Low Density Supersonic Decelerator (LDSD) Supersonic Flight Dynamics Test (SFDT) Plume Induced Environments Modelling

Brandon Mobley: NASA Marshall Space Flight Center, Huntsville, AL

Sheldon Smith: Plumetech, Inc., Huntsville, AL

John Van Norman: Analytical Mechanics Associates, Hampton, VA

Suman Muppidi: Analytical Mechanics Associates, Mountain View, CA

Ian Clark: NASA Jet Propulsion Laboratory, Pasadena, CA

13th International Planetary Probe Workshop, Laurel, MD

16th June 2016

Agenda

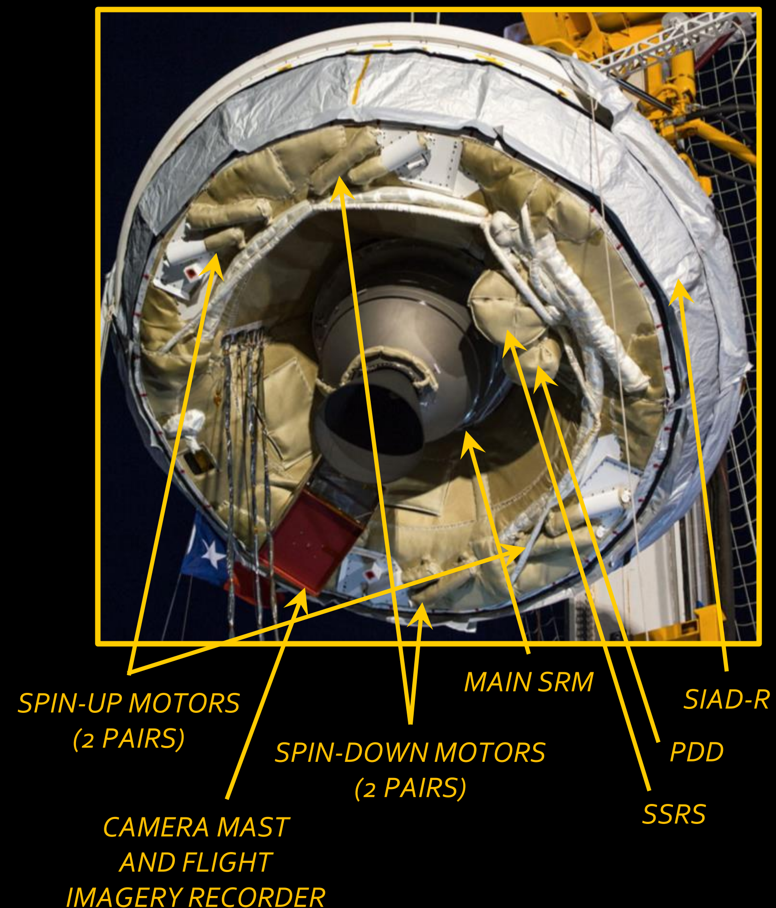
- Background
- Analysis Objectives
- Approach
- Vehicle Impacts & Results
- Conclusions & Lessons Learned

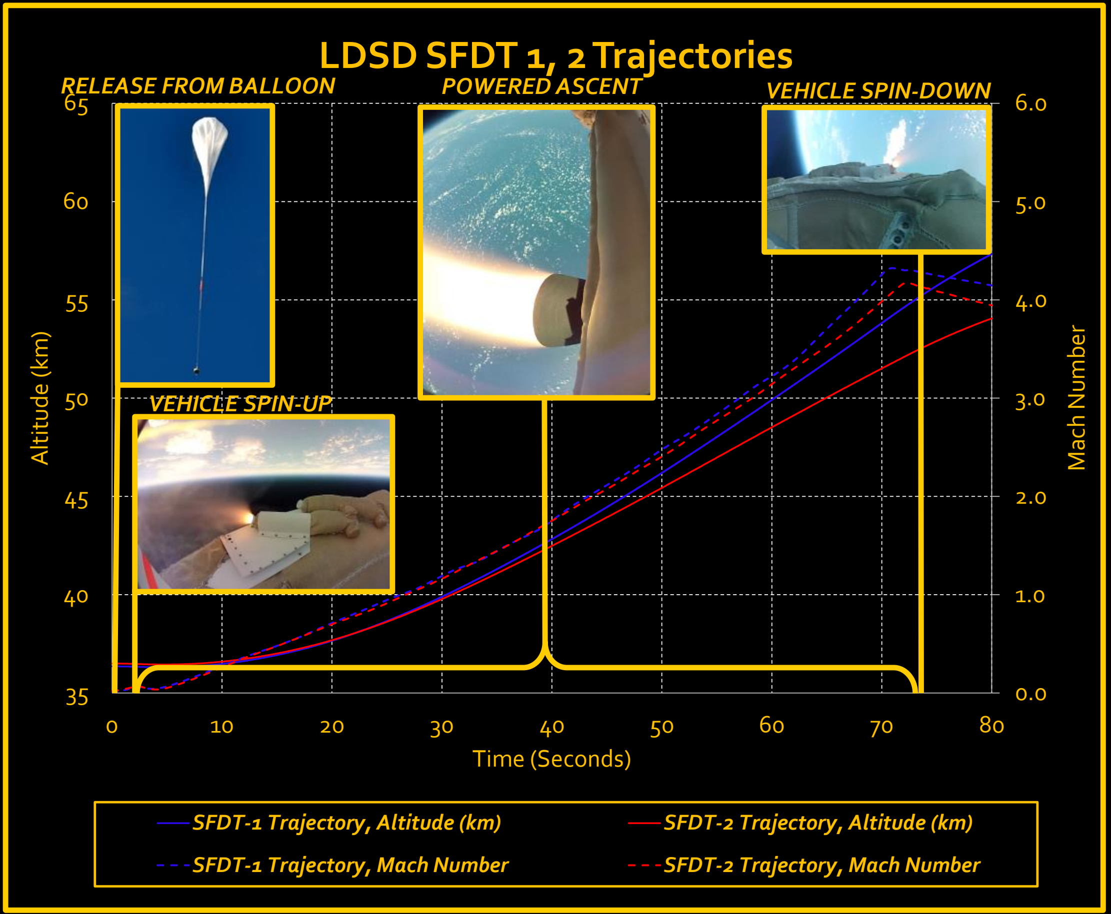
Background

- LDSD Supersonic Flight Dynamics Tests (SFDT-1, 2)
  - Test supersonic deceleration technologies in Earth's upper stratosphere
  - Balloon launched test vehicle, accelerated using a solid rocket motor (SRM) to achieve freestream test conditions (simulate Mars entry)
  - SFDT-1 & 2 Deceleration Technologies
    - Supersonic Inflatable Aerodynamic Decelerator - Robotic class (SIAD-R)
    - Parachute Deployment Device (PDD) – Ballute – parachute extraction
    - Supersonic Disk Sail (SFDT-1) , Ring Sail (SFDT-2) Parachutes
- Marshall Space Flight Center - Aerosciences - Roles
  - Program onset - provide plume induced heating predictions throughout powered flight (main SRM)
  - Spin motor plume impingement (heating and impact pressures)
  - Plume induced aerodynamics (post-SFDT-1 / pre-SFDT-2)

Background

- LDSD Test Vehicle and Trajectories (Best Equivalent)





PICTURE COURTESY OF JPL

Background

Orbital-ATK Star-48B Long Nozzle Solid Rocket Motor	
Expansion Ratio (A/A*)	54.8 (47.2 avg. nozzle erosion)
Throat Diameter	3.98 in / 10.11 cm
Exit Diameter	29.5 in / 74.93 cm
Nozzle Length	35.8 in / 90.93 cm
Chamber Pressure	Approximately 600 PSIA (@ t=0 sec)
Propellant (Approx. % Weight)	
71%	Ammonium Perchlorate
11%	Hydroxyl Terminated Polybutadiene (HTPB)
18%	Aluminum
Duration: Offloaded approx. 20% (400kg) to reduce burn time from 84 to 68 seconds	

PICTURE COURTESY OF NAMMO TALLEY, INC.

Nammo Talley, Inc. Solid Rocket Spin Motor	
Expansion Ratio (A/A*)	6.47
Throat Diameter	0.86 in / 2.2 cm
Exit Diameter	2.2 in / 5.59 cm
Nozzle Length	1.82 in / 4.63 cm
Chamber Pressure	Approximately 3057 PSIA (mean)
Propellant (Approx. % Weight)	
83% Ammonium Perchlorate	1.5% Aluminum
9% HTPB	1.5% Fe_2O_3
5% Plasticizer	
Duration: 0.25 seconds	

Analysis Objectives

- 2012–2013 LDSD Thermal Design Support
  - Star 48 Plume Induced Base Heating
    - Radiation heat flux from Al_2O_3 particles and plume gases
    - Convection from plume-air recirculation
  - Spin Motor Plume Impingement
    - Predict plume heating from convection and Al_2O_3 particle impingement
    - Plume induced forces & moments
- 2014–2015 Plume Induced Aerodynamics Support
    - Predict aerodynamic coefficients (forces & moments) during subsonic and transonic powered flight
    - Investigate plume flow field modeling sensitivities to aerodynamics

Approach

- Simulate plumes throughout a "nominal" flight trajectory at discrete points in time in a quasi-steady fashion
  – Two step approach, model nozzle flows using MSFC engineering codes
  – Nozzle solutions (near nozzle exit plane) used as boundary conditions to CFD domain
- Nozzle Flow Field
  – Model chamber and nozzle flow field chemistry using the NASA Glenn Chemical Equilibrium Combustion (CEC) program
  – Model two-phase nozzle flow, core and boundary layer, using the Reacting and Multiphase Program (RAMP2) & Boundary Layer Integral Matrix Procedure (BLIMPJ) engineering codes (MOC codes)
- Plume Flow Field - Loci-CHEM 3.3 p4 - CFD code
- Radiation – Reverse Monte Carlo – radiation code

Approach

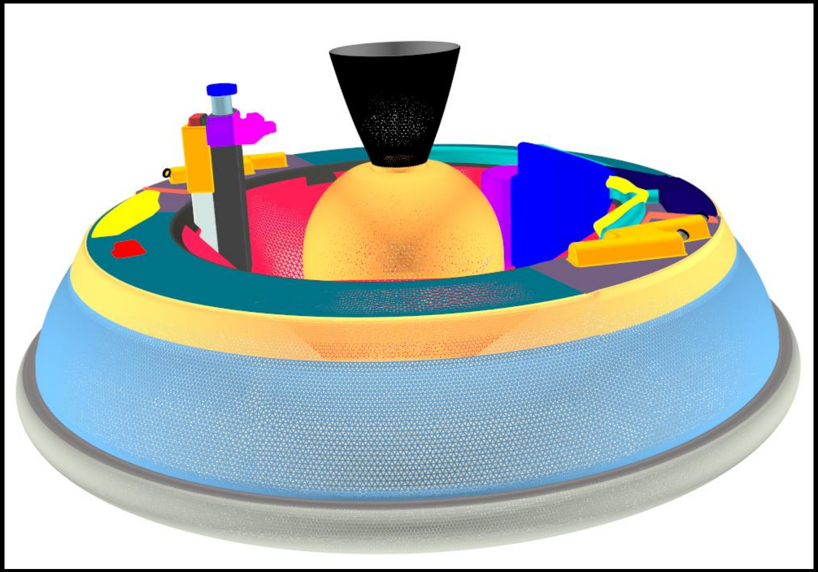
- Grid Challenges
  - Variation of motor firing configurations (1, 2, 4)
  - Variable angles of attack
  - Subsonic / supersonic free stream conditions (shock refinement)
- Grid Characteristics
  - ANSA 14, Solid Mesh 5.9.9 – Surface Grids
  - AFLR3 – Unstructured – Volume Grids
  - Cell Count
    - Spin Motor Cases – Approximately 174 Million Cells (Initial/Final)
    - Star 48 Cases – Approximately 136 Million (Initial), 192 Million (Final)

Approach

CFD Settings

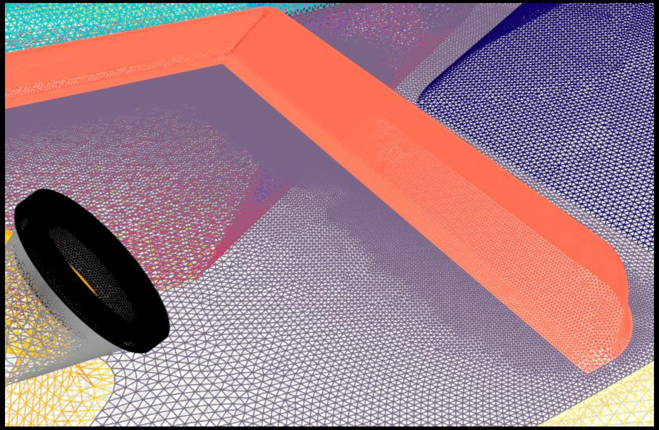
Category	CFD Setup
Case Description	Star 48 Ascent, Spin-Up, Spin-Down Motors
Vehicle/Mesh Geometry	Fully 3D
α, β Angles	Spin-Up Case: α = 163⁰, β = 0⁰ / Star 48 -Trajectory
Chemistry	Frozen
No. Species	2 - Equivalent air & equivalent plume gas
Thermodynamic Properties	Thermally perfect, specie Cp varies with temperature
Viscosity Model	Transport Fit (μ(T), k(T))
Diffusion Model	Laminar-Schmidt
Turbulence Model	Menter's Shear Stress Transport, SST
Compressibility Correction	Sarkar
Urelax (m/s)	0.1
Dt Max (sec)	0.001-0.00001
Accuracy	2nd Order
Wall Temperature	0⁰ F / 255 K(Star48), 255, 973, 1773 K (Spin Motor)
Boundary Conditions	No-slip walls, vehicle spin rate applied
Vehicle Spin (RPM)	0, 50 RPM
Internal Nozzle Wall Thermal BC	Adiabatic

Spin-Up Motor Surface Mesh (Final)



STAR 48 Case Conditions

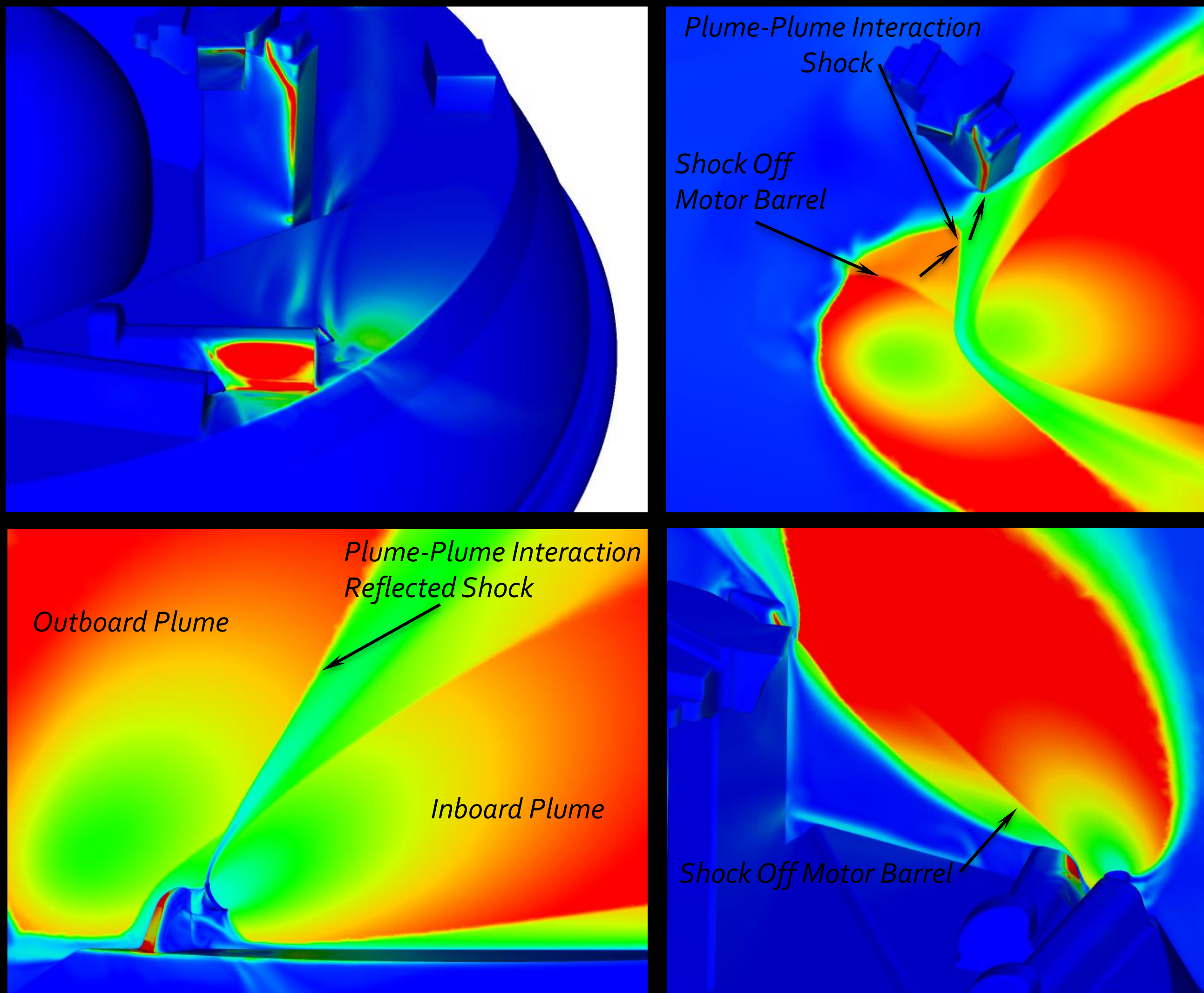
Trajectory Atmospheric Conditions					Star48 Chamber Conditions			Vehicle Attitude
Alt (km)	M_∞	q_∞ (Pa)	P_∞ (Pa)	T_∞ (K)	Po (kPa)	P_{lip} (kPa)	$\theta_{Press\ Exp\ Ratio}$	α_{Total} (deg)
36.322	0.100	3.458	494.00	242.00	4438	11.135	22.54	40.4
36.390	0.200	13.711	489.69	241.88	4438	11.135	22.74	30.0
36.514	0.300	30.303	481.00	242.00	4438	11.135	23.15	22.3
36.993	0.500	78.750	450.00	244.00	4180	10.804	24.01	17.7
37.617	0.700	141.659	413.00	244.00	4187	10.928	26.46	17.1
38.449	0.900	208.656	368.00	246.00	4187	10.928	29.70	14.7
38.682	0.950	225.535	357.00	248.00	4187	10.928	30.61	14.4
39.469	1.100	271.040	320.000	253.00	4248	11.576	36.18	12.7
39.936	1.200	304.416	302.000	257.00	4248	11.576	38.33	11.5



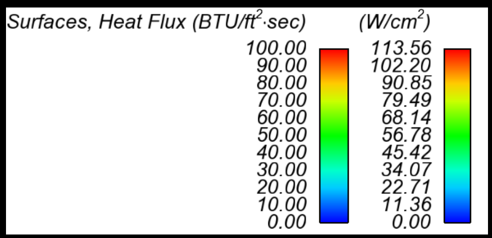
Spin Motor Analysis

INITIAL ANALYSIS

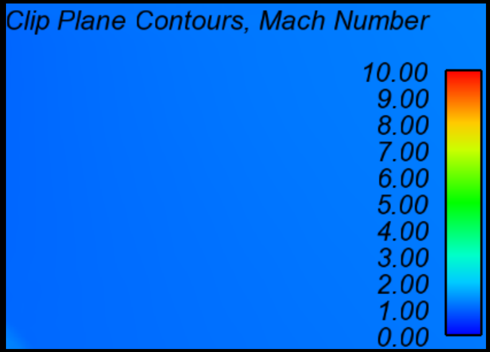
SPIN-UP – 120 Kft (36.6 km), P_∞= 0.72 PSIA (499 Pa) - ALL SPIN-UP MOTORS "ON"



Surface Contours



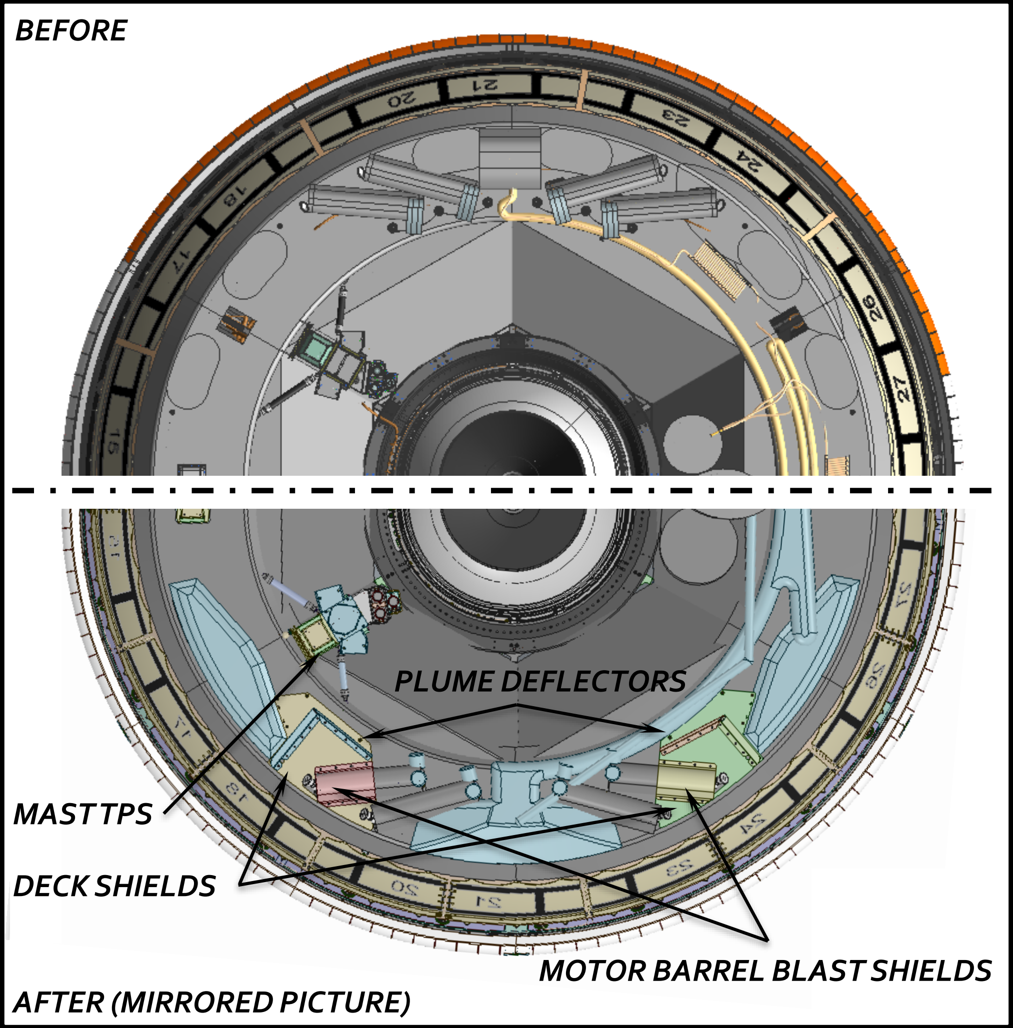
Solution Plane Contours



Spin Motor Analysis

- Spin Motor Plume Impingement Environment Summary
  - Motor casings, bridle coverings - severe heating areas, heat rates in excess of 500 BTU/ft^2sec (568 W/cm^2)
  - Camera mast, heating in excess of 200 BTU/ft^2sec (170 W/cm^2)
- Thermal Design Impact - Two week “Tiger Team” to provide thermal protection options
  - Incorporated plume blast shields and deflectors
  - Additional thermal protection (TPS) on camera mast
  - Staggered firing configurations (driven by flight dynamics as well)

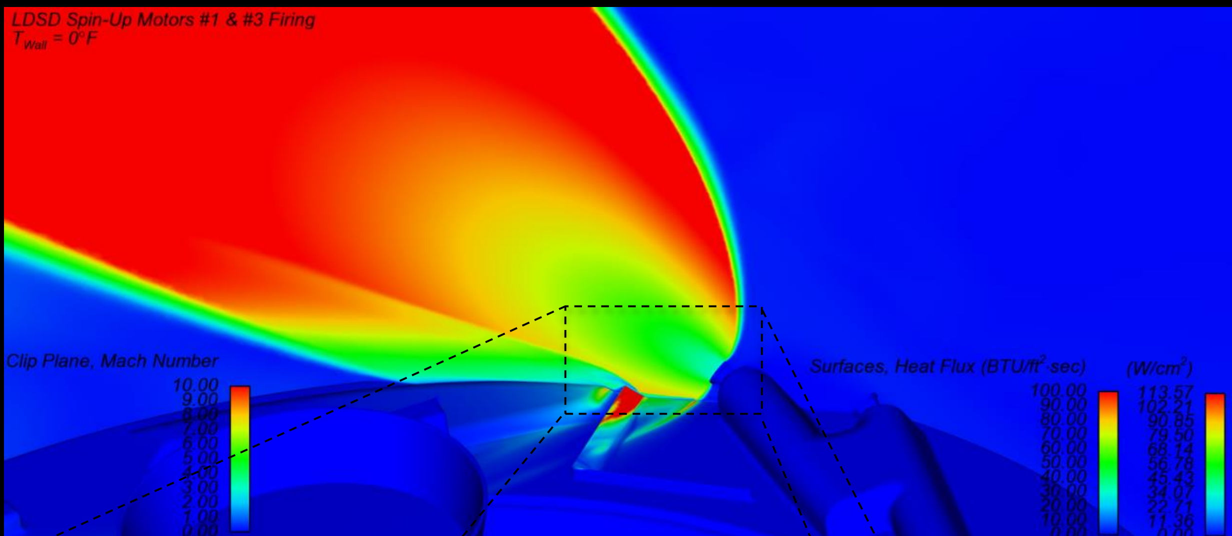
Analysis Impacts & Results

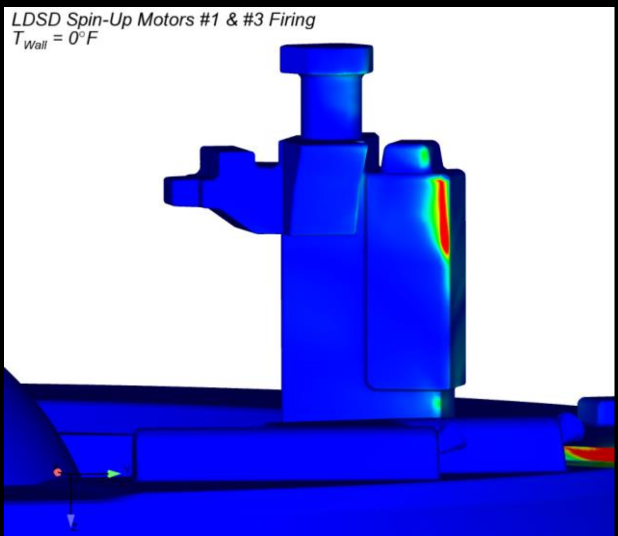


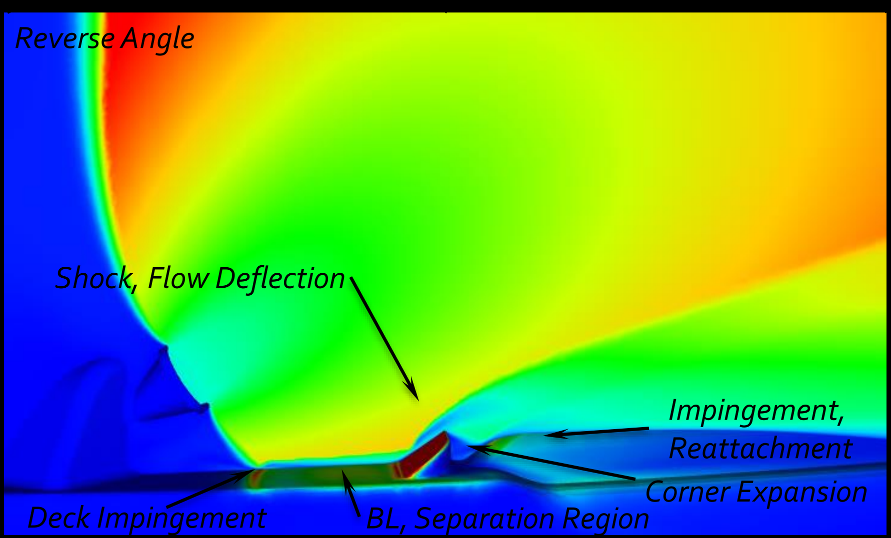
Spin Motor Analysis

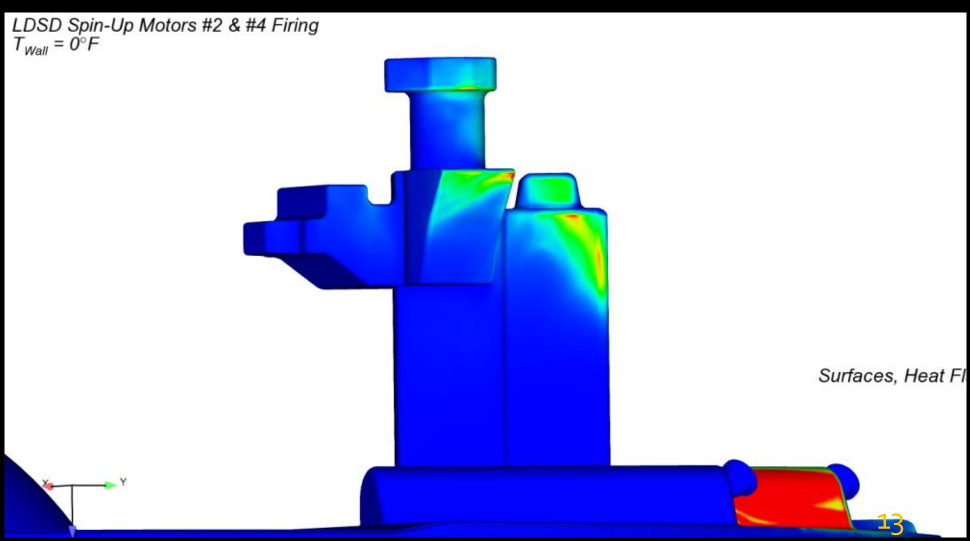
FOLLOW-UP ANALYSIS

SPIN-UP – 120 Kft (36.6 km), P_∞= 0.72 PSIA (499 Pa) - ALL SPIN-UP MOTORS "ON"





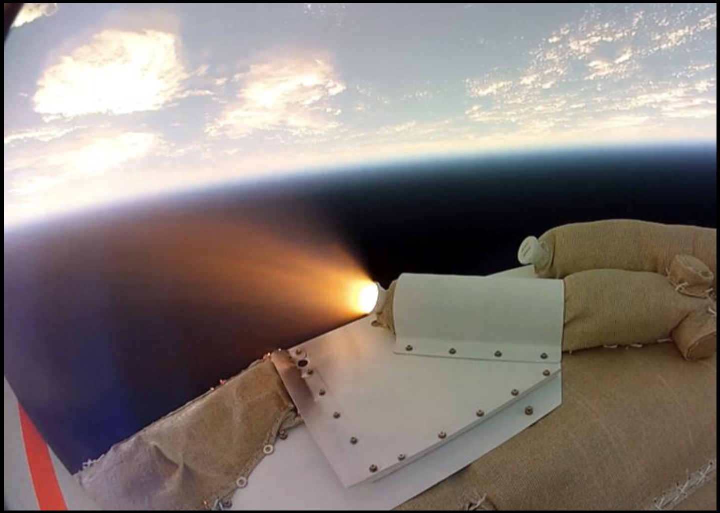


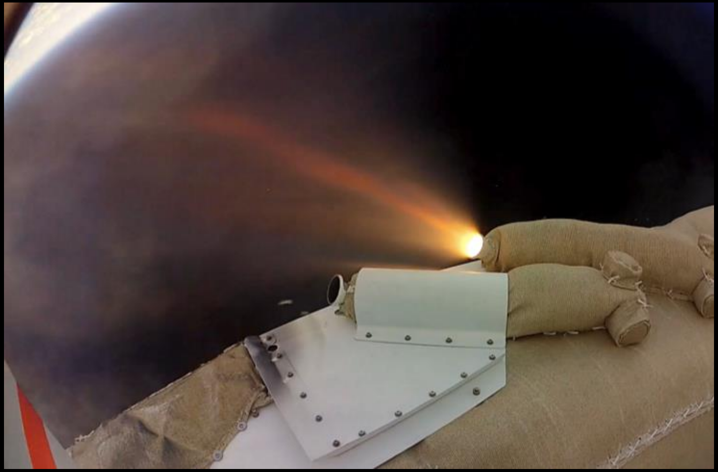


Impacts & Results

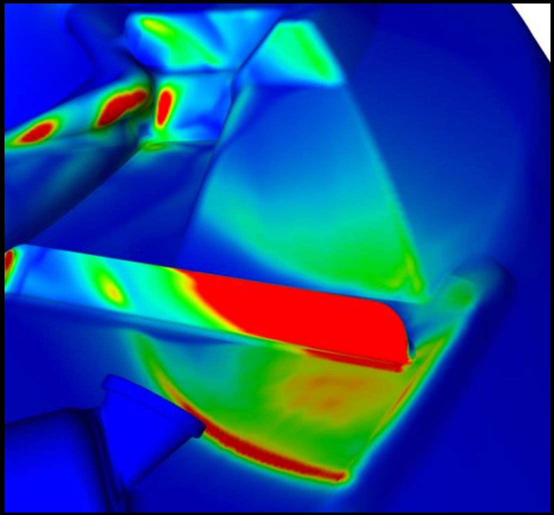
SFDT-1

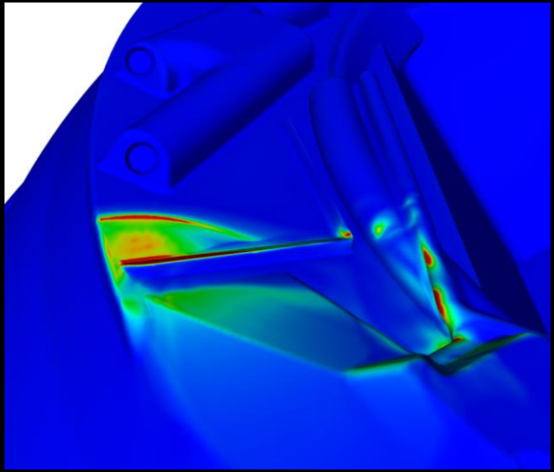
Spin-Up Motor Firings





Pre-flight Heating Contours





Post-flight Charring

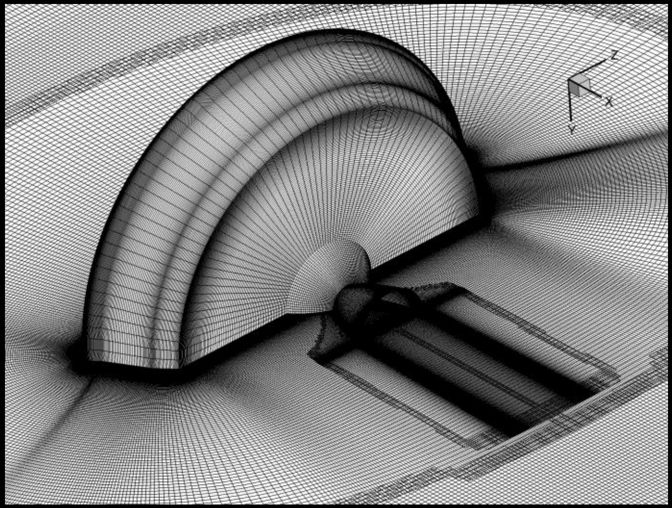
Star 48 Analysis

- SFDT-1 flight reconstruction revealed the test vehicle over shot the targeted altitude approximately 10Kft
  - Chamber pressure measurements failed, no distinct way to decouple thrust and drag (challenge on determination of C_A)
  - Reconstruction analysis revealed slightly over performing solid and over prediction of plume induced drag (higher predicted axial coefficient, C_A)
  - Over predicted total moment (pitch-yaw) coefficent, vehicle lofted more than expected

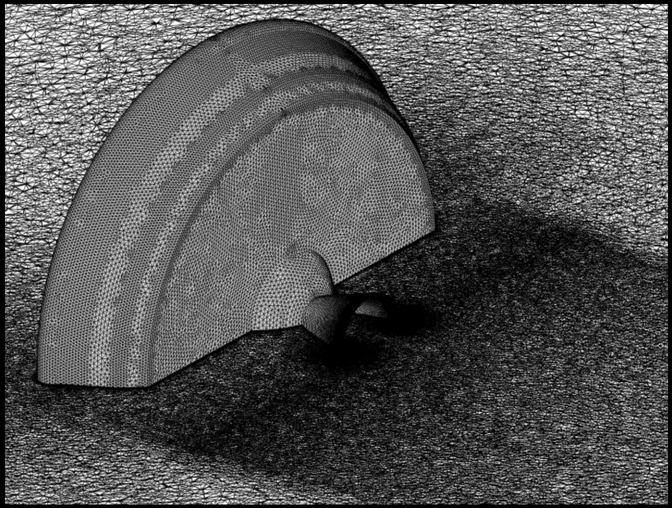
Star 48 Analysis

Aerodynamic Database 1.5

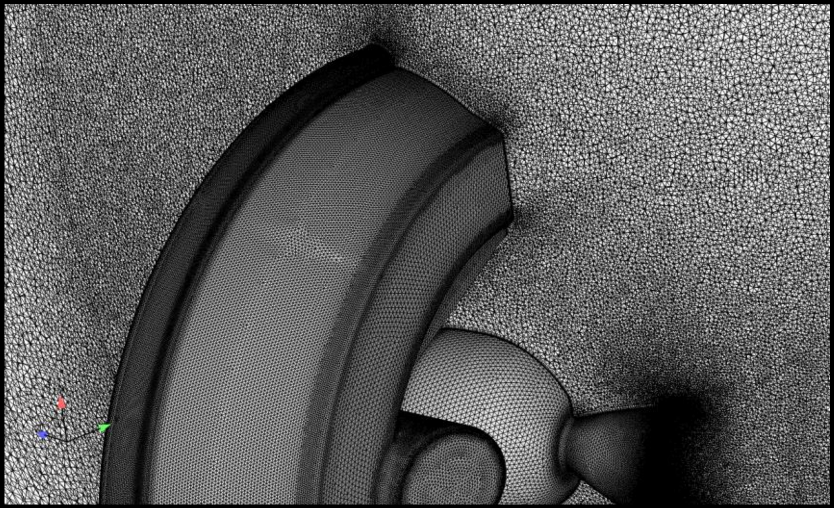
OVERFLOW



FUN3D

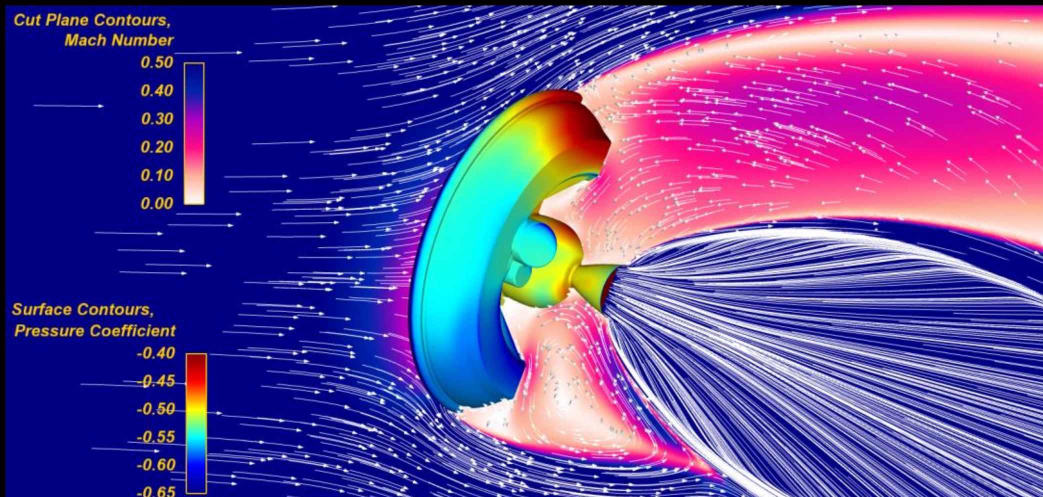


Loci-CHEM Runs

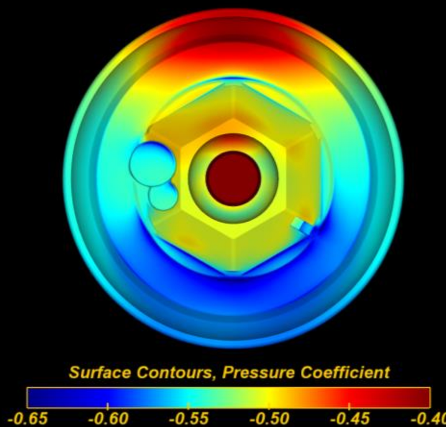


Impacts & Results

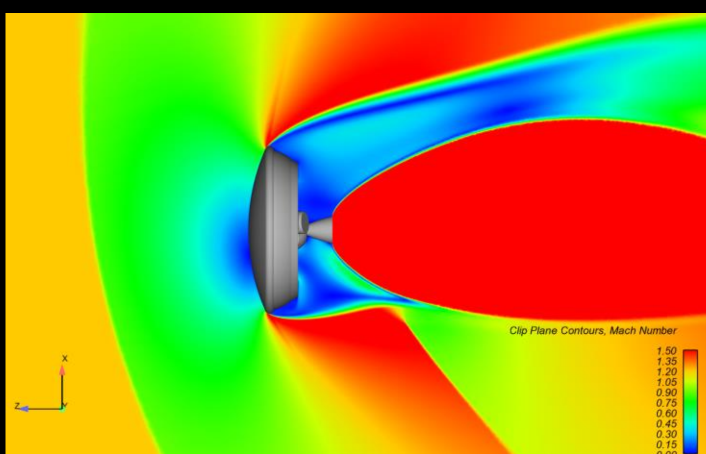
STAR48 PLUME INDUCED AERODYNAMICS
Mach = 0.7, Angle-of-Attack = 17.1°



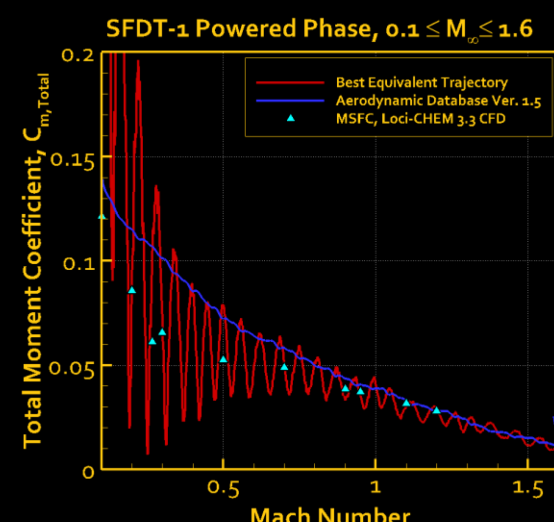
Base Pressure Coefficient



Mach = 1.2, Angle-of-Attack = 11.5°

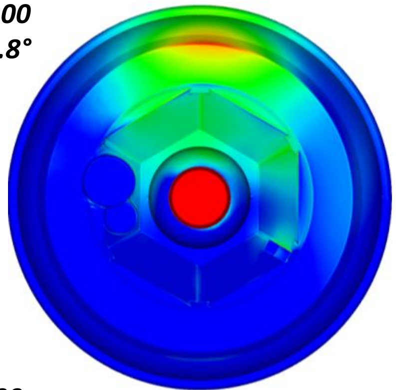


SFDT-1 Lofting Impact

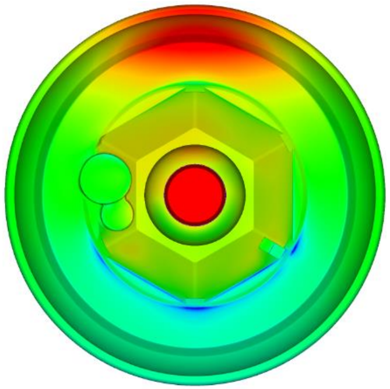


Impacts & Results

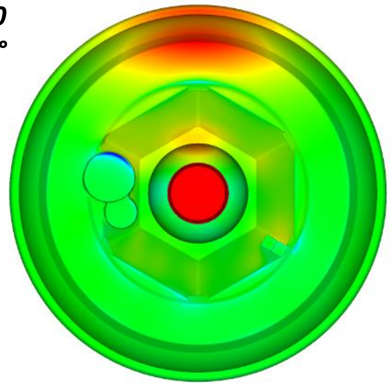
M=0.100
α = 40.8°



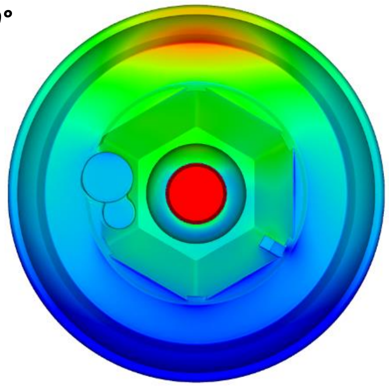
M=0.500
α = 17.7°



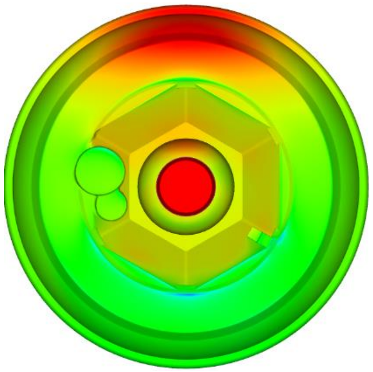
M=0.950
α = 14.4°



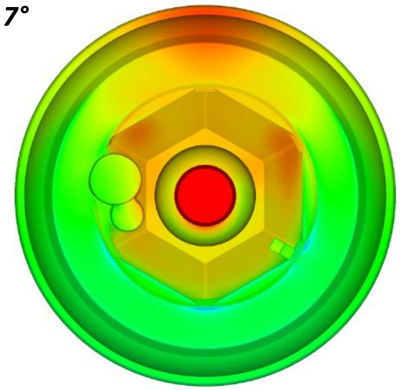
M=0.200
α = 30.0°



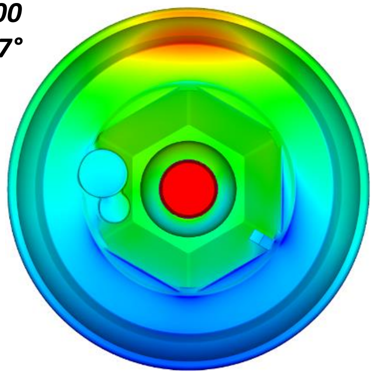
M=0.700
α = 17.1°



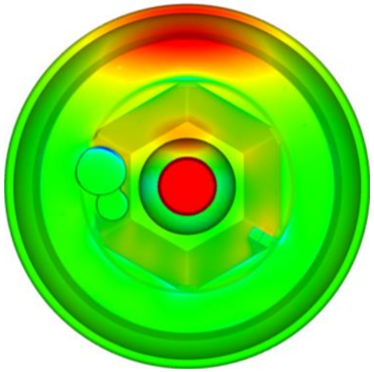
M=1.10
α = 12.7°



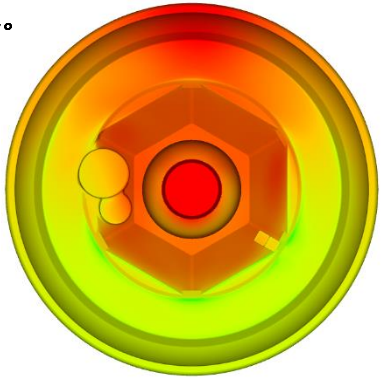
M=0.300
α = 14.7°

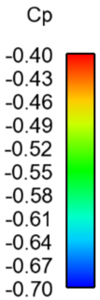


M=0.900
α = 14.7°

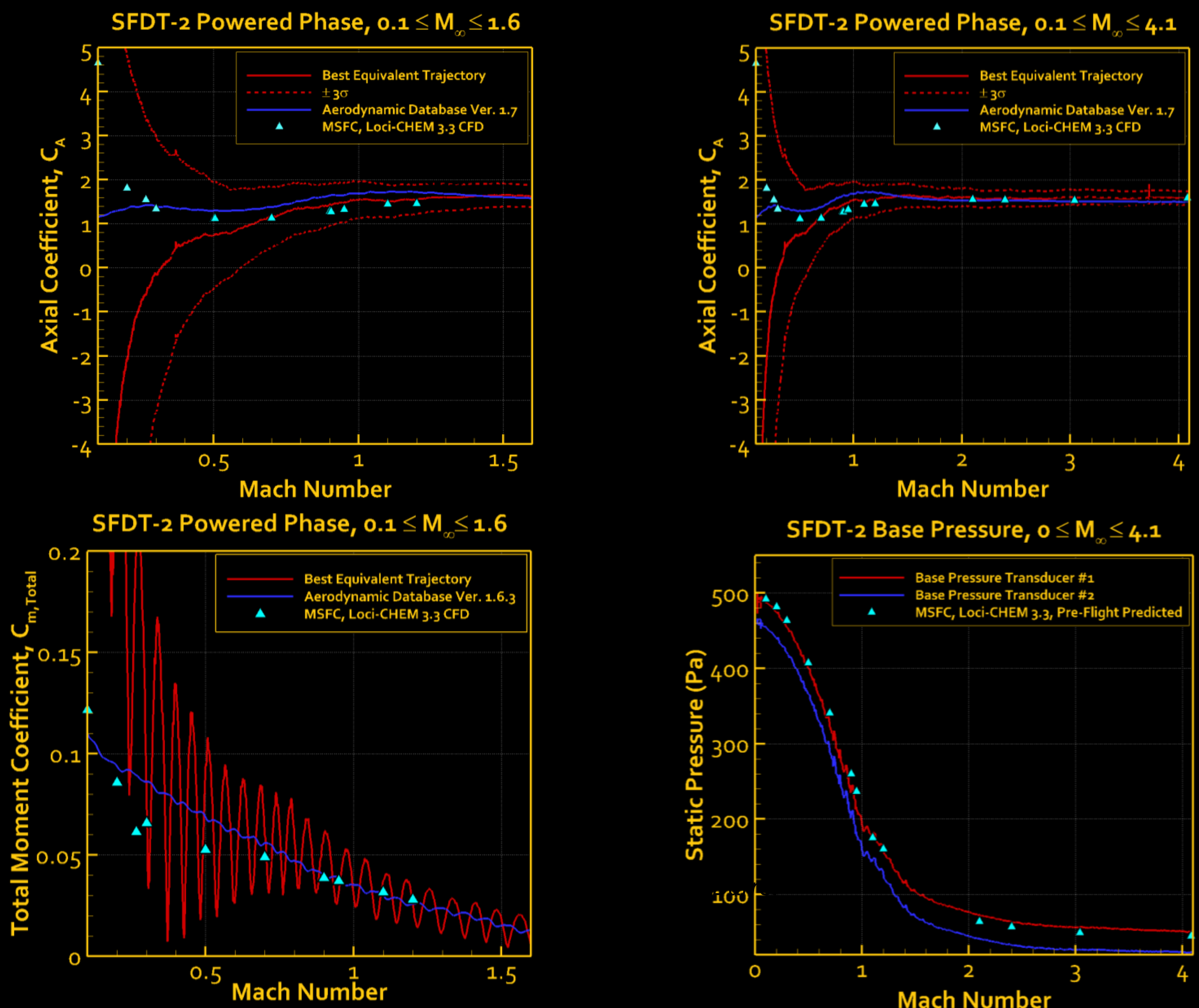


M=1.20
α = 11.5°





Impacts & Results



Conclusions & Lessons Learned

Summary

- Spin motor plume impingement - all thermal requirements met!
- Star48 power-on aerodynamic data base updated
  - SFDT-2 great agreement with pitching moment coefficient and base pressures

Conclusions

- Highly under expanded plume-air interactions can be significant
  - Observed similar plume induced environment issues with separation motors
  - Changes in altitude and angle of attack angle change the plume, affects degree of entrainment, base pressure distribution
- Modeling base flow fields with single plume-air interaction with CFD
  - Match nozzle total enthalpy and nozzle boundary layer flow characteristics- low momentum gases interacting with freestream
  - Adequate grid resolution to capture:
    - Reverse jet impingement and recirculation eddies
    - Base features affecting recirculation eddies

Back-Up