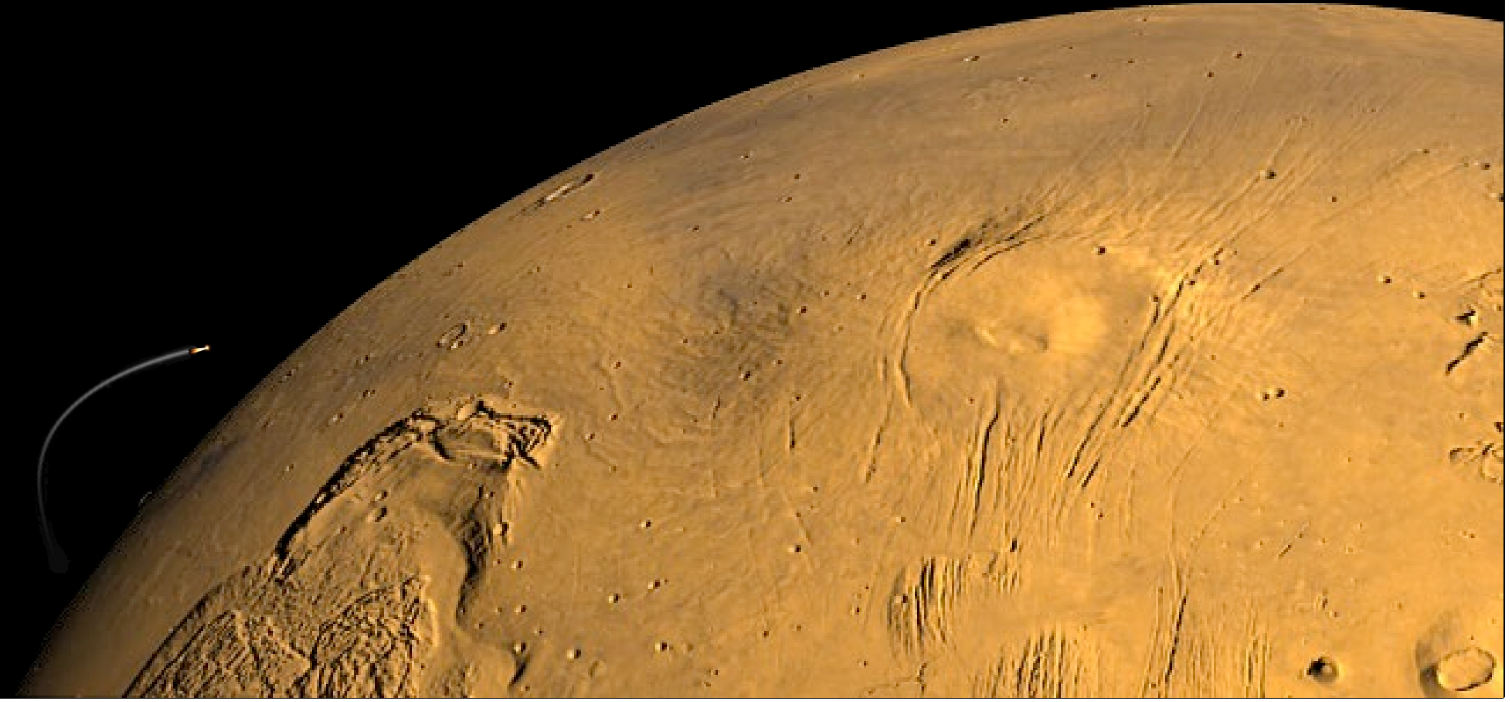
Mars Launch System



Based on charts taken from 3.1-MS-SEIA-TIM-AerodynamicsDraft4.pptx (March 25, 2022)

Jet Propulsion Laboratory
California Institute of Technology

MARSHALL
SPACE FLIGHT CENTER

www.nasa.gov

MLS Aerodynamics

Mark Schoenenberger
Bil Kleb, Sam Shehata, Chris Glass, Ashley Korzun, Craig Hunter, Gabe Nastac, Craig, Streett, Rick Thompson, Bill Wood, Drew Hinkle

June 22, 2023

Aerodynamics: OUTLINE

Intro/Vehicle Configurations

Aerodynamic Tools

Basic Aerodynamic Database, Data and Interface with Simulation

Trajectory Considerations Assessment

Aero/RCS Interactions (Continuum and Rarefied)

Engine-On Aerodynamics

Uncertainty Modeling

Validation Wind Tunnel Test

Aero Environments for Systems Engineering

- **Line Loads, Aeroheating, Aeroacoustics**

MLS Aerodynamics Team

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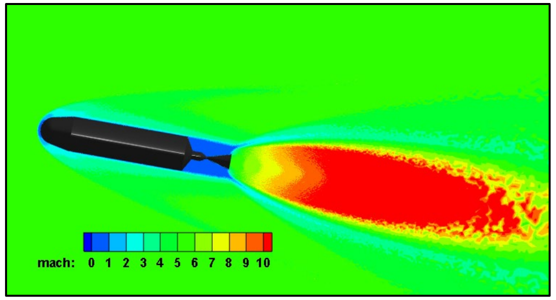
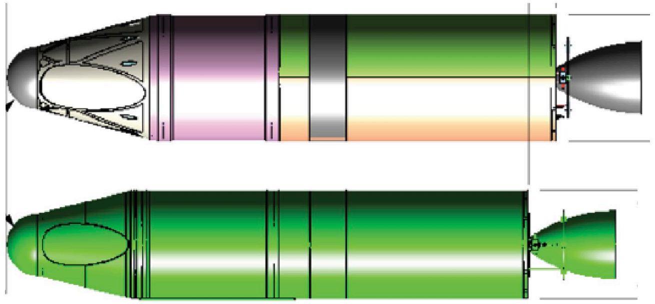
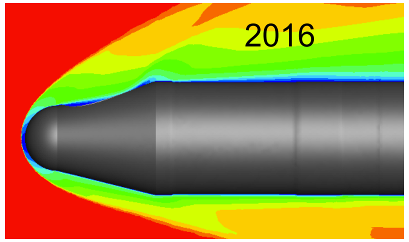
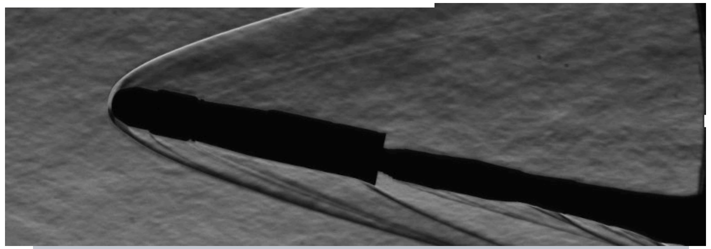
Aerodynamics Support



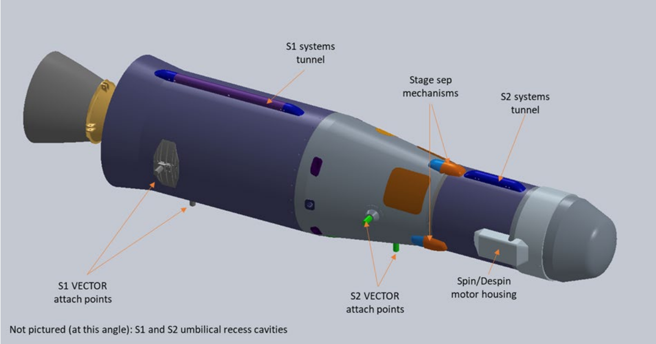
2015







SRC 2021



PDC,2022

NASA LaRC Aero team has provided aerodynamic data supporting DAC, SRC and PDC configurations (and earlier) Assessing aero and helping perform geometry trades during those design cycles

Data products include

- Static Aerodynamic Database
- Shape trade studies (e.g. effects of ramps and fins on stability)
- Line Loads
- Aeroheating data
- Preliminary Aero/RCS interaction calculations
- SRM1 Engine-On Calculations
- Aeroheating, Aeroacoustics and other environments
- Wind Tunnel Test/CFD comparisons for V&V and uncertainty quantification

Data Required for Analysis:

The following data is required as input for aerodynamic database analysis:

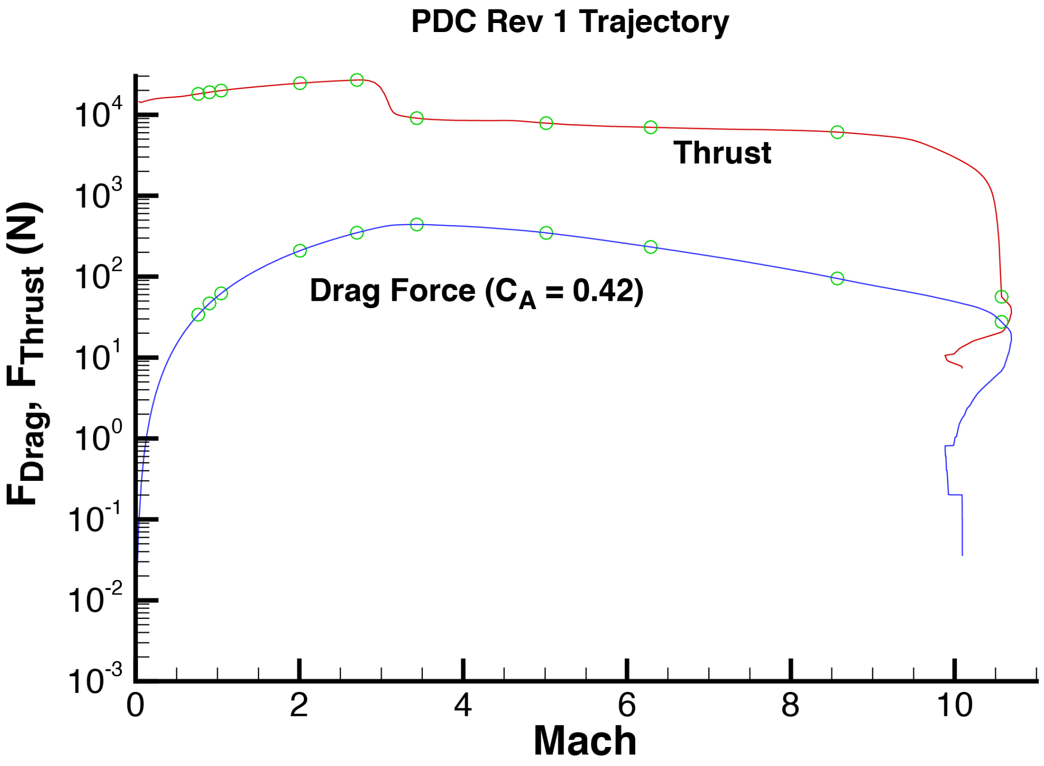
- Watertight surface CAD model of OML

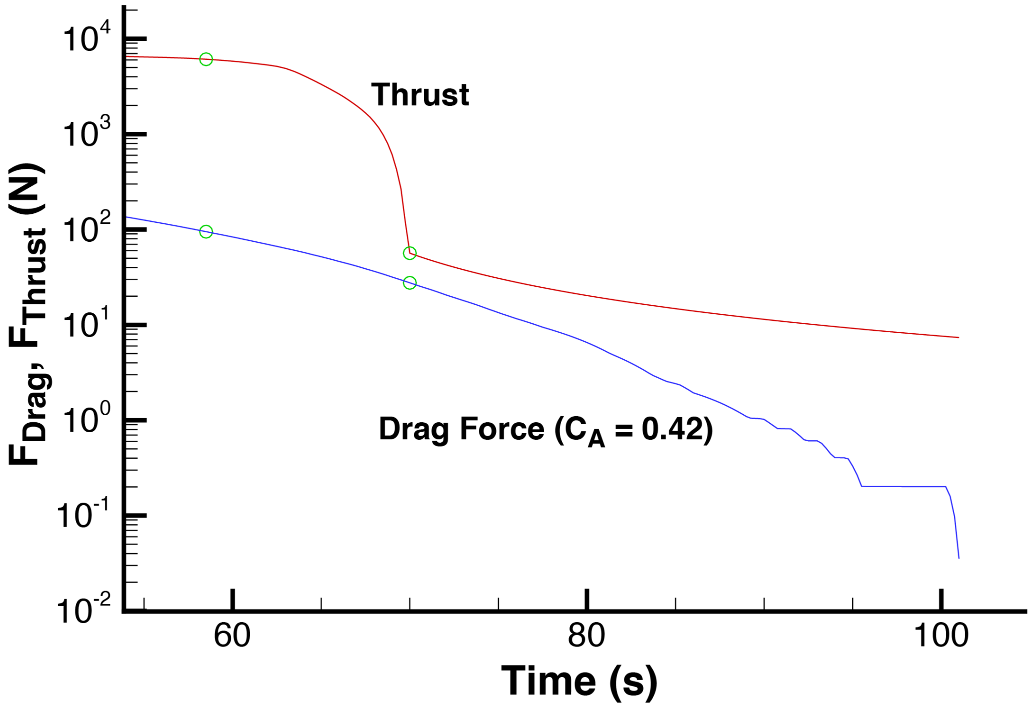
- Reference trajectory including atmospheric conditions (updated iteratively as new aerodatabases are released to run new trajectories)

- Mass Properties
  - center of gravity as function of time along trajectory
  - mass and moments of inertia history

- RCS design
  - CAD model of nozzle contour
  - Chamber conditions
  - Nominal thrust
  - Location and pointing vectors

Reference Trajectory





For ascent performance, Thrust dominates aerodynamic forces
Reasonable drag stability predictions and are sufficient for trajectory design
(Still pay attention to RCS interactions, roll torques from protuberances, etc.)

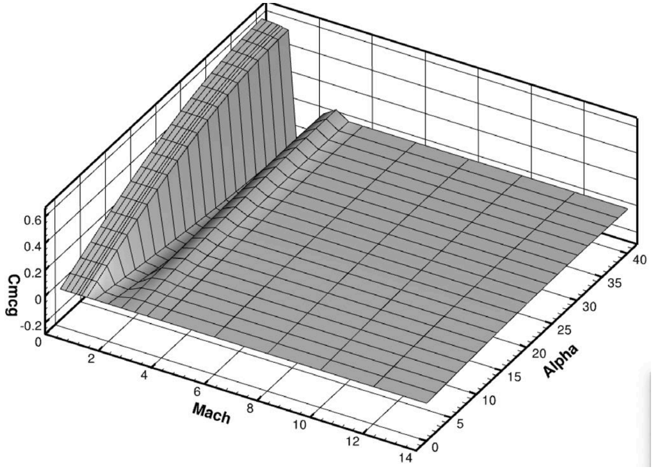
At MECO, thrust and aero forces are changing rapidly. Trajectory may determine where RCS is active and if aft ramp is necessary

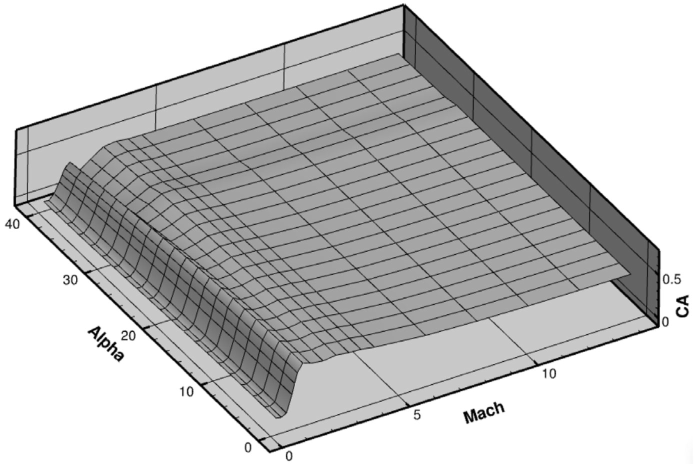
- What is the variation in thrust fall-off of SRM1?
- What is the variation dynamic pressure history (velocity, altitude and flight path angle) at MECO?
- Current studies are investigating how flight performance is affected by aerodynamic considerations in this dynamic region

Aerodynamic Tools For Aerodatabase

Missile Datcom (phased out for most part)

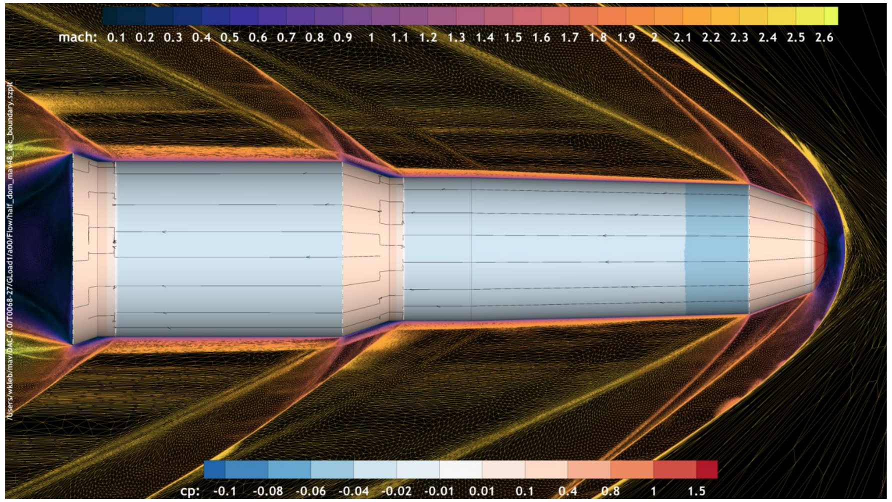
- Mach: Low subsonic through Hypersonic
- Total angle of attack: 0° – 40°
- Geometry based on key breakpoints of DAC 0.0 geometry
- Aerodynamics based on engineering methods (Empirical charts or slender body theory for transonic or lower, modified Newtonian aerodynamics at high supersonic and hypersonic Mach)
- Results sensitive to settings. Small vehicle features (like PLA sphere/cone transition) can have large ramifications on results





FUN3D (Sketch to Solution)

- Navier-Stokes 3D unstructured grid flow solver
- Currently running SA-RC-QCR2000 turbulence model
- Thermally- and calorically-perfect gas (fixed γ = 1.293)
- Agency workhorse tool for SLS ascent aerodynamics, including booster separation



Aero Database/Simulation Interface: FORTRAN

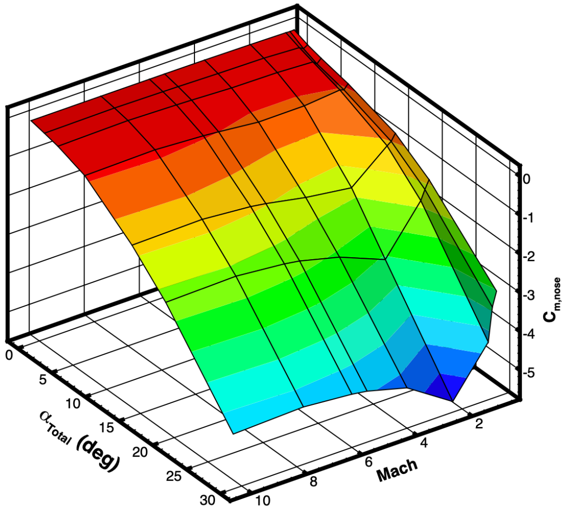
FUN3D Aerodynamic Database

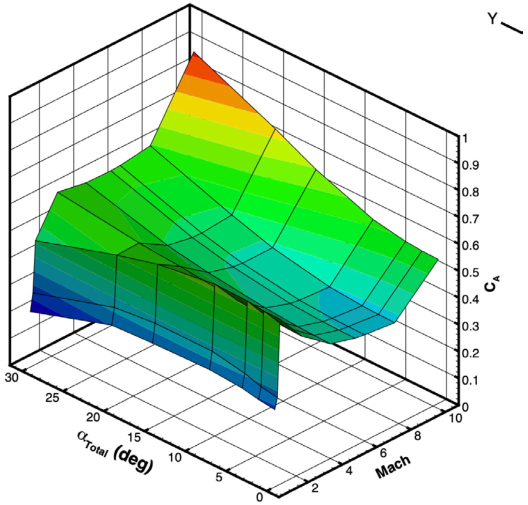
Higher fidelity data including Protuberances

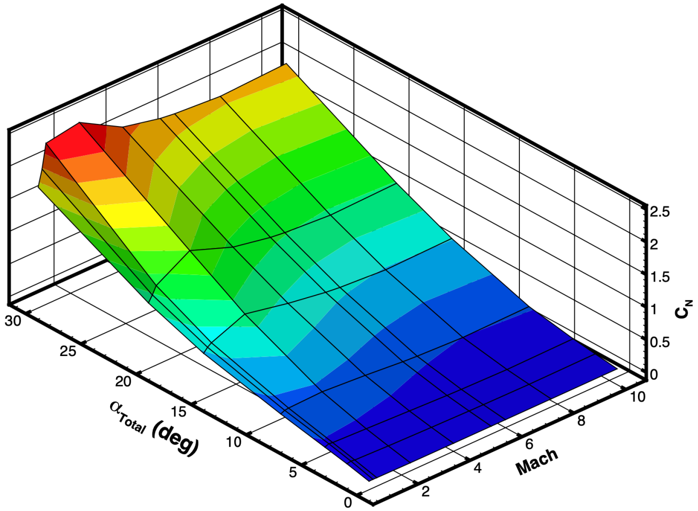
- Trajectory conditions taken from prior SRC Trajectory (01-25-2021) pending update for PDC vehicle
- Mach = 0.75, 0.901, 1.050, 2.341, 4.002, 5.450 (Peak Q), 6.001, 7.760, 10.306
- Total angle of attack: 0, 2, 8, 15, 20, 30
- CFD run on PDC with protuberances and SRM1 Nozzle, modeled as axisymmetric (future releases will be function of total angle of attack and roll angle, output as 6-DoF coefficients in body coordinates)

Fortran90 Subroutine

```
C::SSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSS

C::::::                        VERSION Solid v0.3FUN3D
C::::::                DATE:   Friday July 31, 2020

      subroutine mav_aero_solid_v0_3FUN3D (xcgod,ycgod,zcgod, xdens,
     &                   machd,vel,alphad,betad,
Check&                          gamma,
     &                          cnd, cad, cyd, cmd, cwd, clld,clp,cmqd, cnrd,
     &                  ddref,uncrts,rcsunc,rcsthr,idisperse,rcsflg)

C::SSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSS

c  children:  bridge, decomp, freem, hyper_kn2, trans3 sub_super_2, {scale,super}_hyp

c       Questions regarding this routine should be addressed to
c   Mark Schoenenberger (757-864-1833) m.schoenenberger@larc.nasa.gov
c ----------------------------------------------------------------------
c solid_v0_3FUN3D
c   Replaced continuum aerodynamics with FUN3D data provided by Bil Kleb for continuum aerodynamics:
c   Approximate geometry (using DATCOM Option 2 geometry definition)
c   created from configuration defined in "June 10 Ref Design.xlsx"
```







FUN3D

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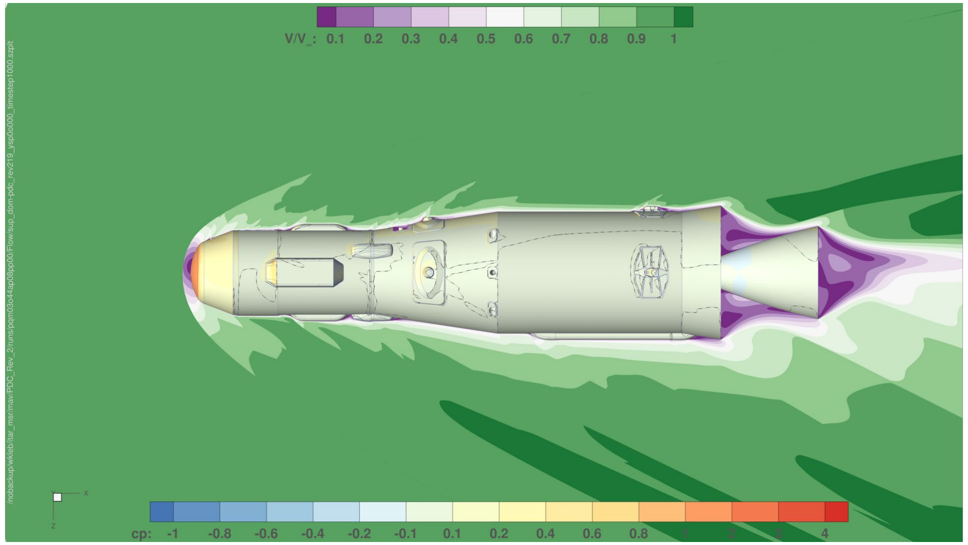
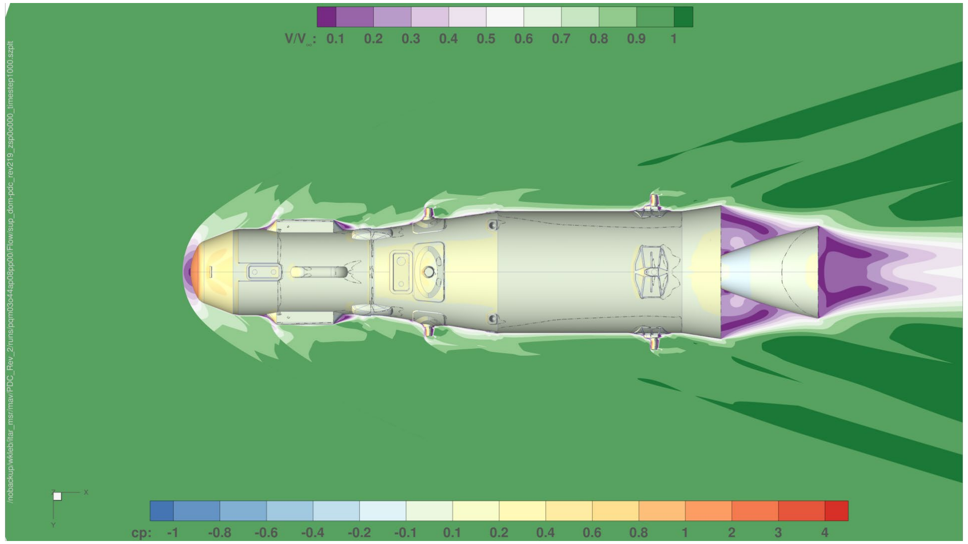
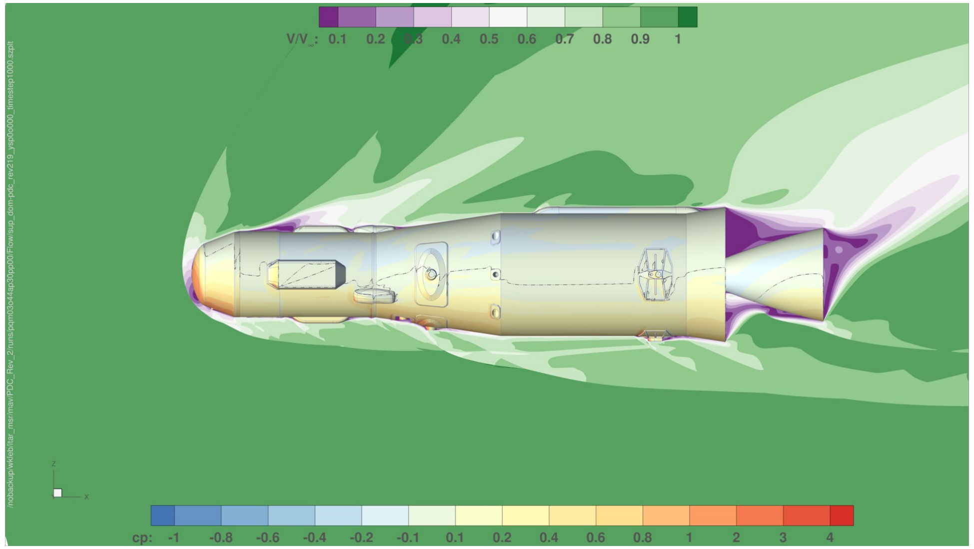
PDC Rev 2 FUN3D Aerodatabase Cases

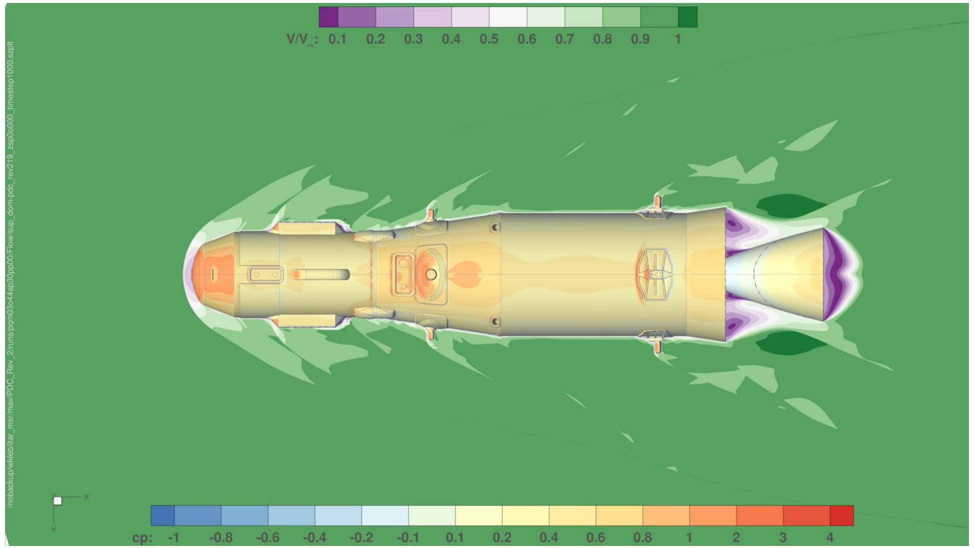
Peak Dynamic Pressure, Alpha = 8





Peak Dynamic Pressure, Alpha = 30

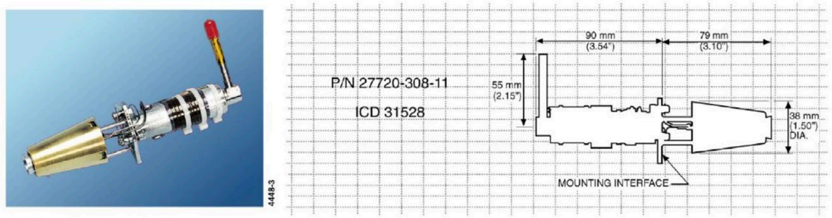




RCS Jet Interactions: Engine Simulation

Engine information on public website

MR-111C 4 N (1.0-lbf) ROCKET ENGINE ASSEMBLY



Design Characteristics
- Propellant .... Hydrazine
- Catalyst S405
- Thrust/Steady State .... 5.3 – 1.3N (1.2 – 0.3 lbf)
- Feed Pressure .... 27.6 – 5.5 bar (450 – 50 psia)
- Chamber Pressure .... 12.1 – 3.4 bar (200 – 35 psia)
- Expansion Ratio 74:1
- Flow Rate ...... 2.4 – 0.6 g/sec (0.0053 – 0.0014 lbm-sec)
- Valve .... Dual Seat
- Valve Power .... 8.25 Watts Max @ 28 Vdc & 21°C
- Valve Heater Power .... 1.54 Watts Max @ 28 Vdc & 21°C
- Cat. Bed Heater Pwr ... 3.85 Watts Max @ 28 Vdc & 21°C
- Mass .... 0.33 kg (0.73 lbm)
  - Engine .... 0.13 kg (0.28 lbm)
  - Valve .... 0.20 kg (0.45 lbm)

Performance
- Specific Impulse .... 229 – 215 sec (lbf-sec/lbm)
- Total Impulse .... 260,000 N-sec (58,500 lbf-sec)
- Total Pulses 420,000
- Minimum Impulse Bit ...... 0.08 N-sec @ 6.9 bar & 15 ms ON .... (0.0171 lbf-sec @ 100 psia & 15 ms ON)
- Steady State Firing .... 5,000 sec min – Single Firing

Status
- Flight Proven

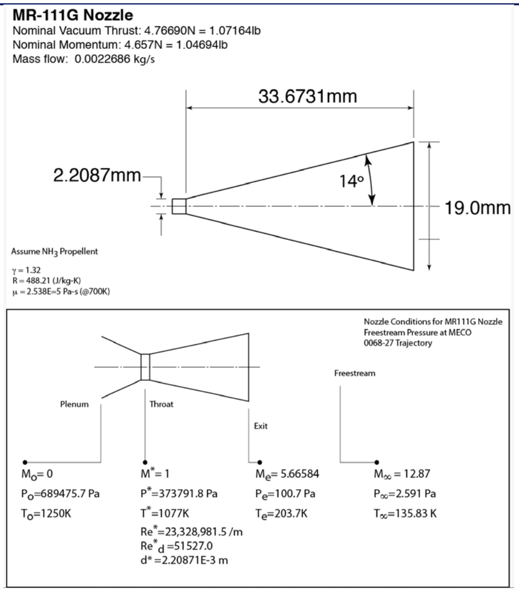
Status
- AIAA-1999-2469

Rev. Date: 4/26/06

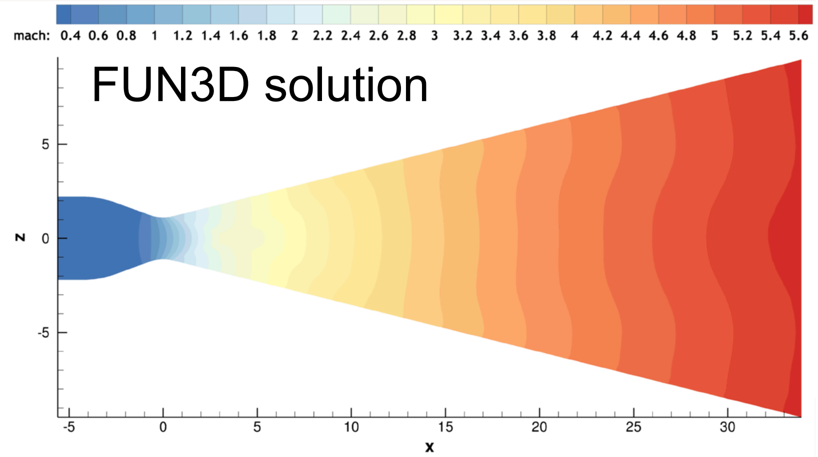
11411 139th Place NE • Redmond, WA 98052
(425) 885-5000 FAX (425) 882-5747

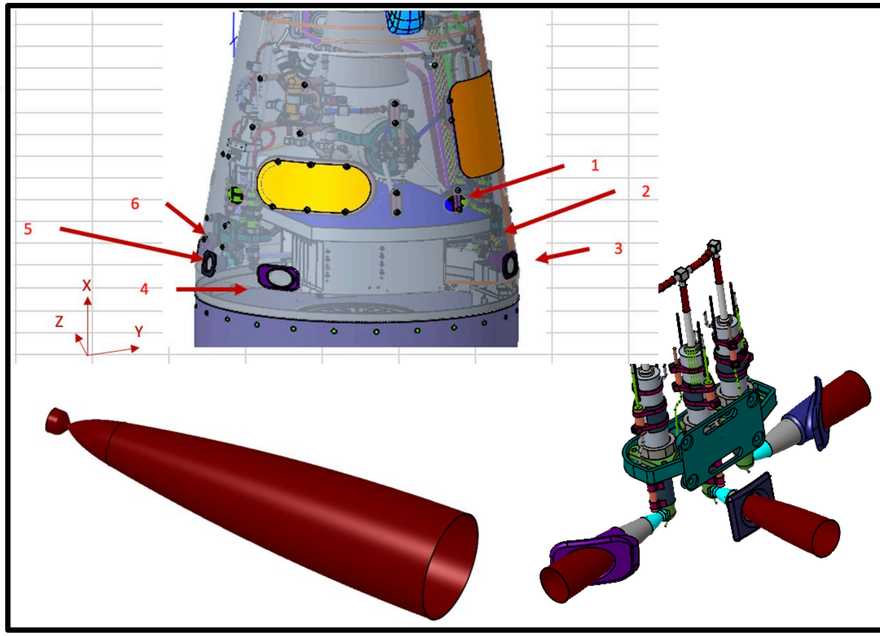
Approved for public release and export

AEROJET



- First nozzle designed for FUN3D CFD, based on publicly available data (Aerojet website) for 4N engine
- 1-D Nozzle equations for chamber, throat and exit conditions in FUN3D solutions
- Conditions modified to run with single gamma FUN3D solution
- Standalone nozzle calculations agree with 1-D equations to within 1-2%



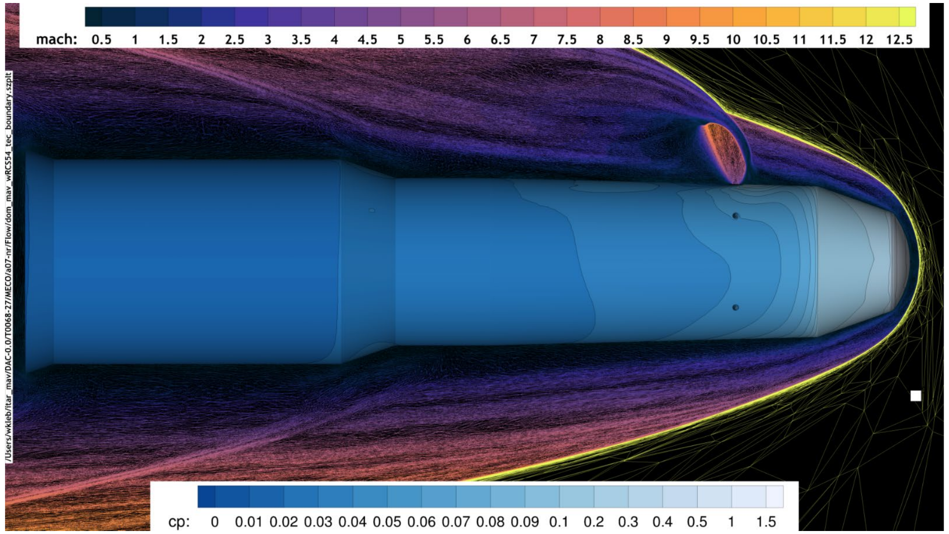


SRC 2.0 RCS Jet Interaction Cases have been run (interactions being calculated)

RCS engine have very large expansion Aero team is investigating nozzle flow to assess confidence in exit flow and plumes

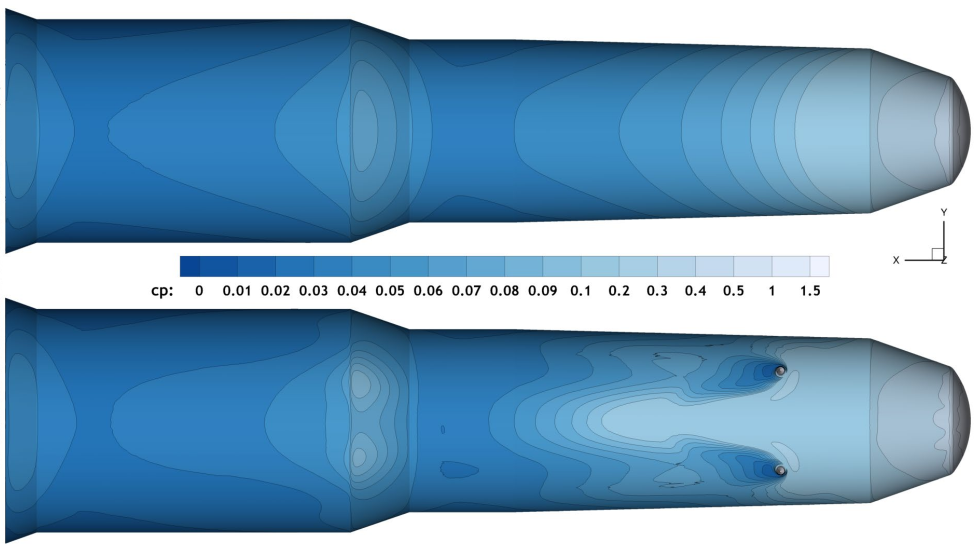
RCS interaction and engine flow findings will inform analysis on PDC vehicle, when RCS configuration is provided

Aero/RCS Interaction Prediction/Calculation



MECO, a = 7°
Nose-right jet

Plumes stagnate flow ahead of RCS and disrupt flow downstream



MECO, a = 7°

Pitch-up jets
Net high-pressure region ahead of cg augmenting RCS authority

$C_{m,JI}^{+Pitch} = 0.163 = +16.3\%\ augmentation$

Preliminary DAC 0 RCS cases run at MECO conditions,

- α=0, 6.9° , Mach = 12.86, Q=257Pa
- +Pitch, -Pitch, +Yaw (Nose Right), +Roll
- Jet interactions described in terms of ideal jet authority

Example Jet Interaction Calculation

$$C_{m,JI}^{+Pitch} = \frac{C_{n,On}^{+Pitch} - C_{n,Off}}{C_{n,jet}^{+Pitch}}$$

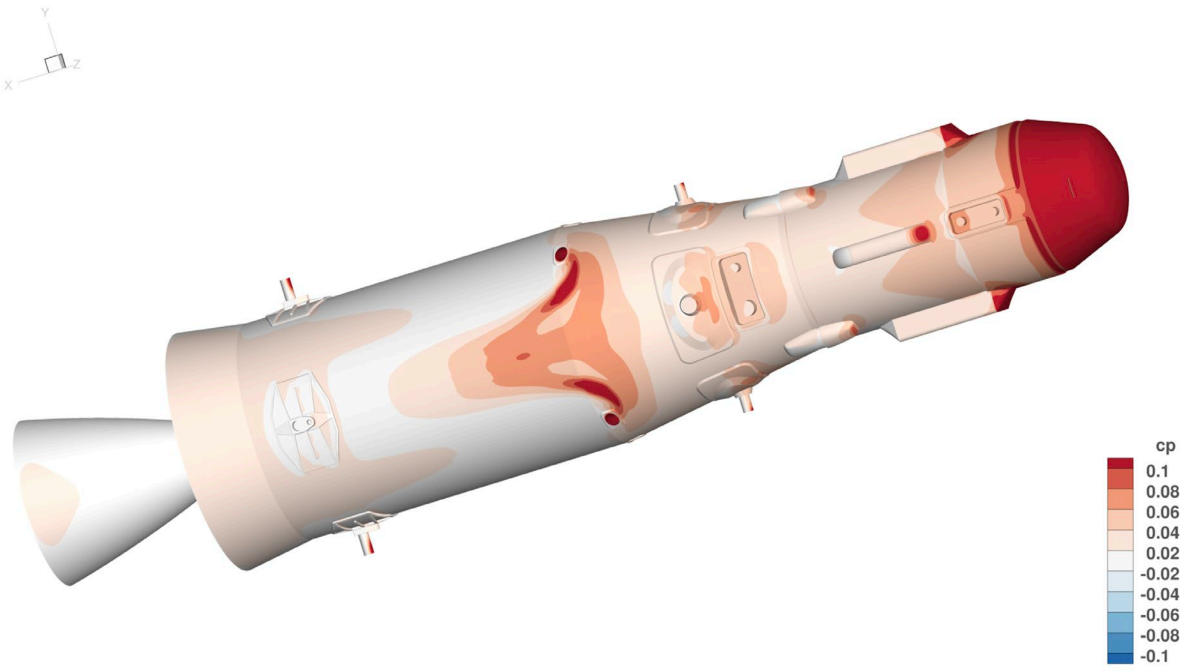
$$C_{n,jet}^{+Pitch} = \frac{T_{jet}^{+Pitch}}{q_\infty S_{Ref} d_{ref}}$$

Jet interactions calculated to date all augment commanded authority

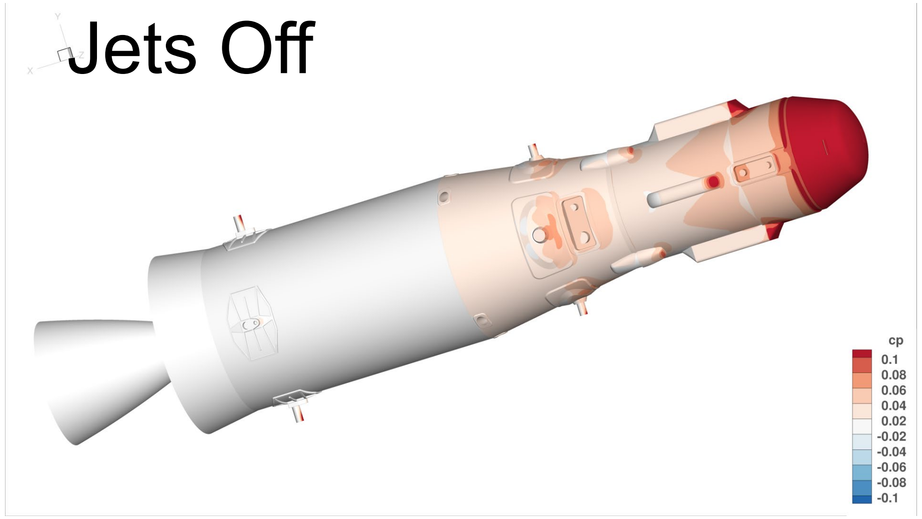
- Augmentations range from +4% of commanded torque up to +40%, depending on jet and vehicle attitude

RCS Jet Interaction Calculations

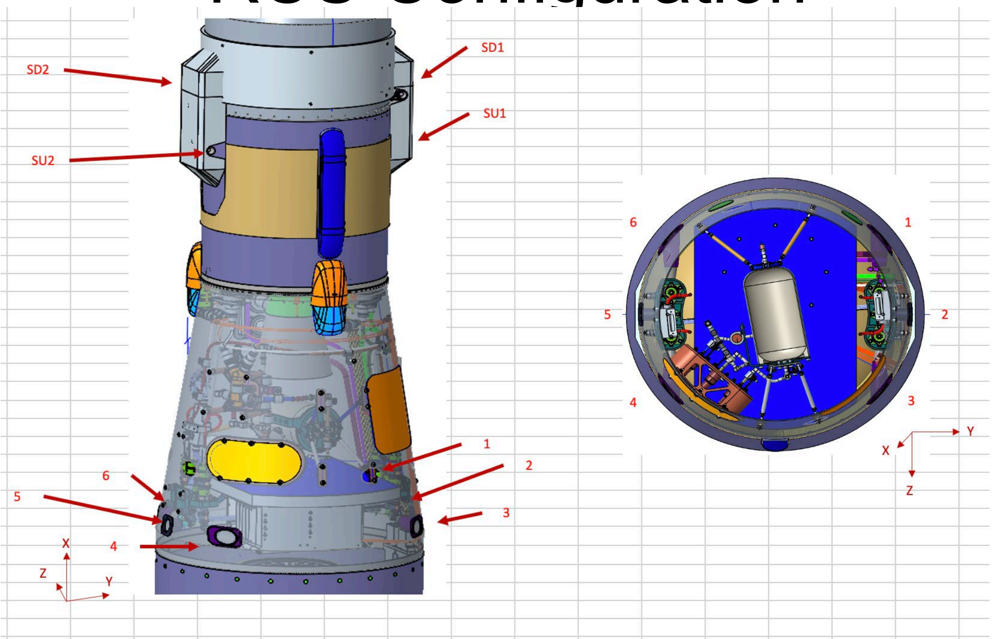
FUN3D CFD analysis conducted to investigate aero/RCS Jet Interactions, compared to RCS torques



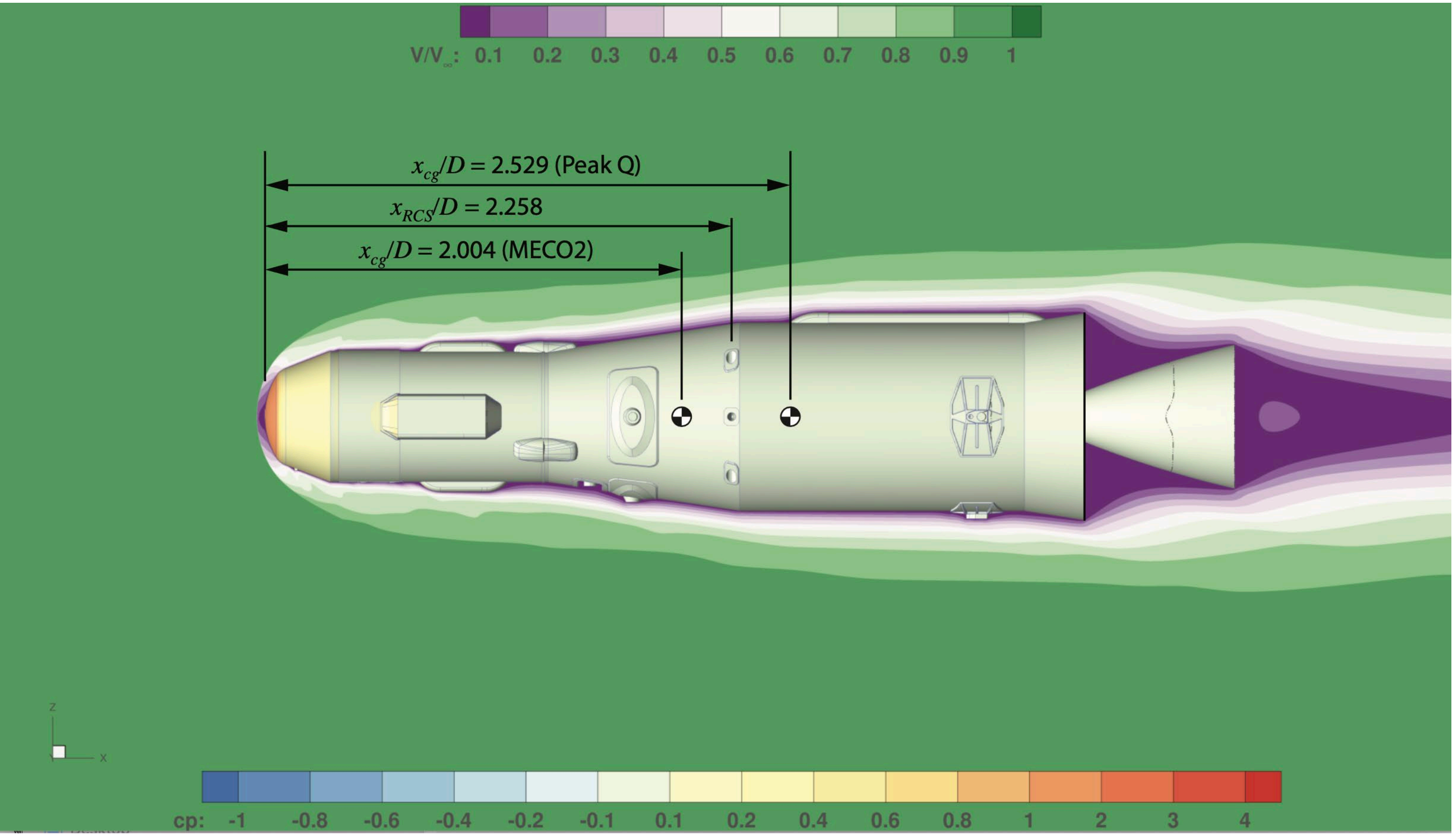
Jets Off



RCS Configuration



Center of Gravity Shift During SRM1 Burn



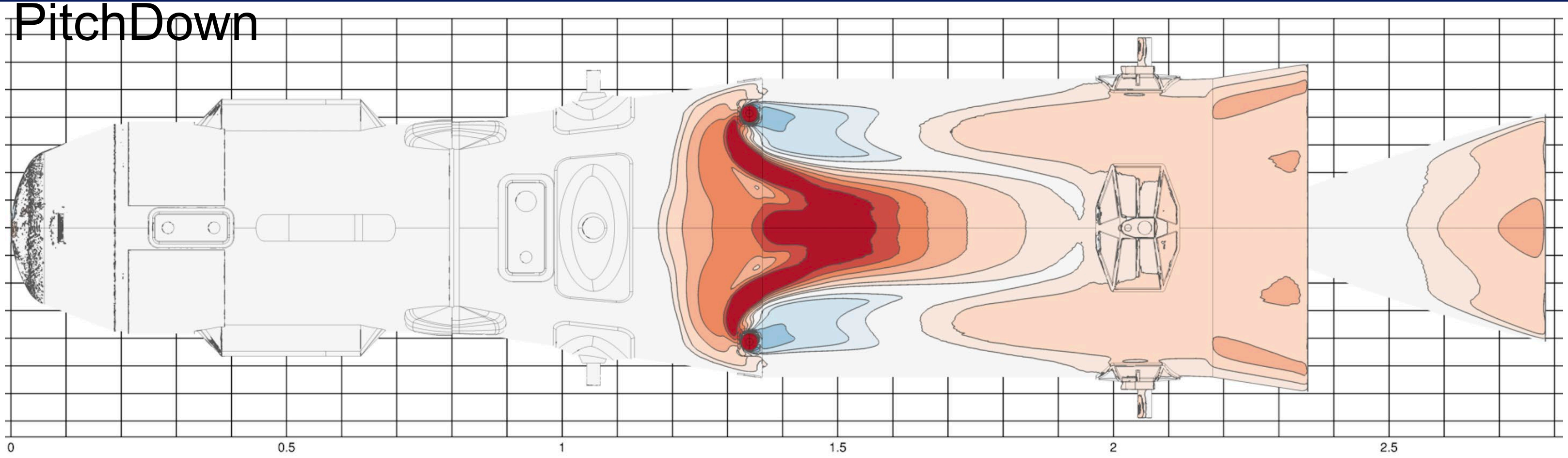
RCS configuration moves from aft of RCS jets to ahead of jets during burn

Pitch and Yaw jets are not nominally active during majority of this cg shift.

Final cg location provides small moment arm for pitch/yaw jets (~15cm)

Jet Interaction Calculations from CFD

MECO2 Jets 1,6 PitchDown



Example contour plot of dCp = Cp(jet-on) – Cp (jet off)

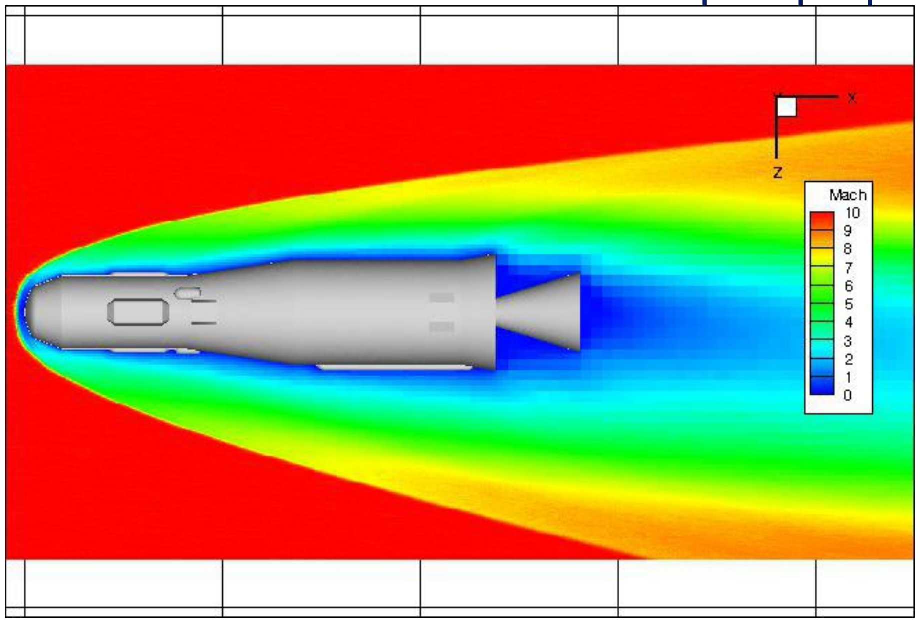
Condition		RCS COMMAND	JETS		dCm JI	dCn JI		dCm RCS	dCn RCS		dCm (%)	dCn (%)
PEAK Q		Nose Left	2		3.61093E-05	0.0013			0.0015			85
		Pitch Up	1,6		-0.000180363	0.0000		0.00307625			-6	
MECO1		Nose Left	2		-2.60966E-05	-0.0102			-0.0054			187
		Pitch Up	1,6		-0.022817659	-0.0001		-0.01089818			209	
MECO2		Nose Left	2		-6.1286E-05	-0.0254			-0.0214			118
		Pitch Up	1,6		-0.041557832	0.0001		-0.04341741			96	

MSR MLS Rarefied Aerodynamics

Low Density Aerodynamics are Modeled using DSMC Methods (needed before MECO for some trajectories)

- MAP DSMC Solver
  - Morton Octree Cartesian grid for flow field; separate unstructured surface grid
  - Dynamic adaptation (flow field grid, local time step, surface temperature)
  - Nonequilibrium internal energy relaxation (rotation, vibration, electronic) and chemistry
- Simulation Parameters
  - X_{CO2} = 0.9537; X_{N2} = 0.0463 (total of 9 species; VSS parameters tuned to match LAURA transport props.)

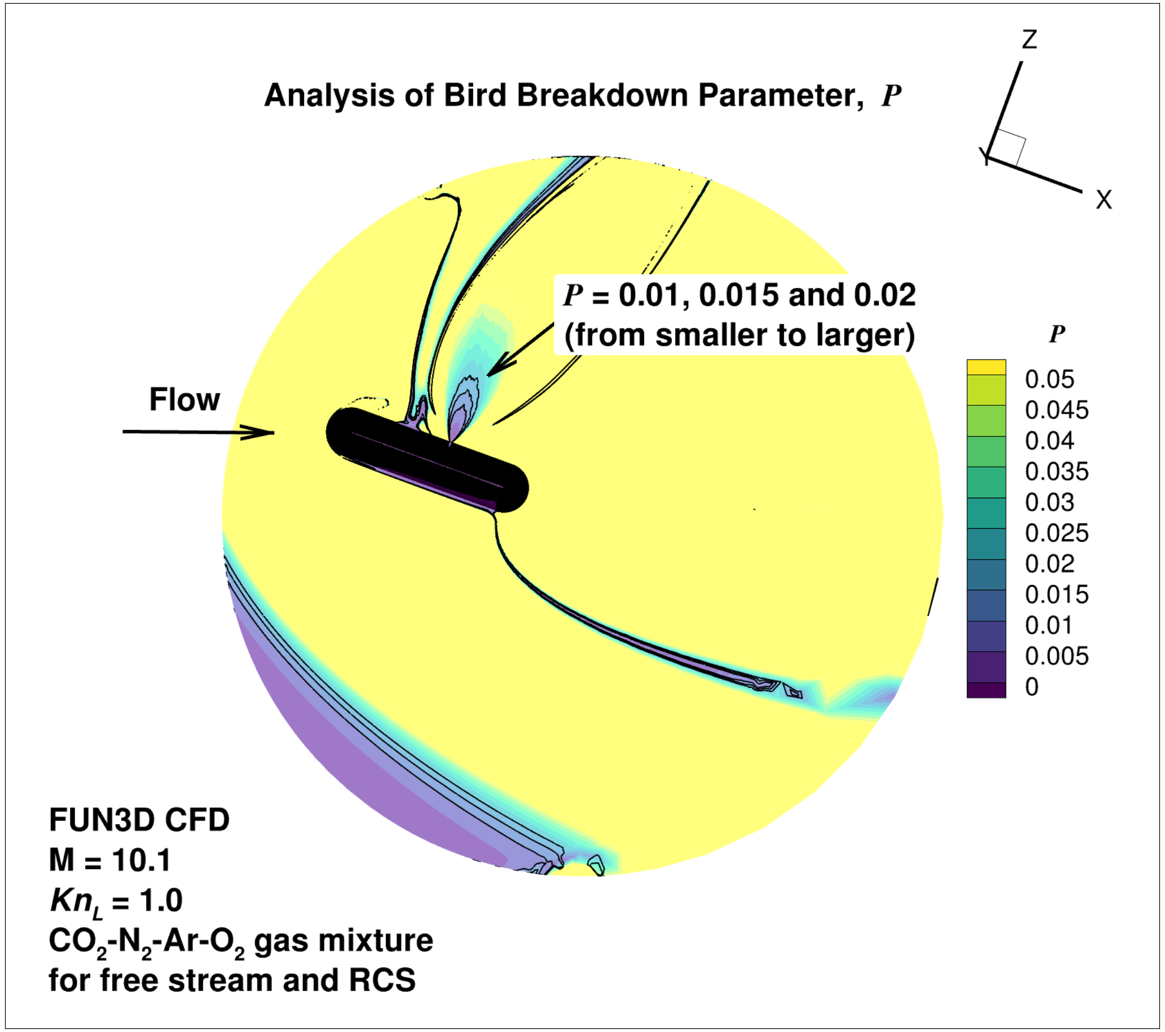
Time (s)	α (deg)	ρ (kg/m^3)	T (K)	V (m/s)	Kn_D
75.03	0,4,10	2.1915e-5	139.3	1927.2	0.0046
89	0,4,10	2.1588e-6	129.1	1842.7	0.0457
103	0,4,10	2.3030e-7	119.8	1814.3	0.4187
116	0,4,10	2.1647e-8	120.3	1791.7	4.460
129	0,4,10	2.0105e-9	148.4	1778.5	51.14
145	0,4,10	2.2482e-10	165.7	1762.0	472.6
166	0,4,10	2.2036e-11	170.4	1722.0	4863.0
194	0,4,10	2.2837e-12	171.5	1667.8	47007.7



Analyze Plume Flow for Continuum Breakdown, P

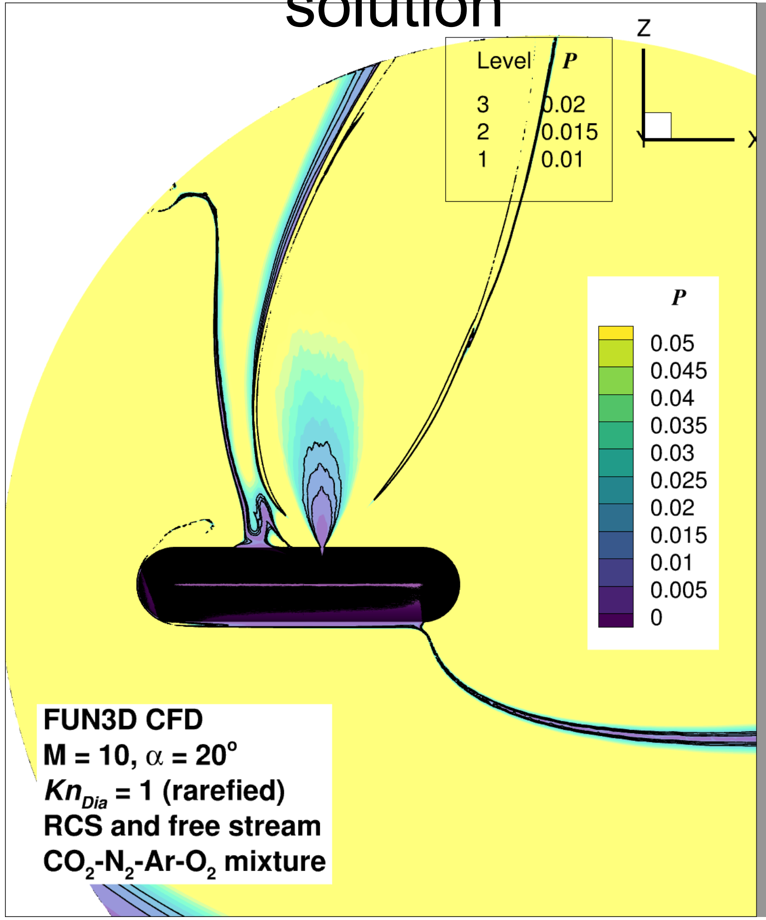
$P = \frac{\vec{V} \cdot \nabla \rho}{\nu \rho}$, ν *is the Intermolecular Collision Frequency*

Atypical Application, Usually Performed on a Freely Expanding Jet

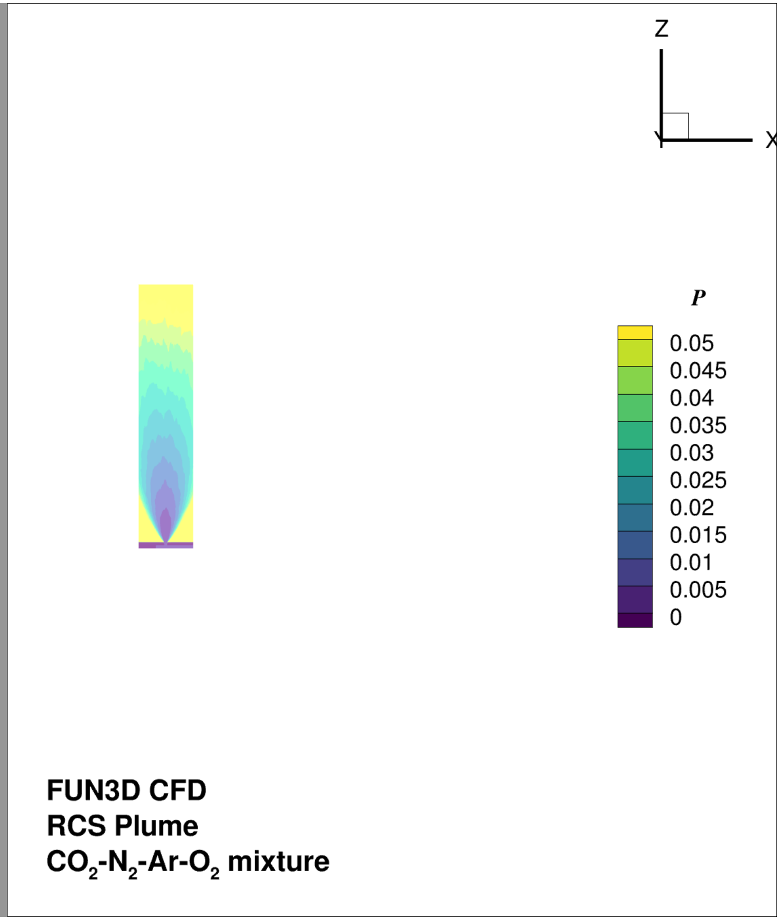


Separate Jet Plume from CFD solution

Nonuniform CFD solution

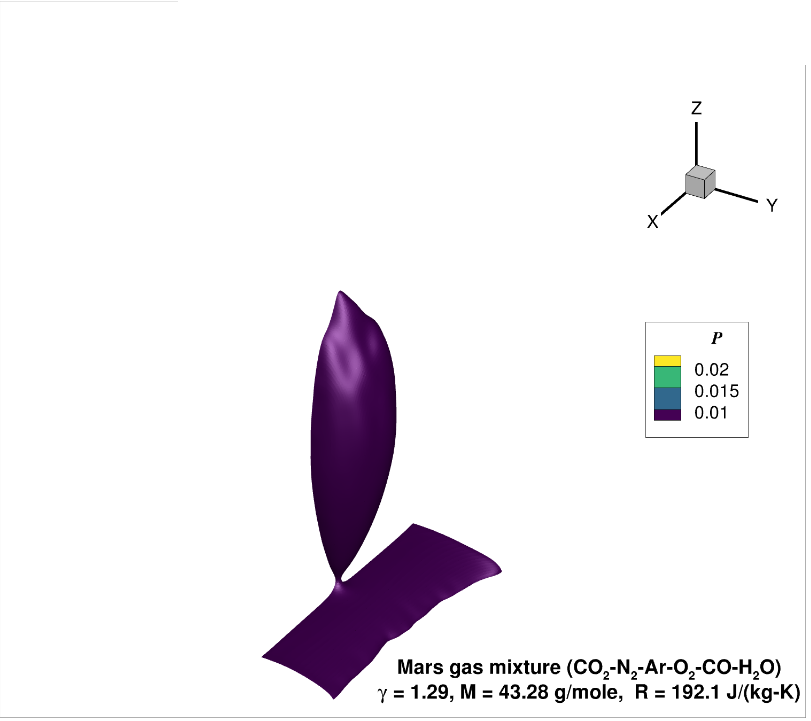


Separated Jet Plume

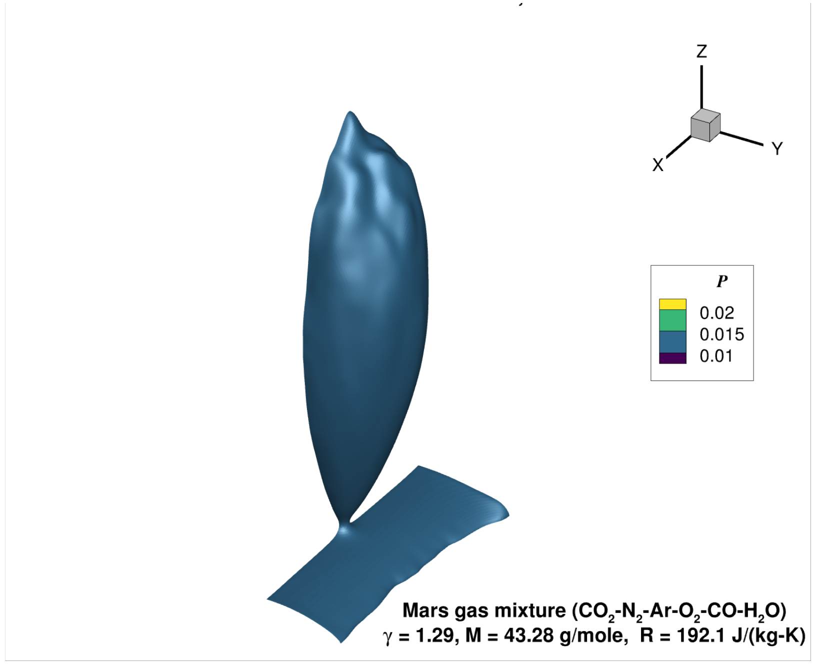


Analyze Jet Plume Flow and Identify Continuum Breakdown Surfaces

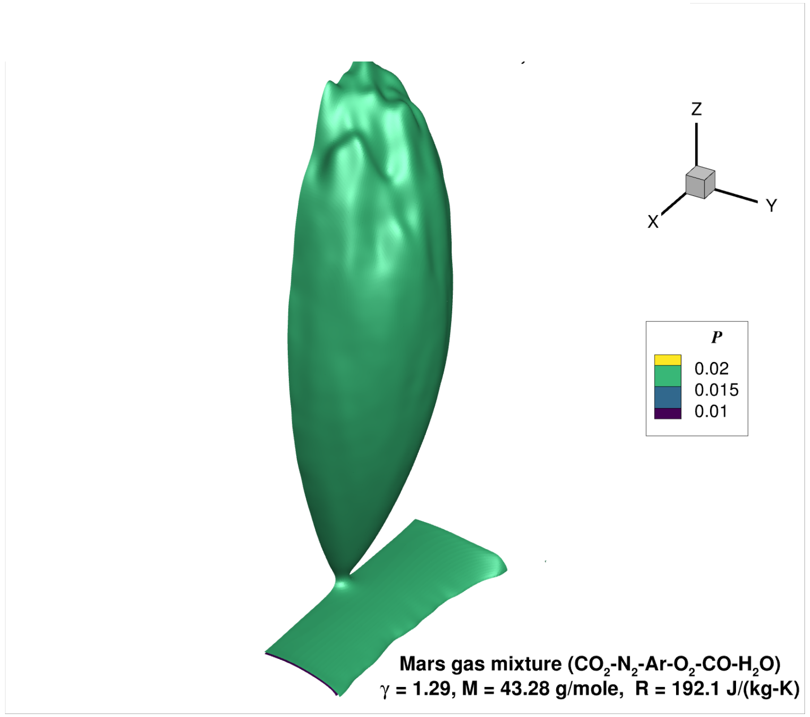
P = 0.01



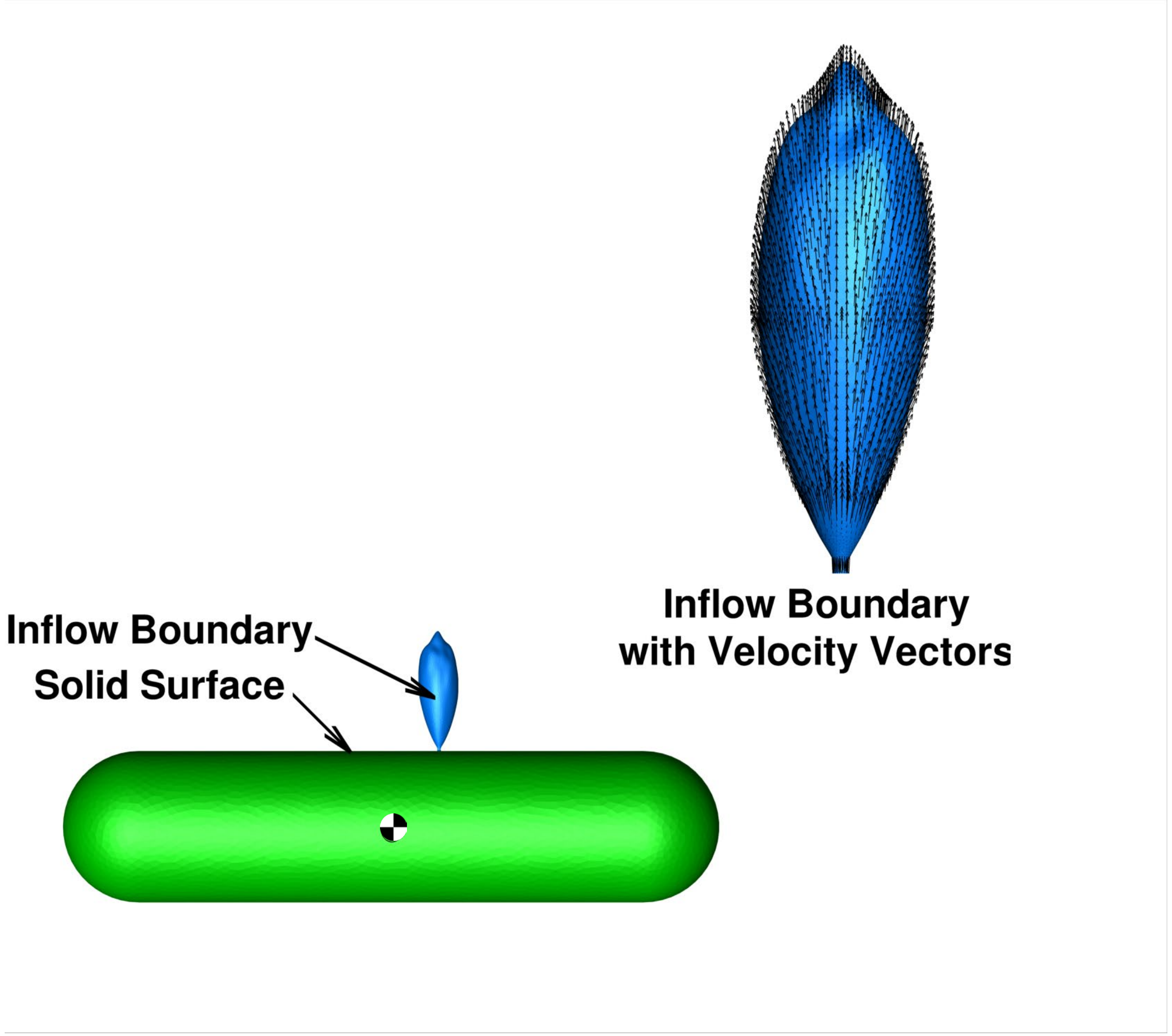
P = 0.015



P = 0.02

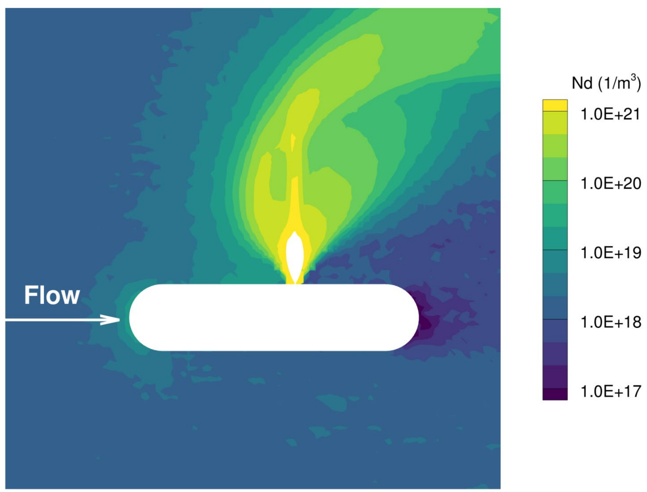


Modified DSMC file

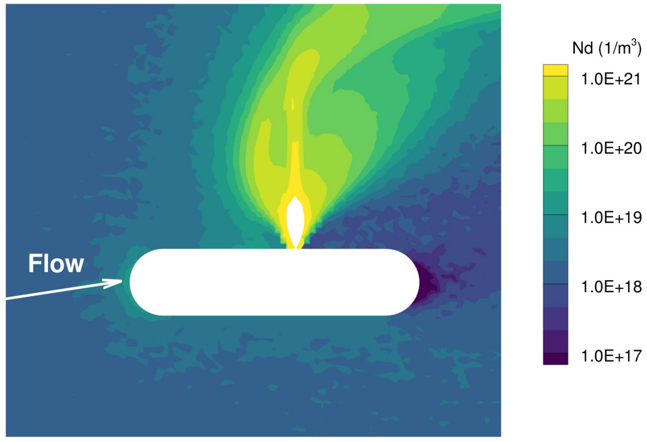


Perform DSMC on Capsule with Jet on

$\alpha = 0^o$



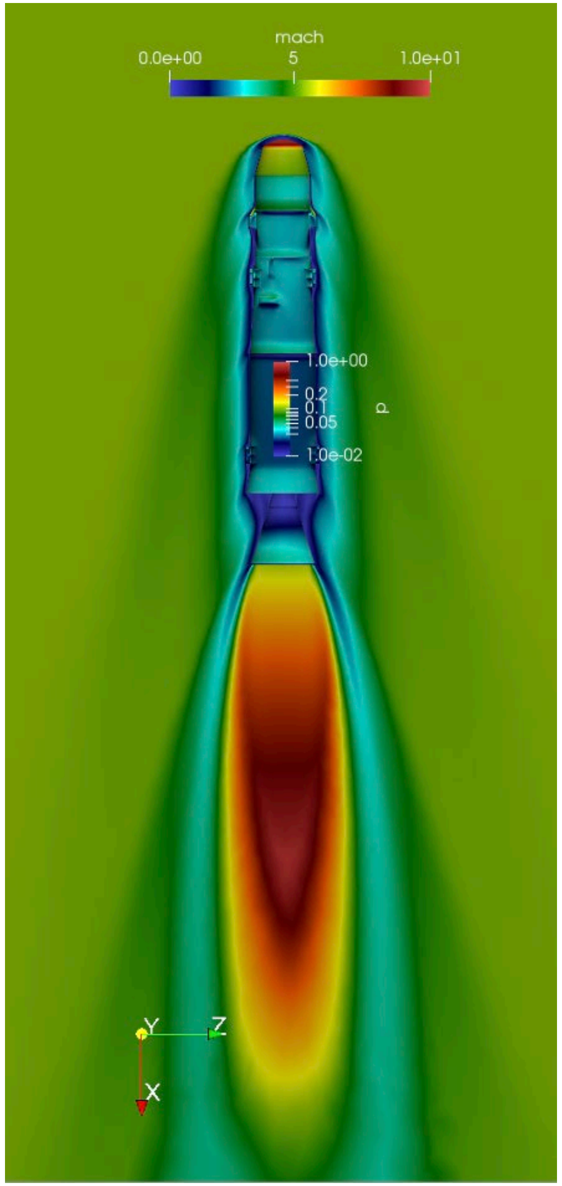
$\alpha = 10^o$



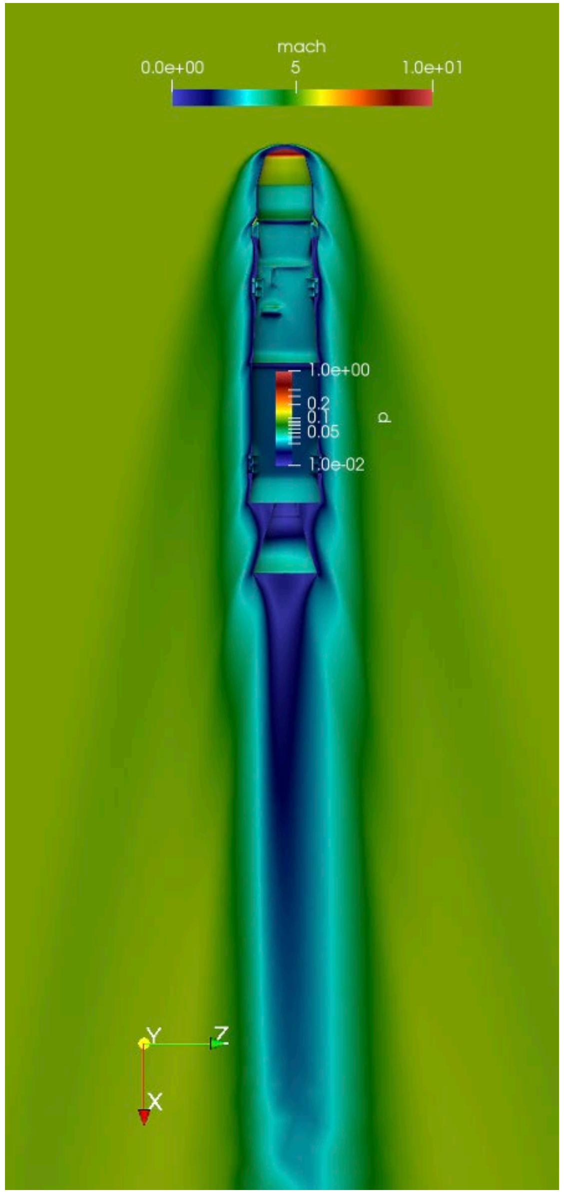
$\alpha = 20^o$

Engine-On Aerodynamics

REACTING FLOW



UNPOWERED



Craig Hunter and Gabe Nastac ran studies of powered vs. unpowered flight

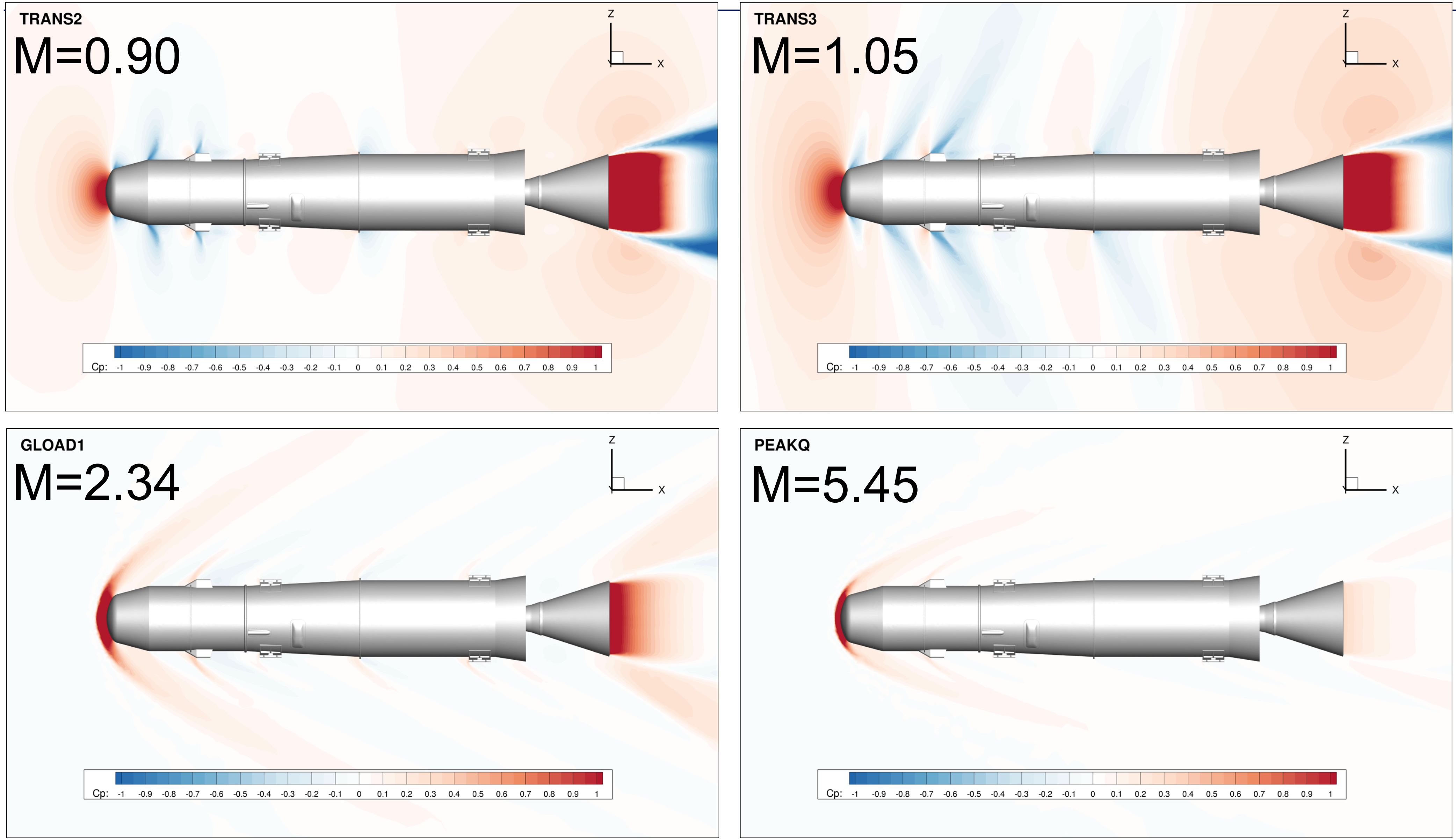
Searching for:

- Deltas to aero coefficients due to engine on effects
- Variation of deltas with Mach number along ascent
- Sensitivity of plume flow to gas chemistry modeling

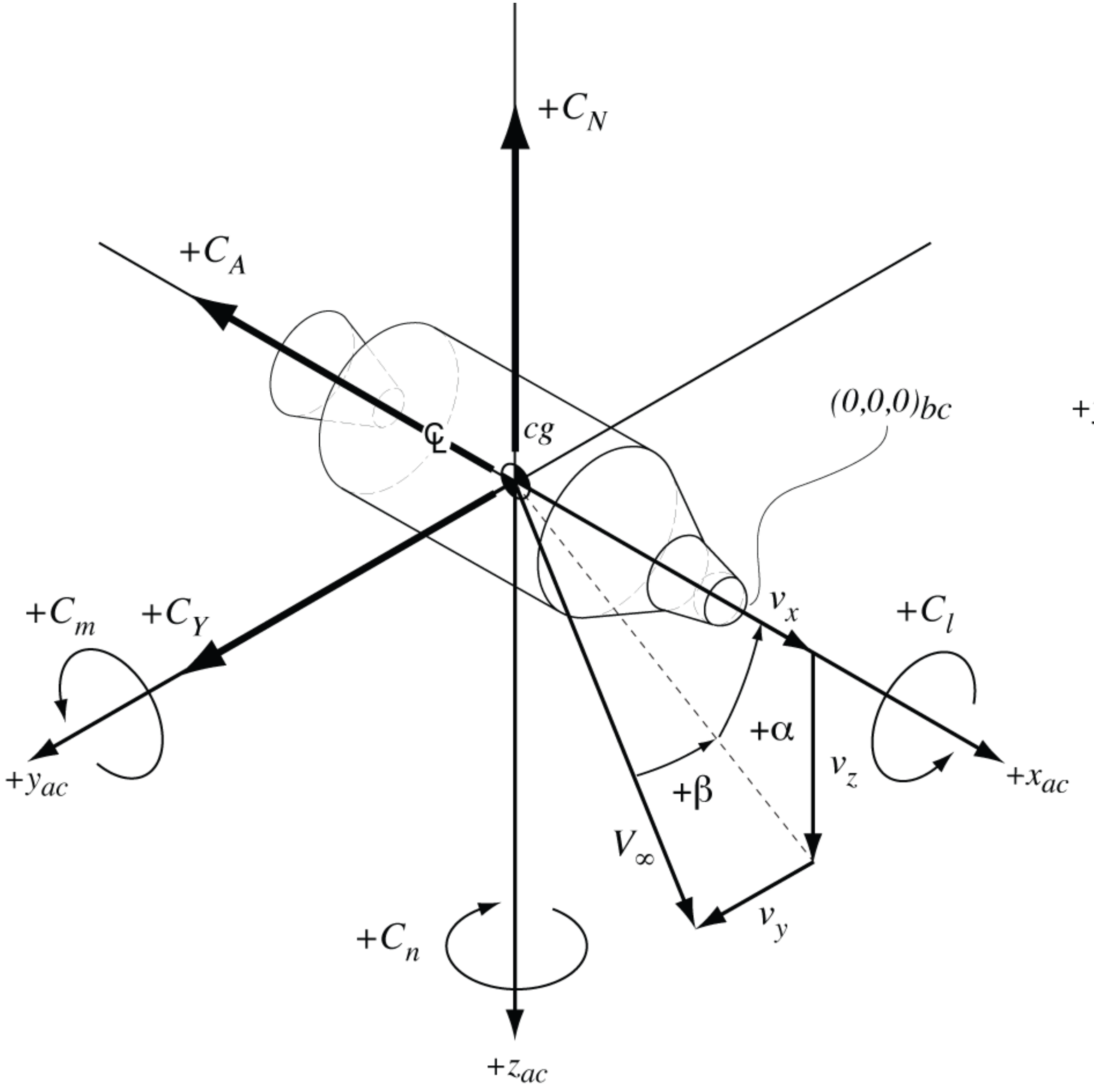
Conclusions:

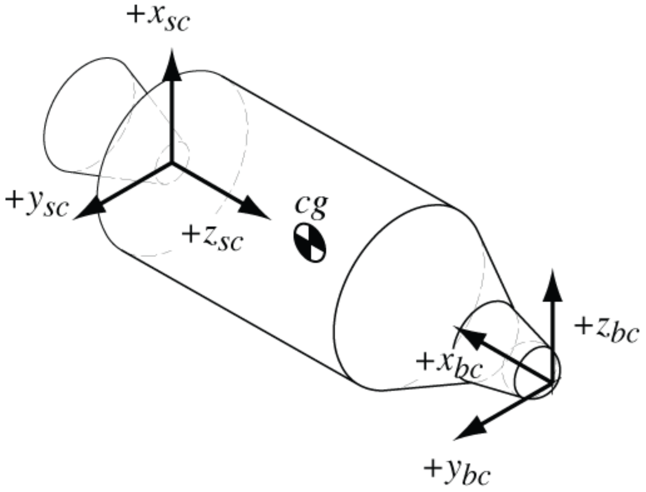
- Noticeable engine effects at transonic conditions.
- Negligible effects at hypersonic conditions
- Gas chemistry assumptions do not affect plume significantly

Engine-On Aerodynamics



Coordinate Systems & Decomposition





$$\cos_D = \frac{\sin\alpha\cos\beta}{\sqrt{\sin^2\beta + \cos^2\beta\sin^2\alpha}}$$

$$\sin_D = \frac{\sin\beta}{\sqrt{\sin^2\beta + \cos^2\beta\sin^2\alpha}}$$

$$C_N = C_{N_T}\cos_D$$
$$C_m = C_{m_T}\cos_D$$
$$C_Y = -C_{N_T}\sin_D$$
$$C_n = C_w = -C_{m_T}\sin_D$$
$$C_A = C_{A_T}$$
$$C_l = C_{l_T} = 0$$

sc: Spacecraft Cordinates
ac: Aerodynamic Coordinates
bc: Body Coordinates

Uncertainty Modeling

Adders and multipliers disperse intercepts and local slope separately

$$C_{A_{Disp}} = C_A(\alpha,\beta)(1+U^M_{C_A})$$

$$C_{N_{Disp}} = \left[C_N(\alpha,\beta)+U^A_{C_N}\right](1+U^M_{C_N})$$

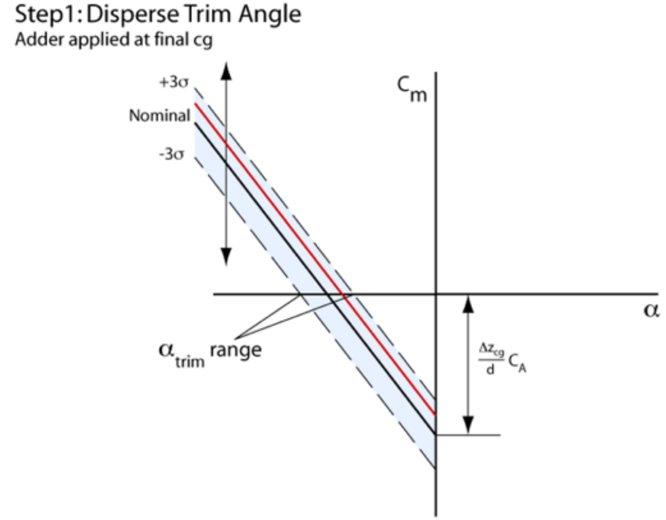
$$C_{Y_{Disp}} = \left[C_Y(\alpha,\beta)+U^A_{C_Y}\right](1+U^M_{C_N})$$

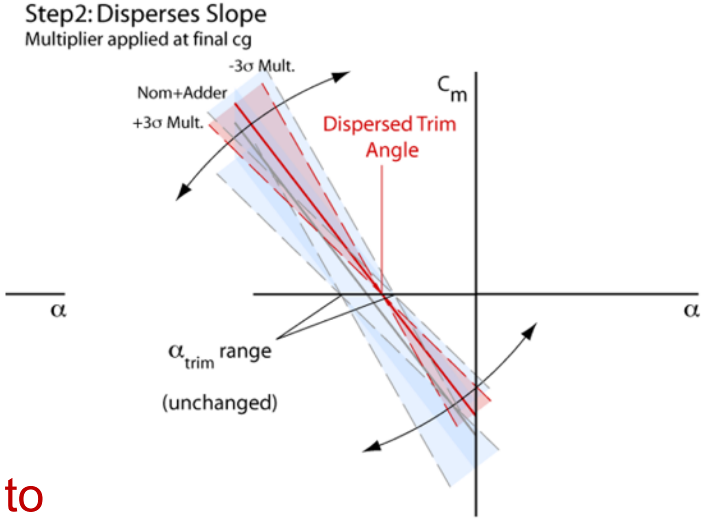
$$C_{m_{Disp}}\big|_{cg} = \left[C_m(\alpha,\beta)|_{MRP}+\frac{\Delta x}{d}C_N(\alpha,\beta)-\frac{\Delta z}{d}C_A(\alpha,\beta)+U^A_{C_m}\right](1+U^M_{C_m})$$

$$C_{n_{Disp}}\big|_{cg} = \left[C_n(\alpha,\beta)|_{MRP}+\frac{\Delta x}{d}C_Y(\alpha,\beta)-\frac{\Delta y}{d}C_A(\alpha,\beta)+U^A_{C_n}\right](1+U^M_{C_n})$$

$$C_{l_{Disp}}\big|_{cg} = \frac{\Delta y}{d}C_N(\alpha,\beta)-\frac{\Delta z}{d}C_Y(\alpha,\beta)+U^A_{C_l}$$

V0.3 3σ dispersion magnitudes		
$U^M_{C_A}$	=	10%
$U^A_{C_N}, U^A_{C_Y}$	=	0.07
$U^M_{C_N}$	=	7%
$U^A_{C_m}, U^A_{C_n}$	=	0.1
$U^M_{C_m}$	=	25%
$U^A_{C_l}$	=	0





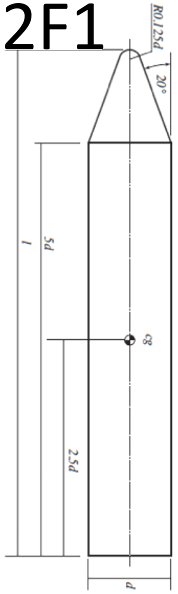
Uncertainties on the 6 static aero coefficients are decoupled

Benefit: If needed, analysis can be done to quantify uncertainties of one coefficient with more fidelity and not effect dispersions of other coefficients

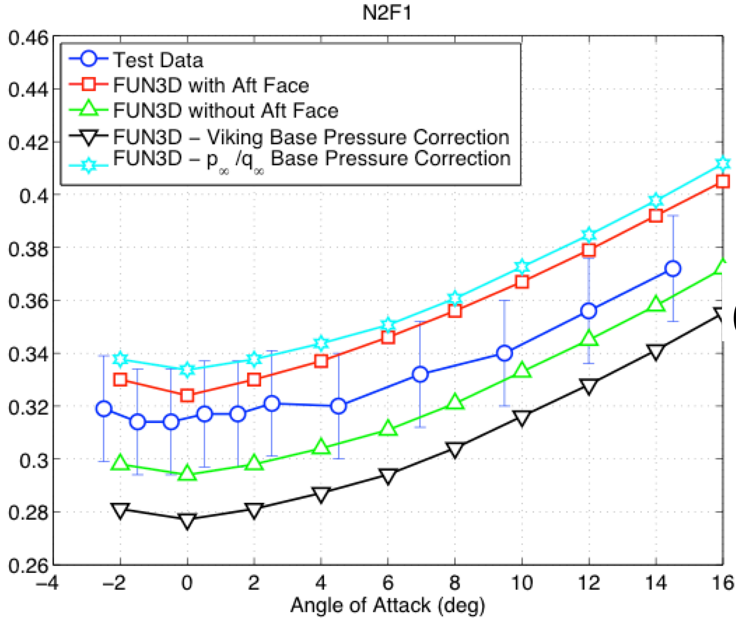
Note: Wind tunnel data analysis will yield Cl dispersion to be added to model
Database maybe expanded as function of α_{Total} and roll angle (ϕ) for future releases to capture protuberance effects

FUN3D Early Code Validation

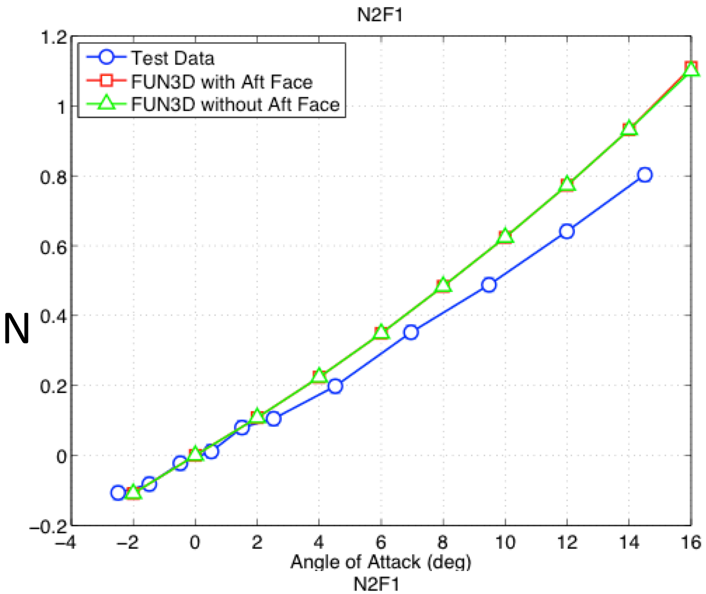
N2F1



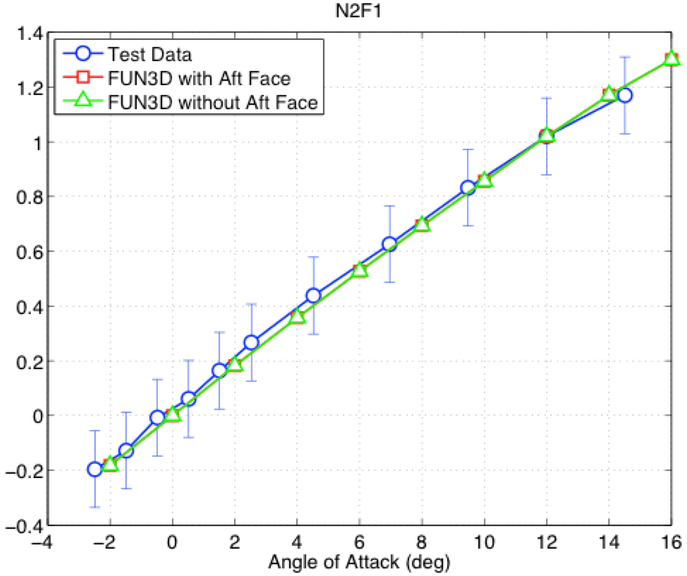
C_A



C_N



C_m



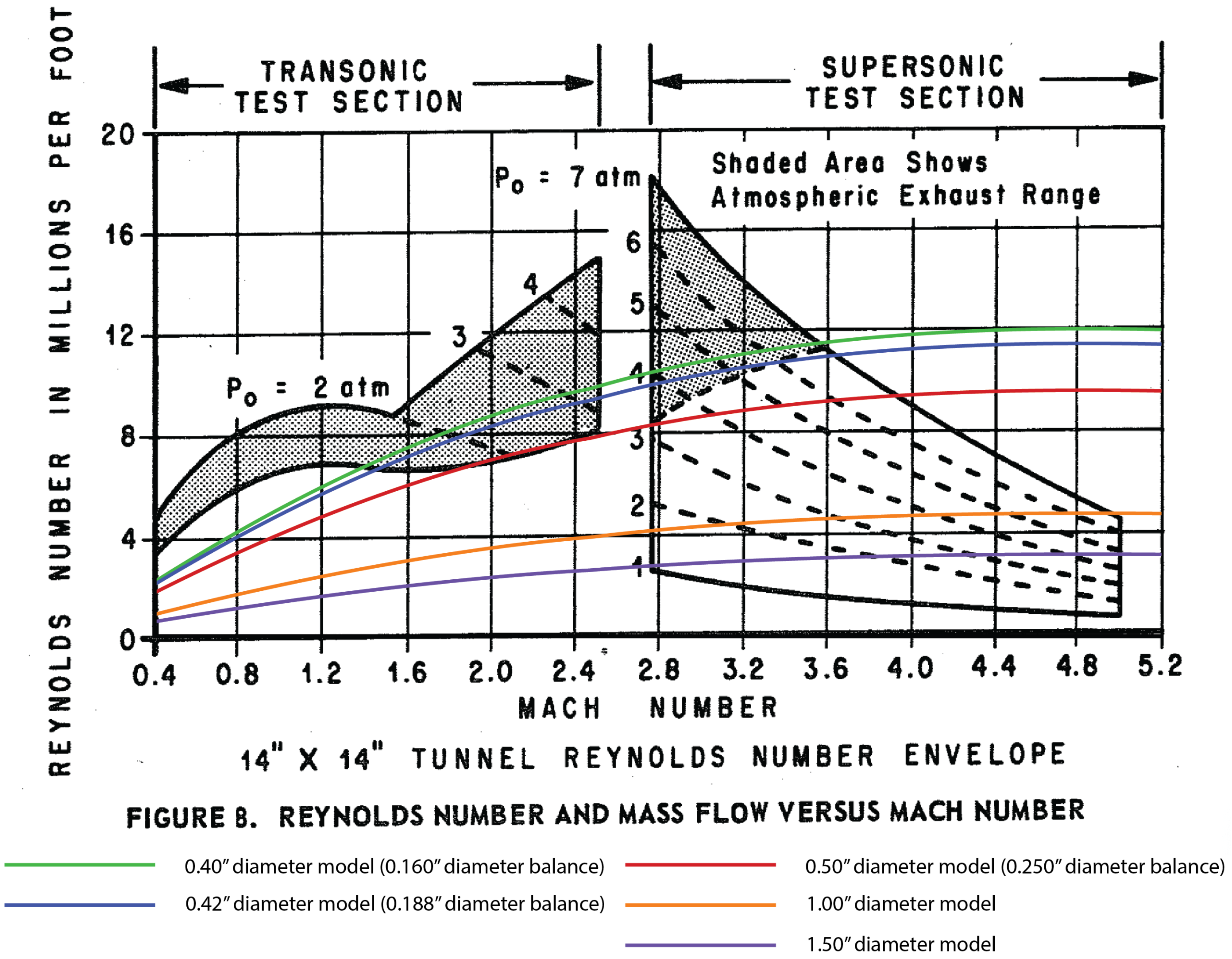
FUN3D CFD code was run on NASA TN D-2853 geometries (N2F1 example shown here)

A number of sensitivities were explored (base contributions, turbulence, etc.)

Settings for MAV solutions were identified, good agreement with experiment

Wind Tunnel Scaling Considerations

Conditions Using SRC 1.0 3DoF Trajectory

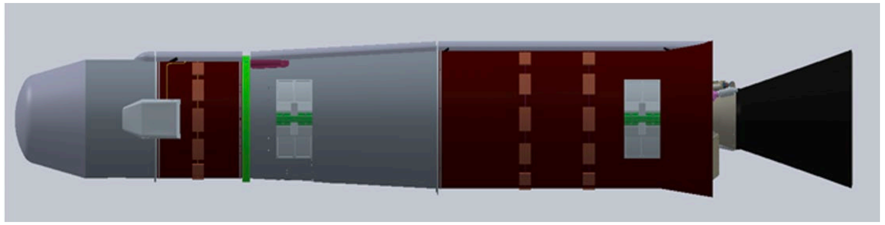


Unlike many wind tunnel tests, matching Mars ascent conditions (Re) called for smaller than typical models

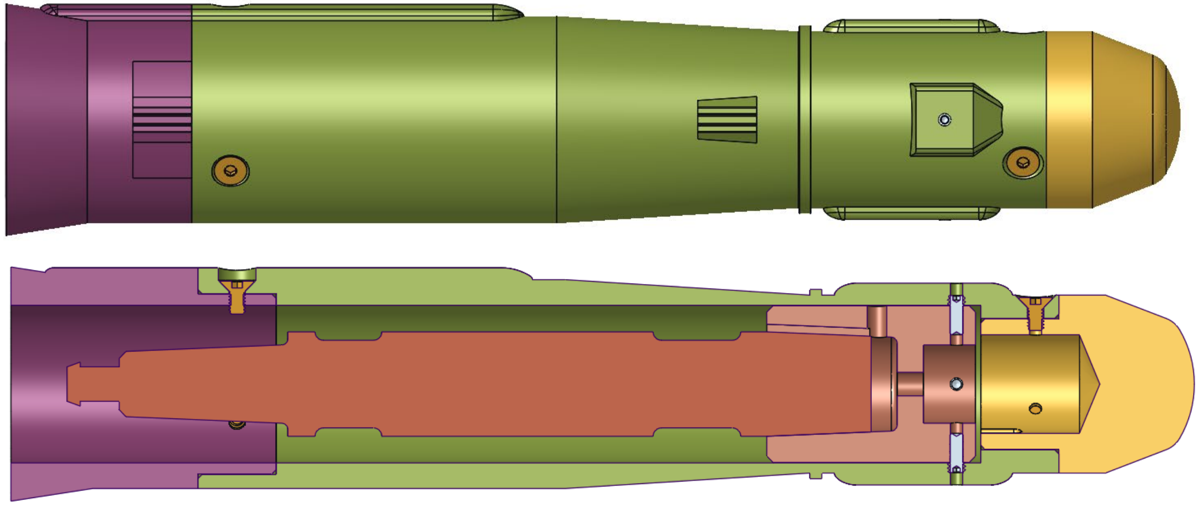
CF studies showed that protuberances were far more significant than Re effects of testing a larger vehicle

0.5" Balance was best option for MAV test: set model diameter

Can Match Flight Re in Supersonic Test section at all conditions with 1.000" Model

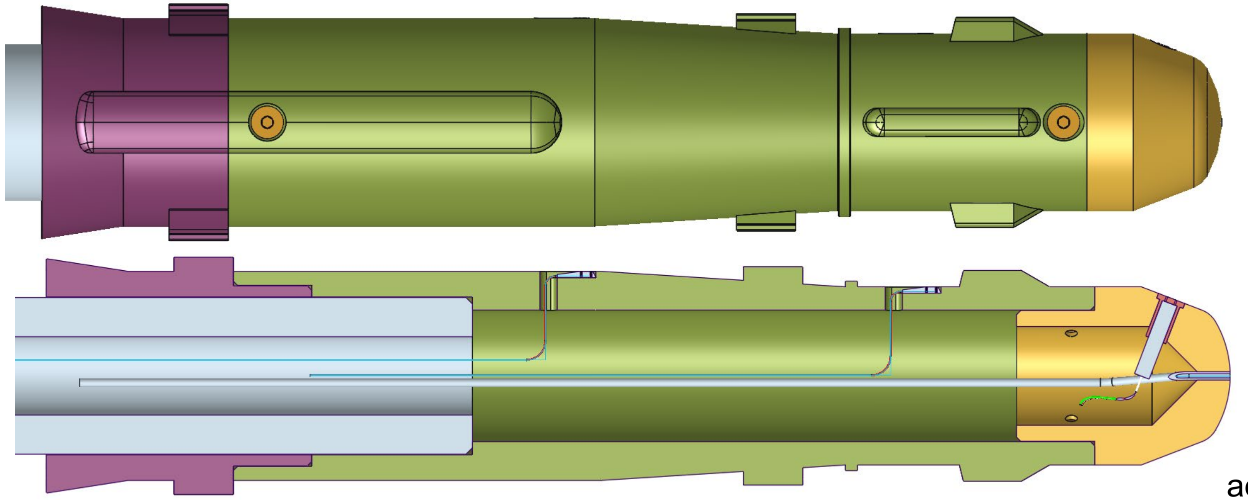


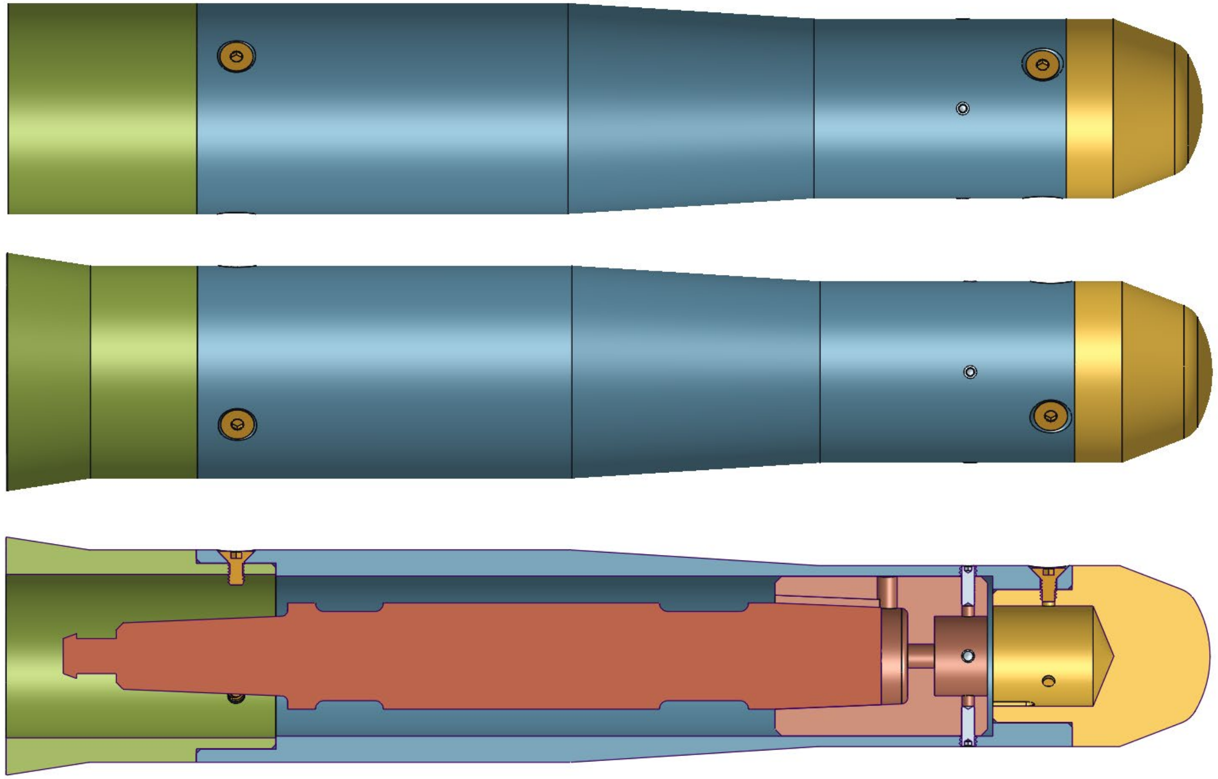
Skirt and Protuberance Model



SRC BASELINE F&M Model

SRC BASELINE Pressure Model





SRC Smooth F&M Model
With and without aft ramp

Pressure Model wil inform unsteady aerodynamics. Scheduled for follow-up test in late June 2022

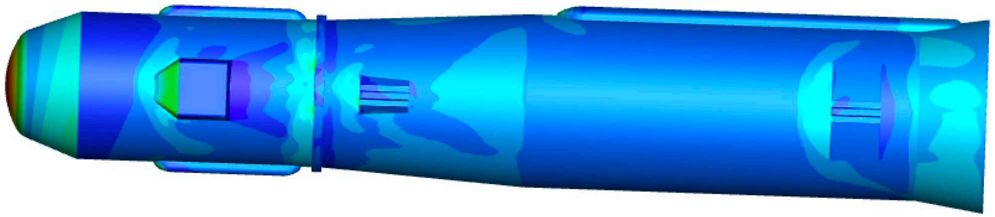
Validation Wind Tunnel Test

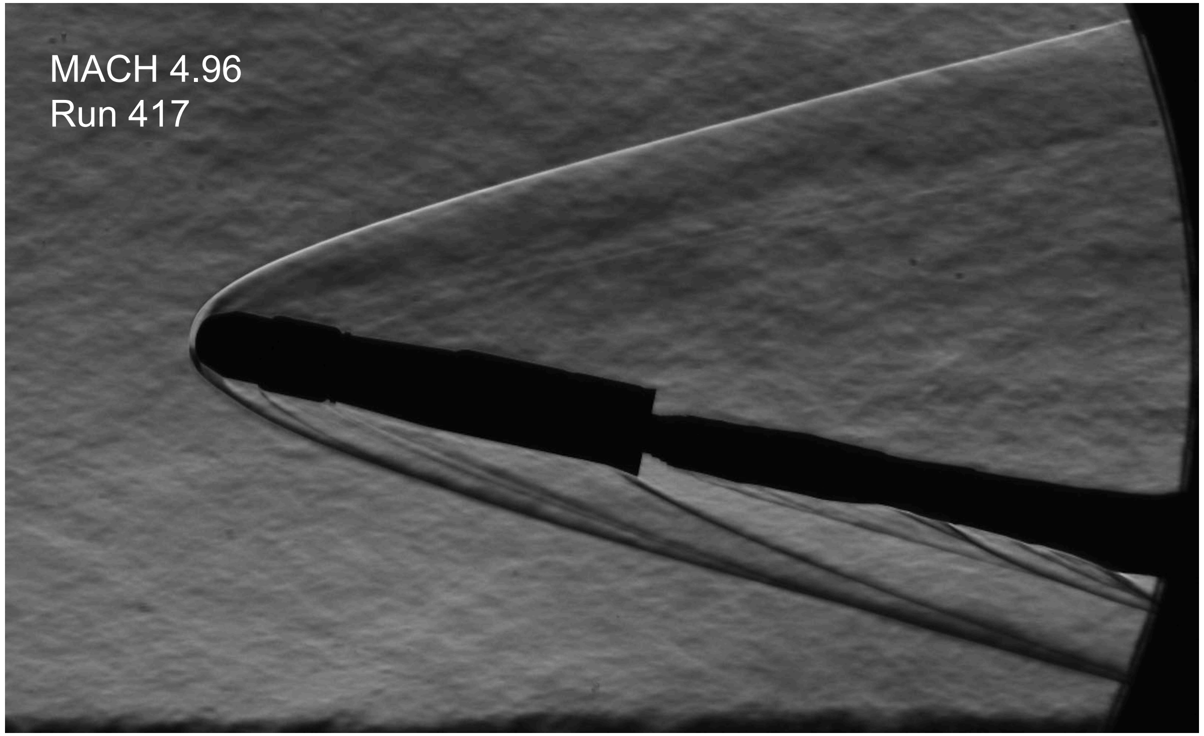
MAV SRC model in MSFC 14" Trisonic Tunnel
October 2021

SRC 2.0 Geometry was selected for testing

- Mach Range: 0.3 to 4.96
- Angle of Attack Range: -1 to +17 deg
- Roll Angles (0, 45, 90, 135, 180)

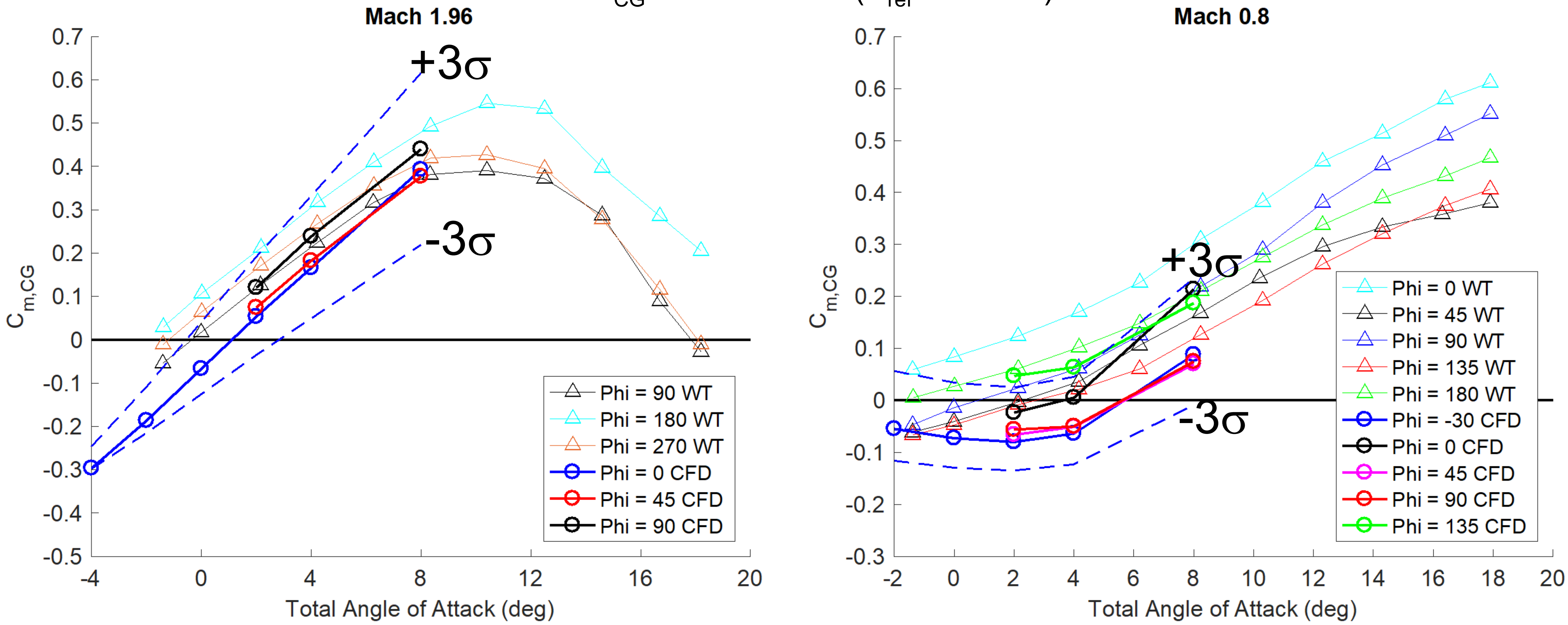
Mach 1.96, $\alpha_{Tot} = 2^{\circ}$, $\phi=0^{\circ}$





Aerodynamics: Pitch Stability

$x_{CG}/D = 2.680747$ (D_{ref} = 1.00 in)

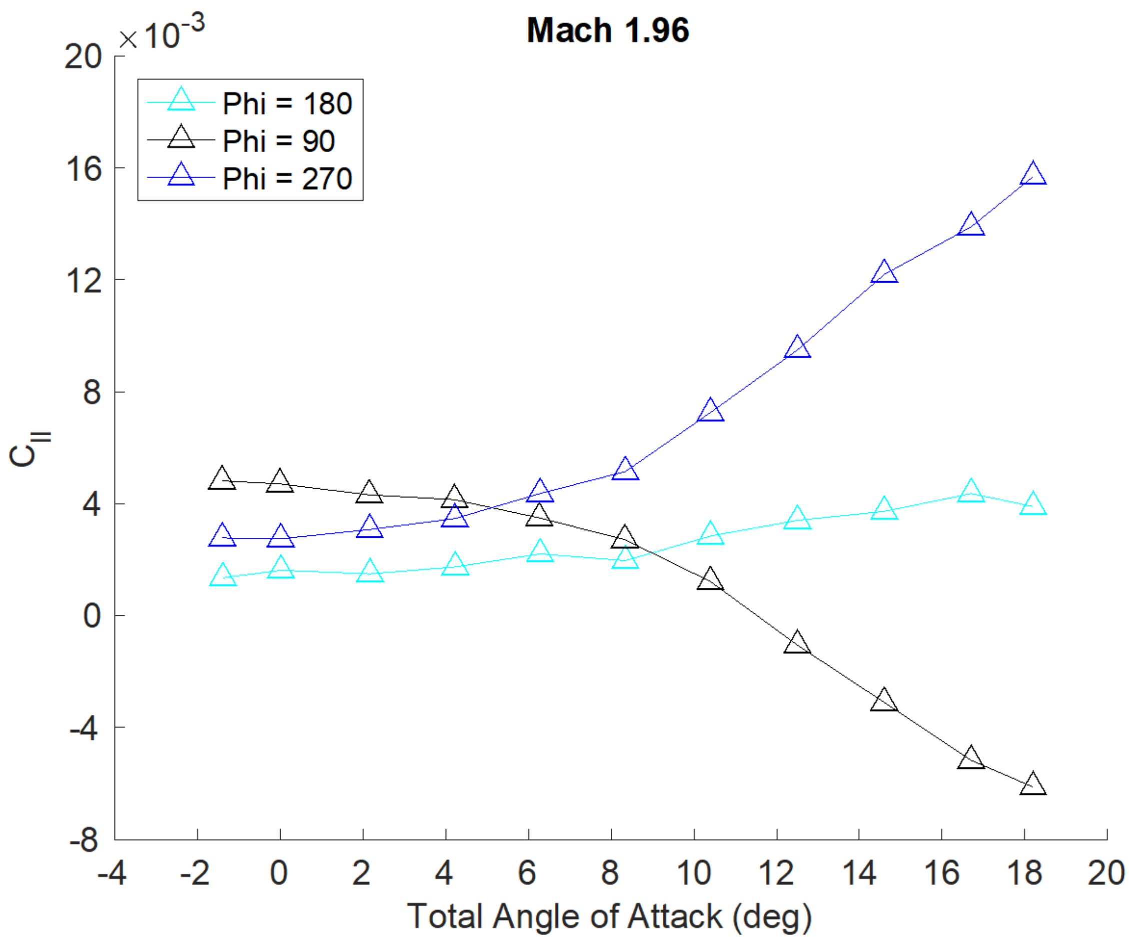


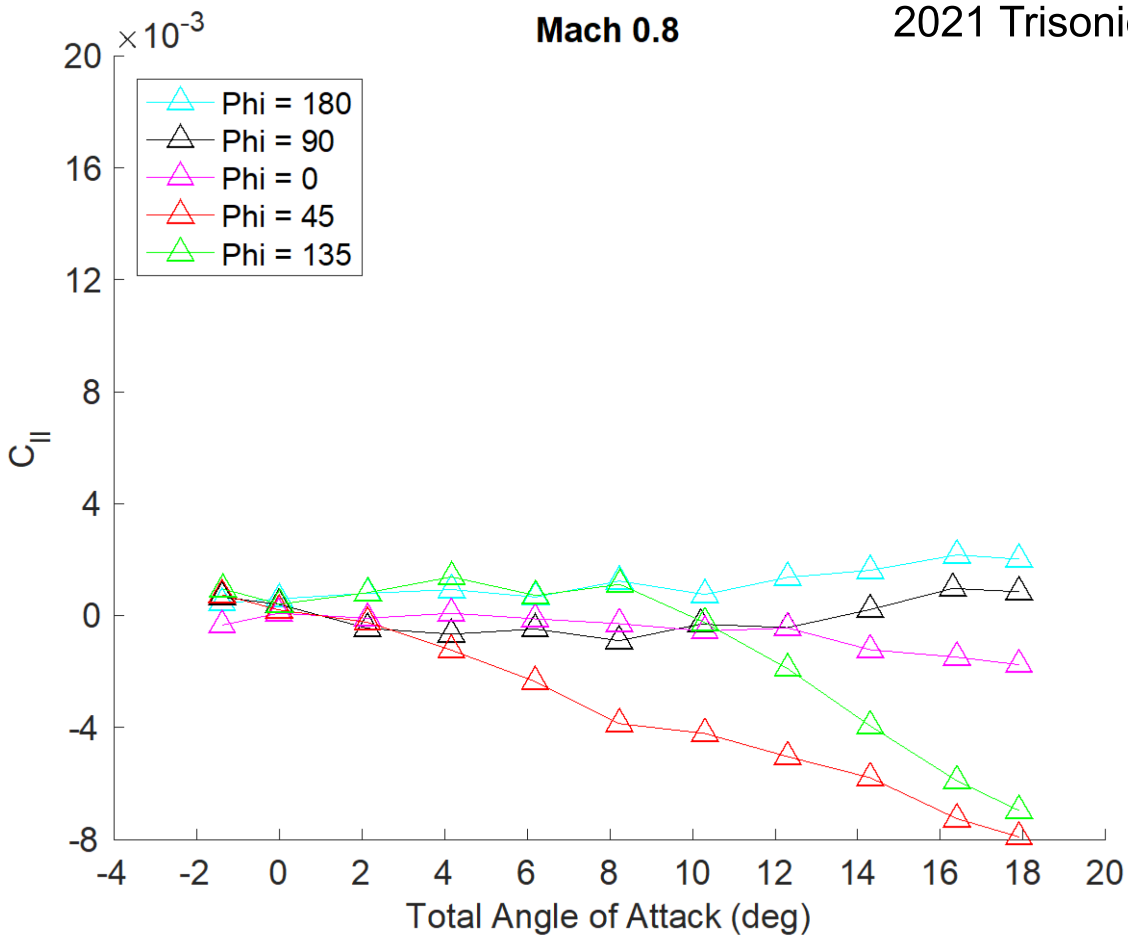
$$C_{m_{Disp}}\big|_{cg} = \left[C_m(\alpha,\beta)\big|_{MRP} + \frac{\Delta x}{d} C_N(\alpha,\beta) - \frac{\Delta z}{d} C_A(\alpha,\beta) + U^A_{C_m} \right] (1 + U^M_{C_m})$$

$$U^A_{C_m}, U^A_{C_n} = 0.1$$
$$U^M_{C_m} = 25\%$$

Aerodynamics: Rolling Moment

2021 Trisonic WT

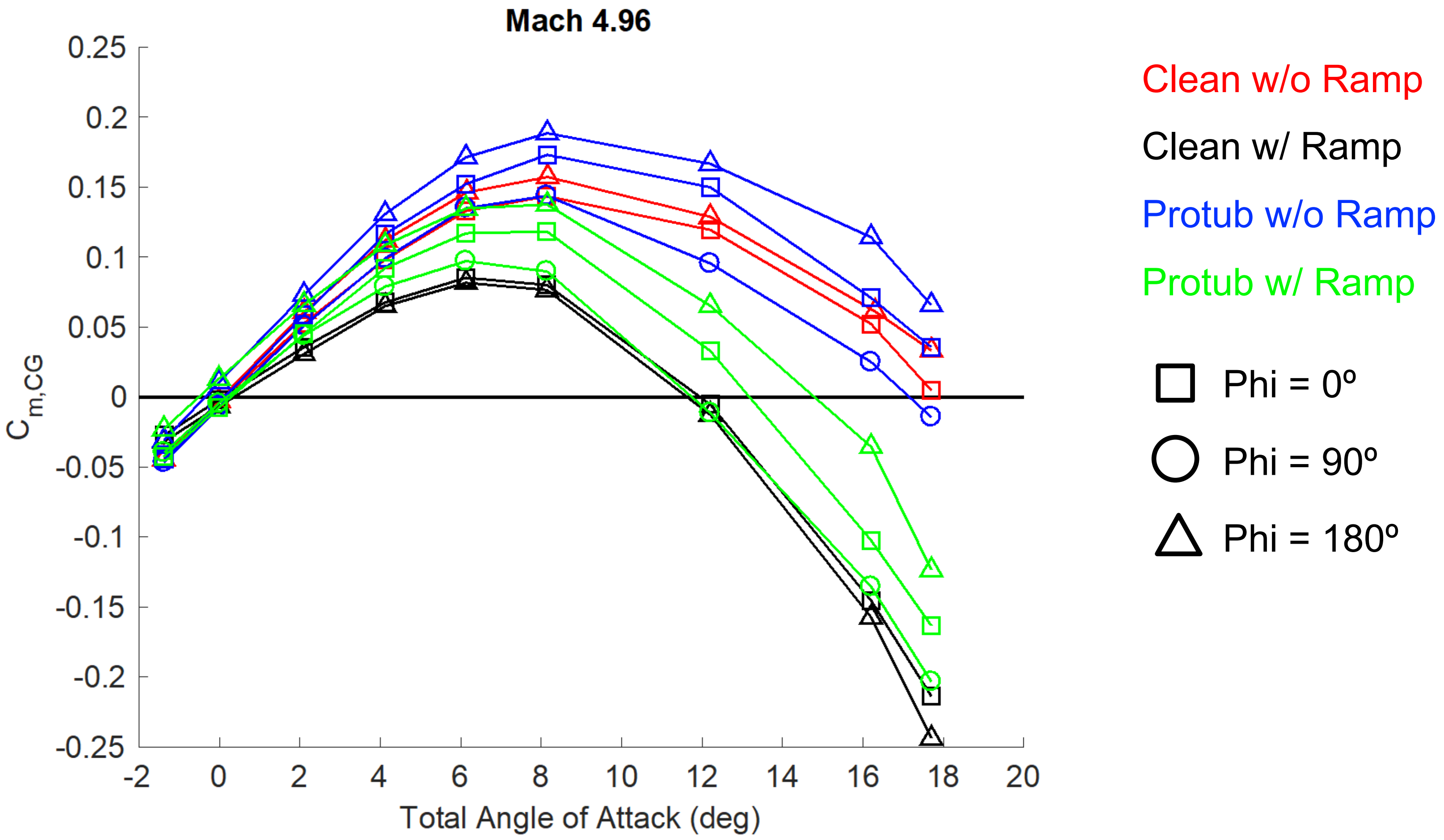




- **Rolling moment increases between Mach 0.8 and Mach 1.96**
- **Rolling moment increases rapidly for α_T > 8 deg, for specific orientations (ϕ)**
- **Identification of favorable roll orientation and establishment of uncertainty in-work**

Aerodynamics: Configuration Effects

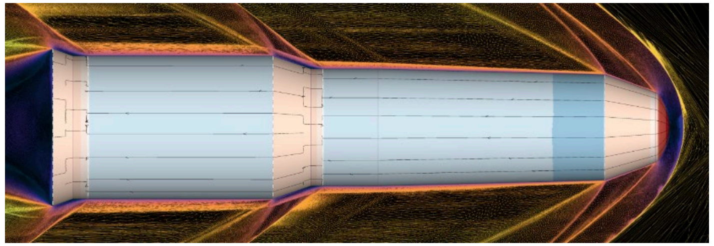
2021 Trisonic WT Data – Mach 4.96

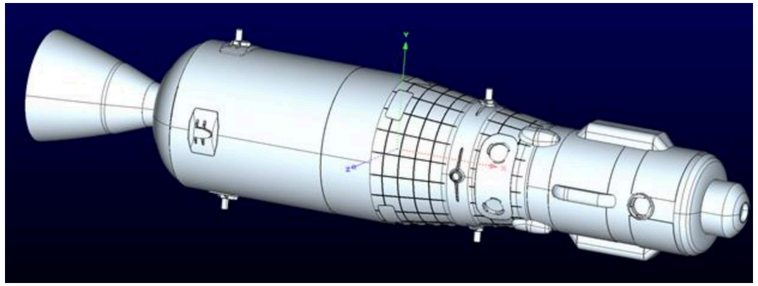


Environments

The AFESB Aerodynamics Team typically provides an aerodynamic database with dispersions to a flight project as the main data product.

While the aerodatabase is important for vehicle and trajectory design, for MLS the environments are also very important to characterize. Why?

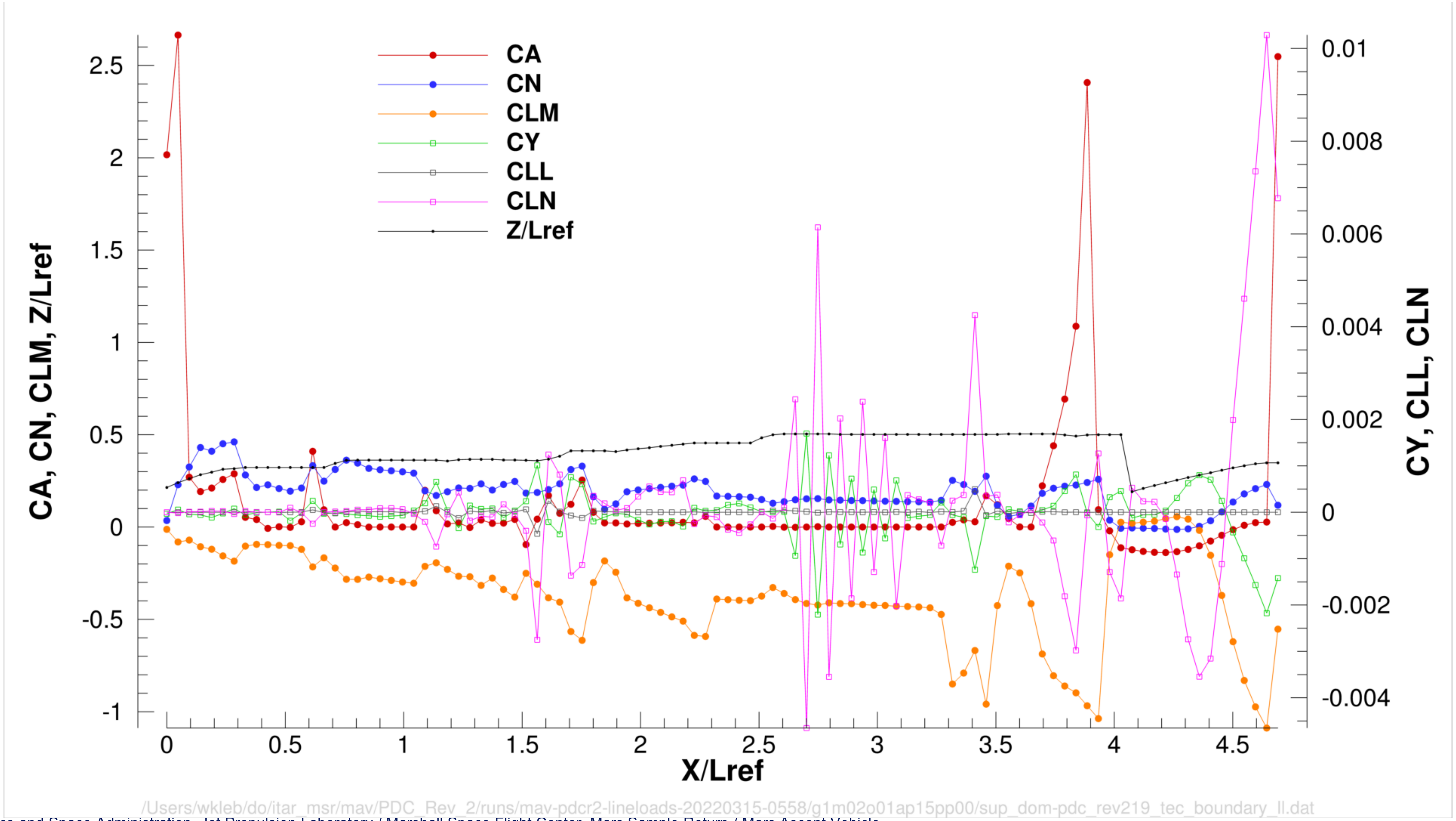




The configuration has become more "dirty" aerodynamically

- **Line Loads**
  The aerodynamic forces and moments provided as distrubutions along the length of the vehicle for mechanical engineers to design the vehicle structure
- **Aeroheating**
  The heating environments during ascent are needed for thermal analysis, TPS sizing and design to ensure the vehicle structure, internal electronics, payload structure, etc. do not get too hot
- **Unsteady Aerodynamics**
  The MLS vehicle is fairly "dirty." It is important to characterize the noise (aeroacoustics) produced as transonic and supersonic flow move past the protuberances. The dynamic loads due to aeroacoustics must be considered as much or more than the static loads for this configuration.

PDC Rev. 2 Line loads



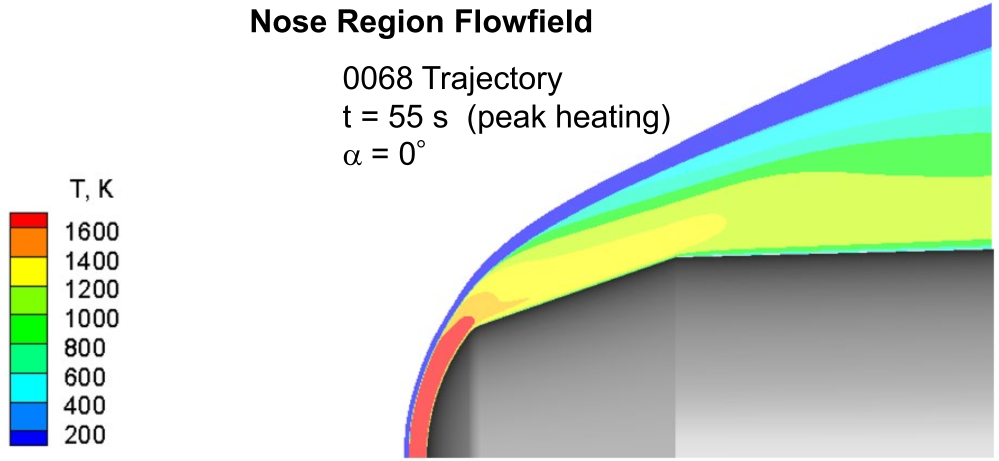
7) Aeroheating Analysis

- Heating indicators constructed using CFD in trajectory simulation (replaces approximate method of Sutton-Graves)

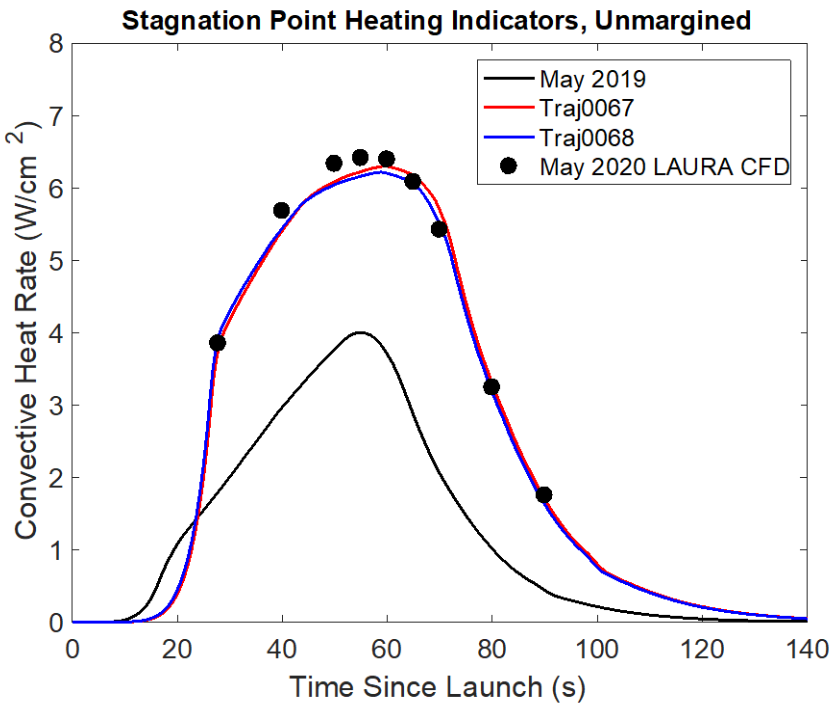
$$\dot{q}_w \sim \sqrt{\frac{\rho_\infty}{r_n}} V_\infty^3$$

- Indicators provided for convective heat rate (and heat load) at 8 body points (Mar 2020)
- Updated fits for recent (March 2020) 0068 trajectory
  - Accounts for differences in ρ-V (trajectory)
  - Prior LAURA-5 CFD solutions generated in May 2019
- Previously scaled convective heat rate for varying nose radii and applied indicators to new ascent profiles (Dec 2019 and Mar 2020)
- Negligible differences between laminar and turbulent solutions in prior analyses (2016, 2019)
- High-fidelity aerothermal analysis is repeated for significant changes in configuration and ascent profiles
- LAURA CFD distributions are used for MAV thermal analysis and TPS sizing

Nose Region Flowfield



High fidelity CFD on forebody (no protuberances)
- LAURA code with 8-species Mars atmosphere
- Fully laminar; 3D with angle of attack
- Chemical non-equilibrium shock layer
- Radiative equilibrium wall temperature
- Trajectory range through peak heating pulse

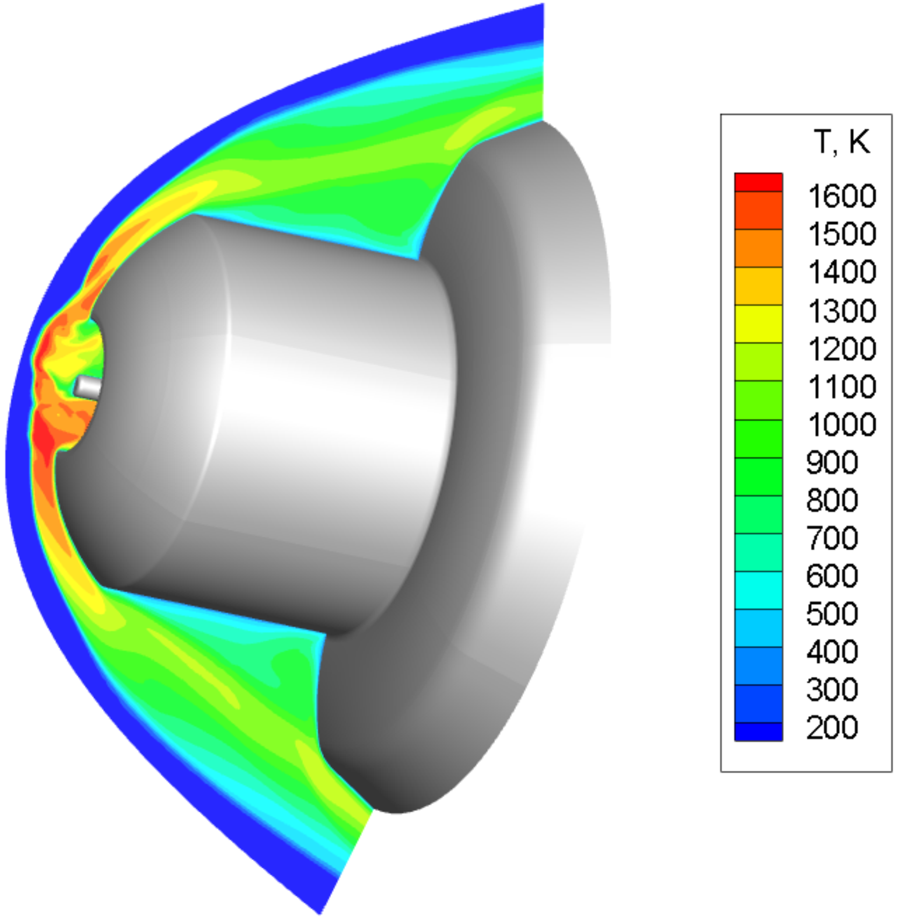


Examples of OS Aeroheating Analysis

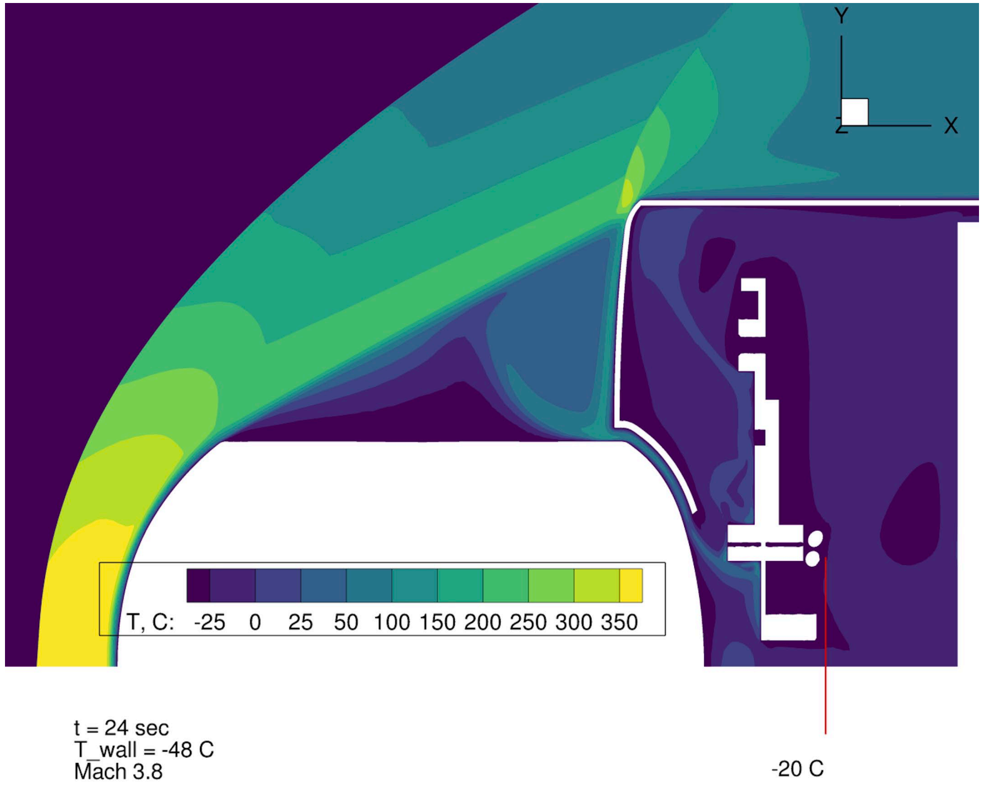
- Full-body solution obtained at peak heating (t=60 sec) and AOA=0 deg
  - Unsteady flow
  - Running for additional time-averaging

M = 8.6

Symmetry plane



- Internal Flow Analysis



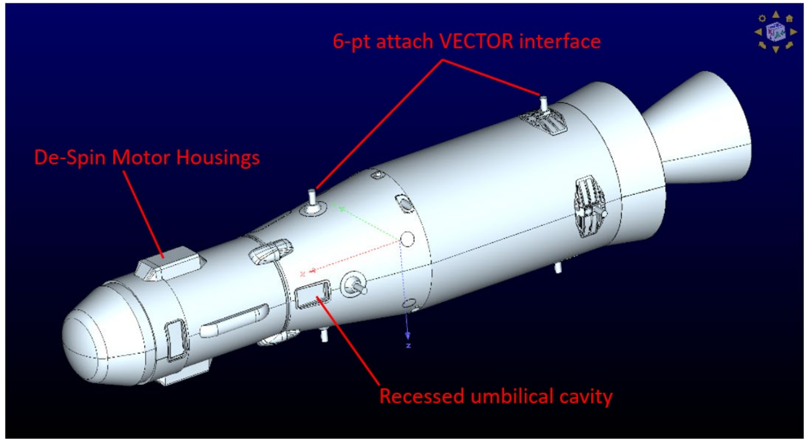
Time-Accurate Flowfield Simulations

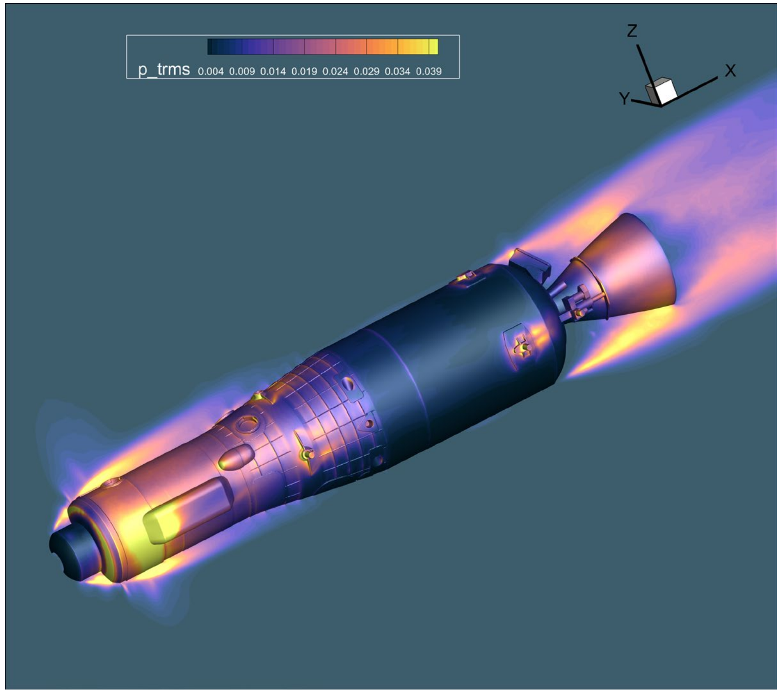
- Use high-resolution time-accurate CFD to generate:
  - Estimates of average surface fluctuating pressure **(SFP)** levels & spectra
  - Estimates of space-time coherence of surface fluctuating pressure
  - Axial distributions of fluctuating sectional forces

… for use in predictions of buffet & vibroacoustic structural response.

- These simulations are performed in an accelerating frame, with varying freestream velocities to simulate trajectory including AoA variation.
  - FUN3D; DDES mode; 166M pt mesh; CO_2 freestream
  - $0.70 < M_\infty < 1.90$; 5.8 sec; 45kHz time step

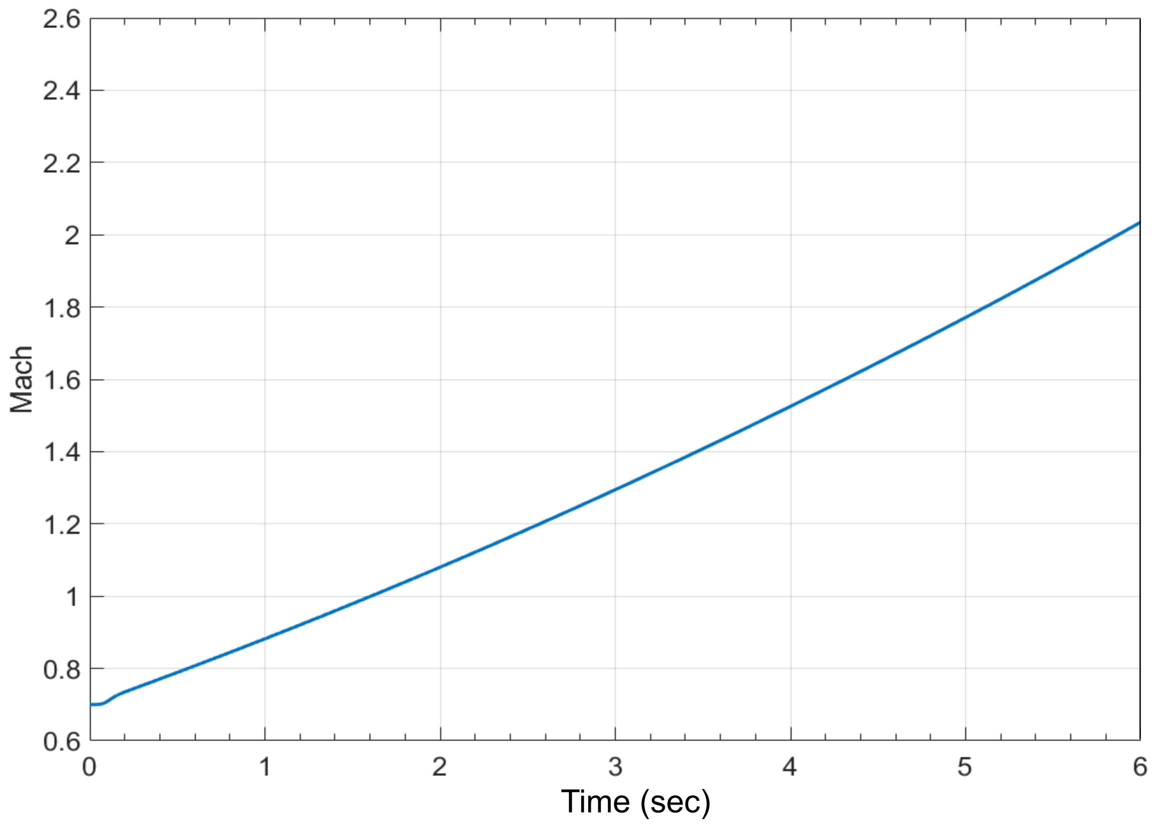
MAV PDC Rev 1.0 CAD





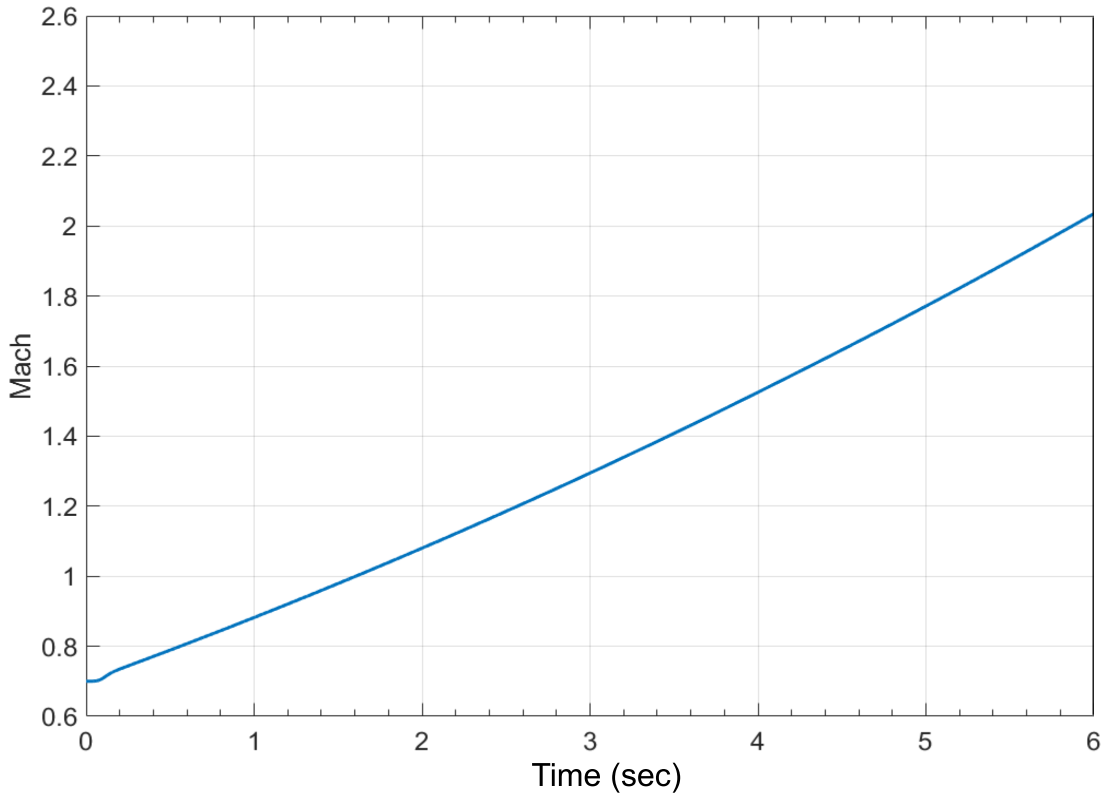
Mach Contours on y=0 Plane

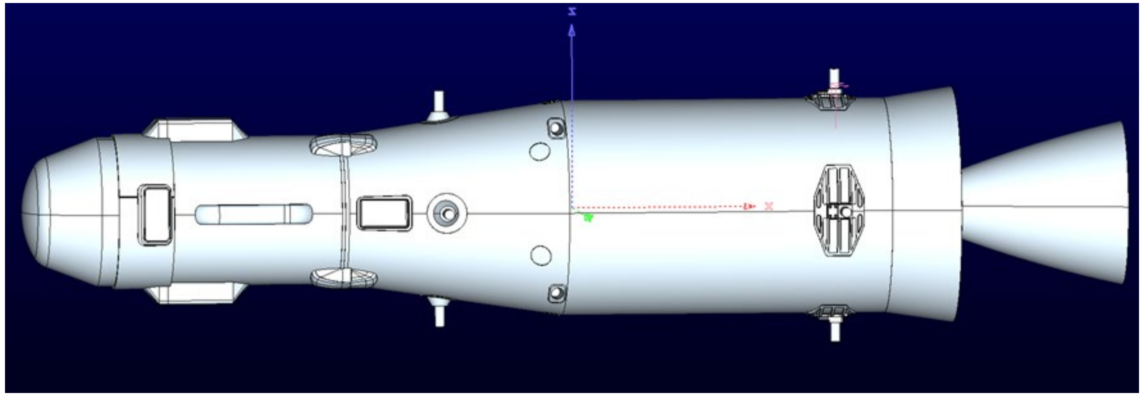
Trajectory $0.70 < M_{\infty} < 1.90$



Evolution of Windowed p’_RMS with Freestream Mach

on unwrapped surface





SUMMARY

Big Picture: How does aerodynamics analysis contribute to MLS success?

- Provide loads and heating environments
- Determine where, along trajectory, aerodynamics impact ascent performance/flight mechanics
- Provide Aerodatabase with sufficient fidelity and bounding uncertainties
- Support RCS system design
  - Identify significant jet interactions
  - Determine JI impact on system design (move jets? High fidelity JI aero model with extensive WT test plan?, determine no-RCS phases of flight?)
- Provide aero loads and acoustic environments for structural design analysis
- Additional aero support to achieve best MLS design
  - Ramp/No Ramp
  - Trajectory design