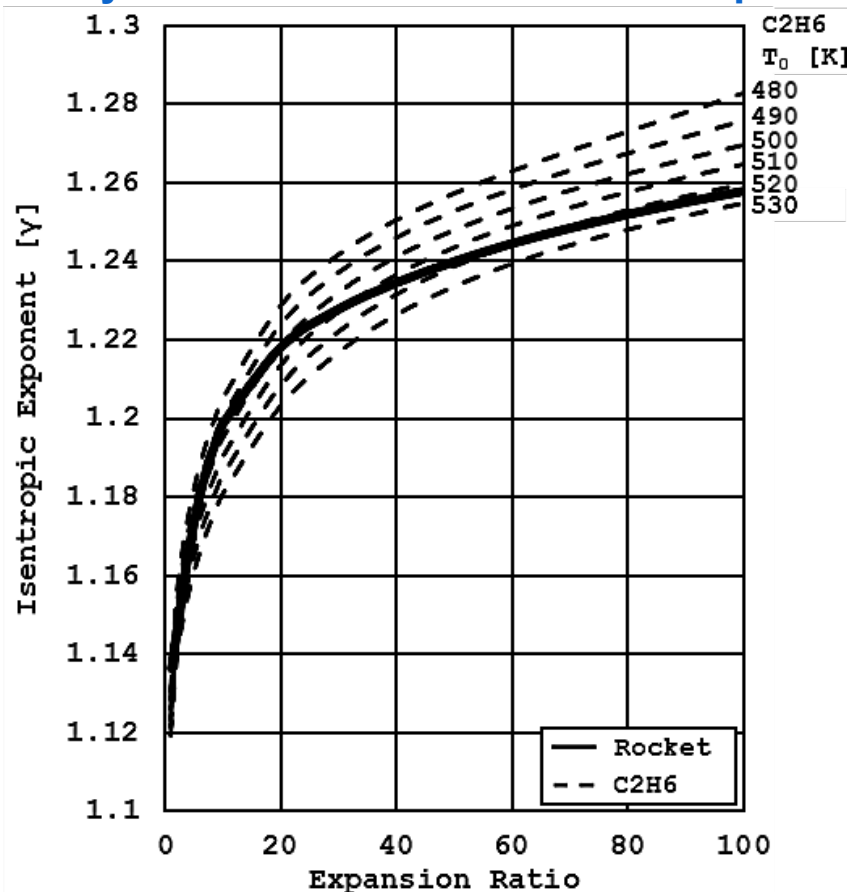
1. Daniel R. Jones, "Physical Simulation Of Rocket Exhaust Aerodynamics Using Heated Ethane: Conceptual Foundations," NASA TM 2019-220446, June 2019
2. Daniel R. Jones, "Physical Simulation Of Rocket Exhaust Aerodynamics Using Heated Ethane: Prototypical Experiments," NASA TM 2020-5009122, October 2020

Heated Ethane Analysis (NASA TM 2019-220446)

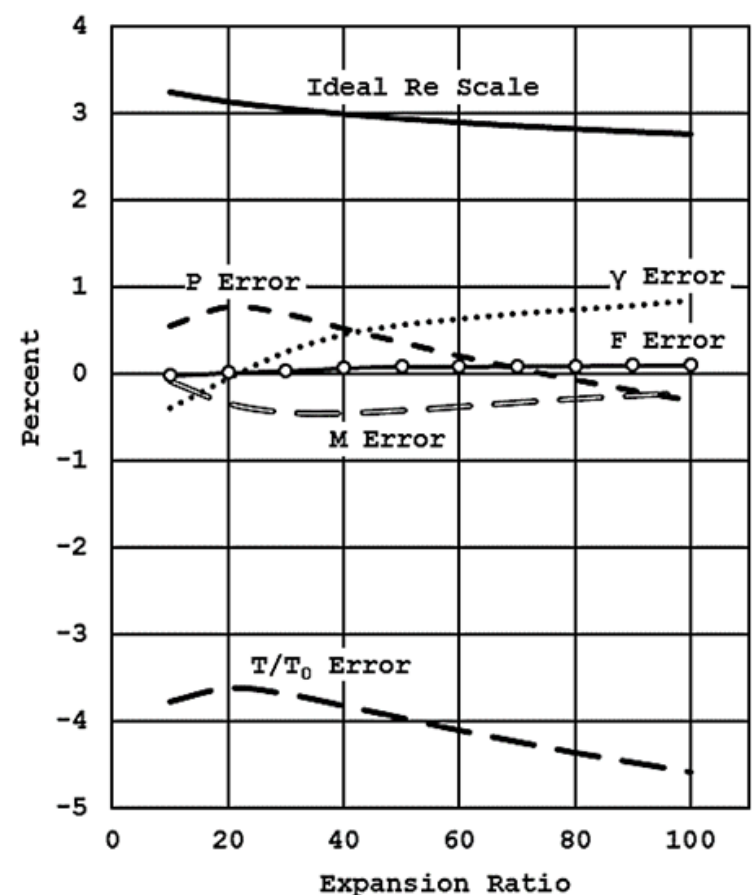


- Matching the specific heat ratio (γ) of combustion products theoretically matches pressure ratio, temperature ratio, Mach number, and thrust
- Stennis and Purdue U. developed test hardware to measure the accuracy of using heated ethane to simulate coupled rocket-diffuser aerodynamics

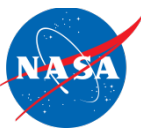
Analysis of LOX/LH2 and Ethane Expansion



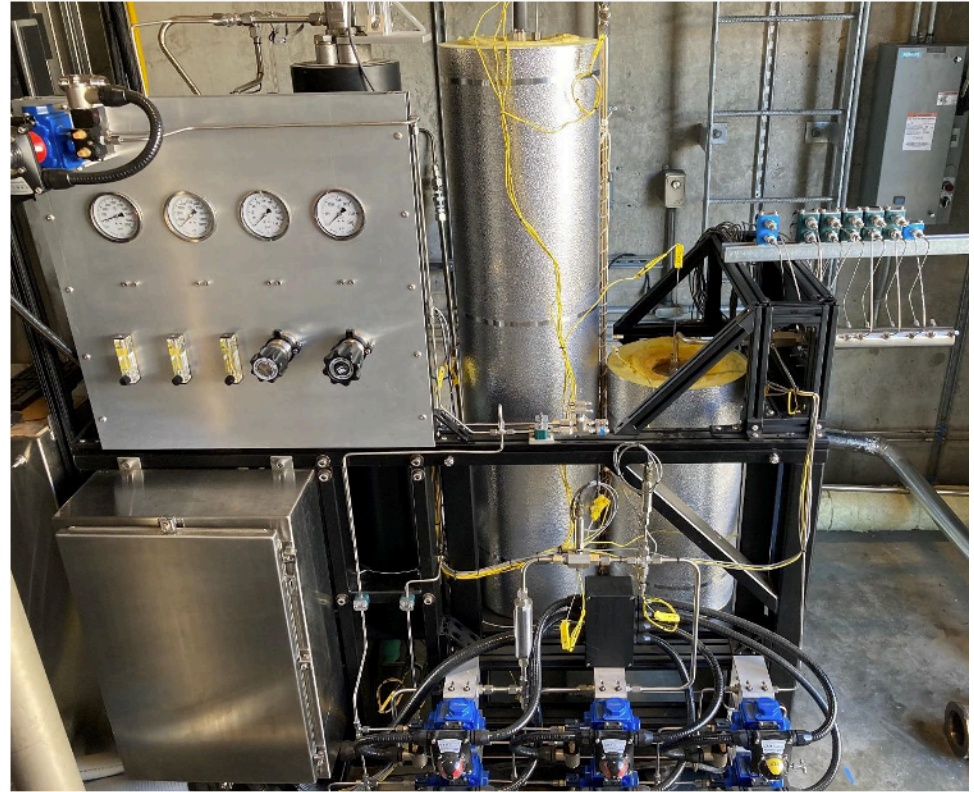
Ethane Errors Relative to LOX/LH2



Hydrocarbon Propellant Delivery System (NASA TM 2020-5009122)



- Designed and built by NASA Stennis and Purdue U.
- Transportable by forklift
- Max. $T_0 = 650$ K
- Max. $p_0 = 20.7$ MPa
- Max. $\dot{m}_{\text{dot}} = \sim 0.3$ kg/s
- Test Duration = ~ 60 s

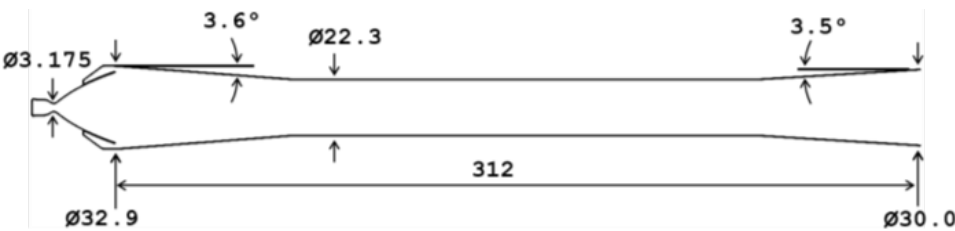


LOX/LH2 Results (NASA TM 2020-5009122)

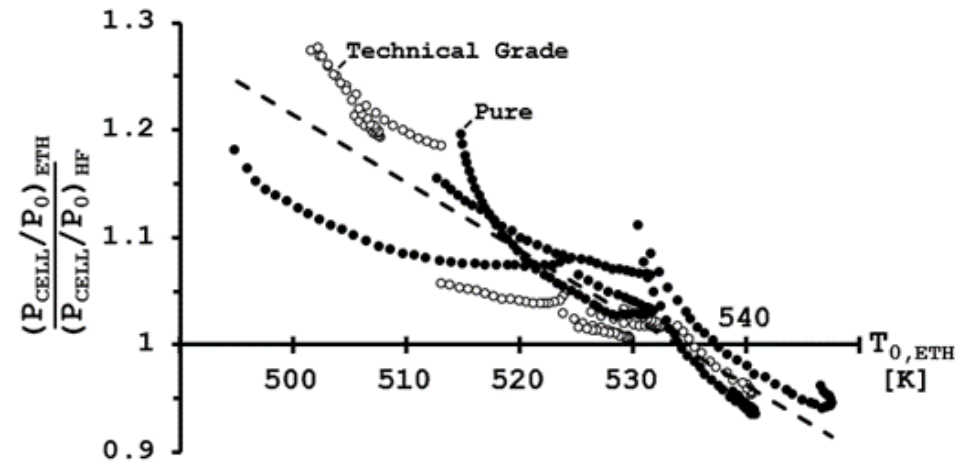


- LOX/LH2 diffuser pressures and flow patterns are matched well using ethane at $T_0=535$ K
 - N_2 could not sustain supersonic diffuser flow

Dimensions (mm)



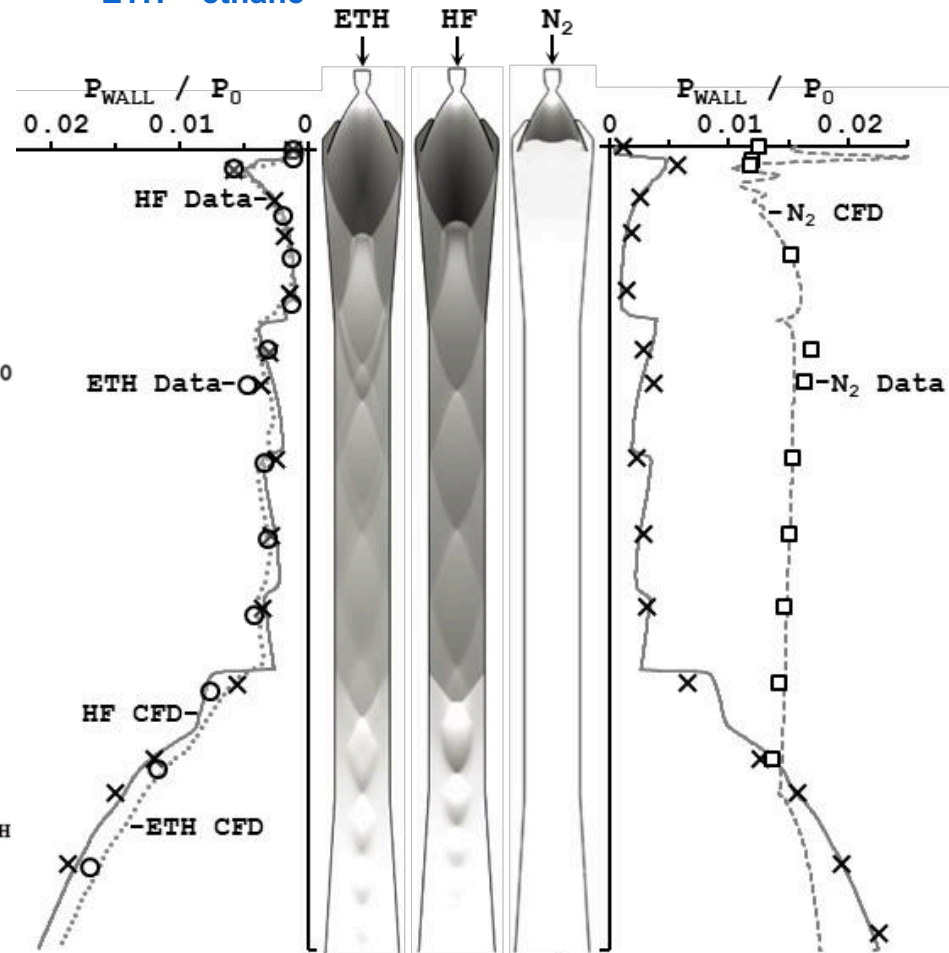
Test Cell Pressure Error



Diffuser Wall Pressure Profiles

HF = LOX/LH2 hot fire

ETH = ethane

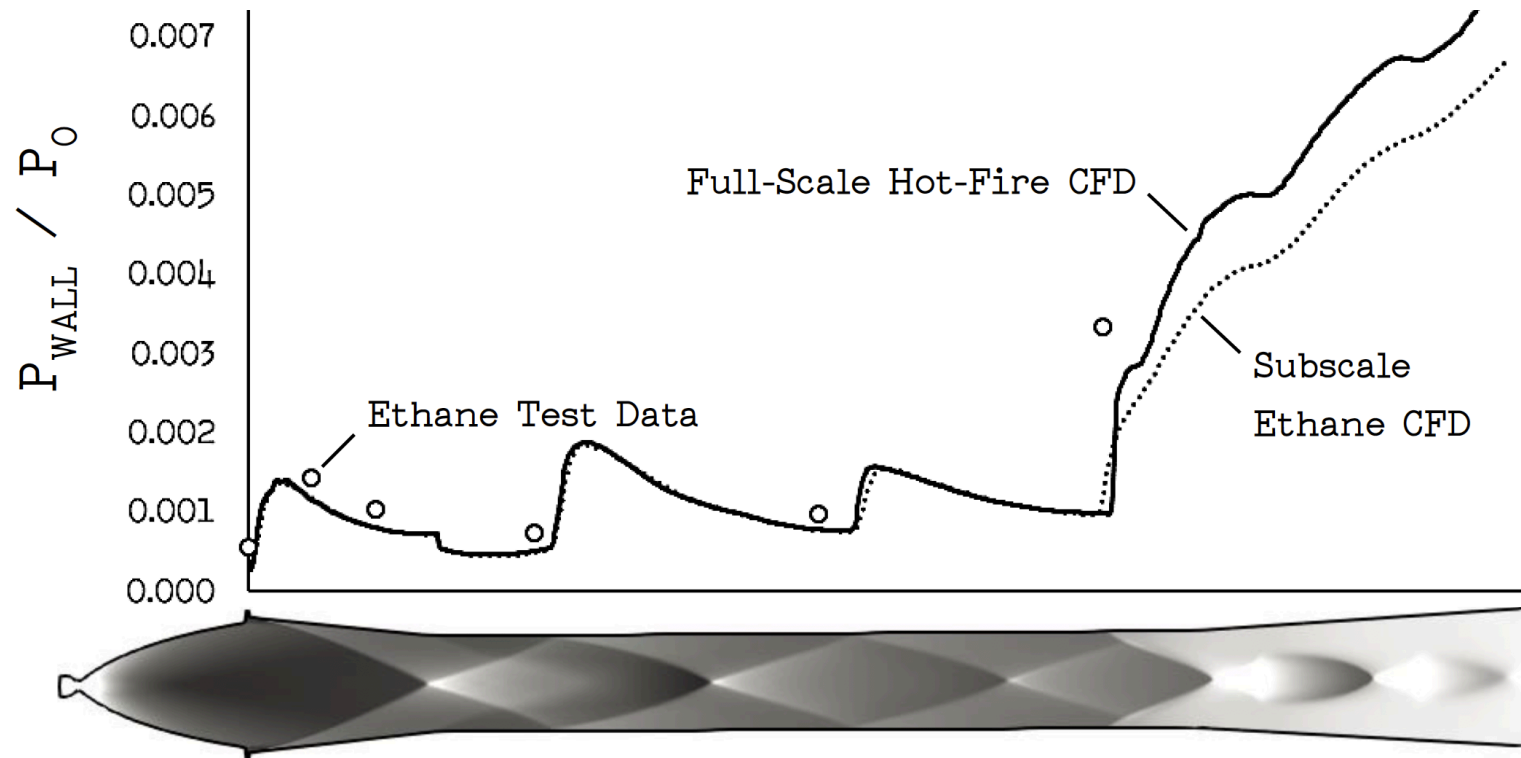


Ethane Results (LOX/LCH4, 177:1 Nozzle)



- LOX/LCH4 expansion through the diffuser is matched well using ethane at $T_0=625$ K

Wall Pressure Profiles



Summary & Conclusions



- New tests and methods for investigating aerodynamic interference effects of retrorockets are needed to reduce risks for future Mars EDL missions
- Two wind tunnel models that are **geometrically-scaled versions** of the current flight reference vehicles will be tested in the Langley Unitary Plan Wind Tunnel in early 2021
 - The test will be followed by extensive uncertainty quantification and comparisons between the test data and CFD models, which will be documented at the 2021 AIAA AVIATION conference
- Parallel development is ongoing for **six-component flow-through balances** and **heated ethane** plume simulants to improve testing methods for future retropropulsion testing

Acknowledgments



- The wind tunnel model and test are funded under NASA's **Aerosciences Evaluation and Test Capability “CFD as a Surrogate for High Supersonic Wind Tunnel Testing”** project
- CFD calculations have been, and will be, run on NASA Advanced Supercomputing Division computers
- CFD analysis to date has been funded by the NASA Space Technology Mission Directorate's Game Changing Development Program

