PLUME INDUCED AERODYNAMIC AND HEATING MODELS FOR THE LOW DENSITY SUPersonic DeCELERATOR TEST VEHICLE

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Presented By:
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Huntsville, AL
Agenda

• Background

• Analysis Objectives

• Approach

• Analyses
  – Spin Motor Plume Impingement Environments
  – Main SRM Plume Induced Environments

• Conclusions & Lessons Learned
Background

- **LDSD Supersonic Flight Dynamics Tests (SFDT-1, 2)**
  - Test supersonic deceleration technologies in Earth’s upper stratosphere, SFDT-1: June 28, 2014, SFDT-2: June 8, 2015
  - 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 – EV33 Aerosciences - Roles**
  - Program onset - provide plume induced heating predictions throughout powered flight (main solid)
  - Spin motor plume impingement (heating and impact pressures)
  - Plume induced aerodynamics predictions (post-SFDT-1/pre-SFDT-2)
Full Scale Testing in Earth’s Stratosphere—Simulating Mars Entry

Figure Courtesy of JPL
Background

• LDSD Test Vehicle and Trajectories\(^1,\)\(^2\) (Best Equivalent)
## Background

### Orbital-ATK Star-48B Long Nozzle Solid Rocket Motor³

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expansion Ratio (A/A*)</td>
<td>54.8 (47.2 avg. nozzle erosion)</td>
</tr>
<tr>
<td>Throat Diameter</td>
<td>3.98 in / 10.11 cm</td>
</tr>
<tr>
<td>Exit Diameter</td>
<td>29.5 in / 74.93 cm</td>
</tr>
<tr>
<td>Nozzle Length</td>
<td>35.8 in / 90.93 cm</td>
</tr>
<tr>
<td>Chamber Pressure</td>
<td>Approximately 600 PSIA (@ t=0 sec)</td>
</tr>
<tr>
<td>Propellant (Approx. % Weight)</td>
<td></td>
</tr>
<tr>
<td>71% Ammonium Perchlorate</td>
<td></td>
</tr>
<tr>
<td>11% Hydroxyl Terminated Polybutadiene (HTPB)</td>
<td></td>
</tr>
<tr>
<td>18% Aluminum</td>
<td></td>
</tr>
<tr>
<td>Duration: Offloaded approx. 20% (400kg) to reduce burn time from 84 to 68 secs</td>
<td></td>
</tr>
</tbody>
</table>

### Nammo Talley, Inc. Solid Rocket Spin Motor

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expansion Ratio (A/A*)</td>
<td>6.47</td>
</tr>
<tr>
<td>Throat Diameter</td>
<td>0.86 in / 2.2 cm</td>
</tr>
<tr>
<td>Exit Diameter</td>
<td>2.2 in / 5.59 cm</td>
</tr>
<tr>
<td>Nozzle Length</td>
<td>1.82 in / 4.63 cm</td>
</tr>
<tr>
<td>Chamber Pressure</td>
<td>Approximately 3057 PSIA</td>
</tr>
<tr>
<td>Propellant (Approx. % Weight)</td>
<td></td>
</tr>
<tr>
<td>83% Ammonium Perchlorate</td>
<td>1.5% Aluminum</td>
</tr>
<tr>
<td>9% HTPB</td>
<td>1.5% Fe₂O₃</td>
</tr>
<tr>
<td>5% Plasticizer</td>
<td></td>
</tr>
<tr>
<td>Duration: 0.25 secs</td>
<td></td>
</tr>
</tbody>
</table>
Analysis Objectives

• 2012–2013 LDSD Thermal Design Support
  – Star 48 Plume Induced Base Heating
    • Radiation heat flux from Al$_2$O$_3$ particles and plume gases
    • Convection from plume-air recirculation
  – Spin Motor Plume Impingement
    • Predict plume heating from convection and Al$_2$O$_3$ particle impingement
    • Plume induced forces & moments (spin performance)
    • Primary concerns, impingement heating on SIAD, parachute bridles and mast cameras and instrumentation

• 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 flight trajectory at discrete points in time in a quasi-steady fashion
  - Two step approach, nozzle flows using engineering codes
  - Nozzle solutions 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) eng. codes (MOC codes)

- CFD (induced forces & convection) - Loci-CHEM 3.3 p4

- Spin Motor Plume Particle Heating – PLIMP eng. code

- Plume Radiation (sep. series of plume solutions, Star 48)
  - RAMP2 & SPF – Gas and Al2O3 particle plume flow field
  - Reverse Monte Carlo – Particle, gaseous band model code
Computational Grid

• CFD Grid Challenges
  – Approach – Generally, try to create one grid to accommodate many cases, opposed to #grids refined for each case
  – Variation of motor firing configurations (2, 4)
    • 1 spin-up and 1 spin-down grid to suit case
    • Tailored surface geometries per spin motor impingement, removed protuberances “behind motors”
  – Variable angles of attack
  – Subsonic / supersonic free stream conditions (shock refinement, aspiration refinement/convergence)

• Grid Generation
  – ANSA 14, Solid Mesh 5.9.921 – Surface Grids, Volume Setup
  – AFLR322 – Unstructured – Volume Grids
### Approach

#### Summary of CFD Settings, RANS

<table>
<thead>
<tr>
<th>Category</th>
<th>Case Description</th>
<th>Model Setup</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Spin-Up Motors</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Spin-Down Motors</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Star48B Motor</td>
<td></td>
</tr>
<tr>
<td>Number</td>
<td>Number of Plumes Simulated</td>
<td>4 (all on) and 2 (staggered firing)</td>
</tr>
<tr>
<td>of</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Plumes</td>
<td>Simulated</td>
<td></td>
</tr>
<tr>
<td>Simulated</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angle-of-Attack, ( \alpha ), and Side-Slip, ( \beta ), Angles</td>
<td>( \alpha = 163^\circ, \beta = 0^\circ ) ( \alpha = 0^\circ, \beta = 0^\circ ) Various, per trajectory</td>
<td></td>
</tr>
<tr>
<td>Plume</td>
<td>Chemistry</td>
<td>Frozen</td>
</tr>
<tr>
<td>No.</td>
<td>Species</td>
<td></td>
</tr>
<tr>
<td>Species</td>
<td></td>
<td>2 - Equivalent air &amp; plume gas</td>
</tr>
<tr>
<td>Thermodynamic and Transport Properties</td>
<td>Specific Heat, ( C_p )</td>
<td>Thermally perfect gas, specie ( C_p ) varies with temperature, polynomial</td>
</tr>
<tr>
<td>Viscosity and Conduction Models</td>
<td>Transport Fit (equivalent ( \mu(T), k(T) ) per specie)</td>
<td></td>
</tr>
<tr>
<td>Diffusion Model</td>
<td>Laminar-Schmidt</td>
<td></td>
</tr>
<tr>
<td>Particle</td>
<td>Model</td>
<td>Aluminum-Oxide</td>
</tr>
<tr>
<td>Model</td>
<td></td>
<td>Lagrangian (1 Case)</td>
</tr>
<tr>
<td>Type</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number</td>
<td>of Particle Bins &amp; Sizes</td>
<td>5, 1.662 - 4.557( \mu m )</td>
</tr>
<tr>
<td>Urelax</td>
<td>(m/s)</td>
<td>0.10</td>
</tr>
<tr>
<td>Dt Max</td>
<td>(sec)</td>
<td>Varied per case, generally 0.001 - 0.0001 sec</td>
</tr>
<tr>
<td>Accuracy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2nd Order, steady-state solutions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface Boundary Conditions</td>
<td>Wall Temperatures</td>
<td>No slip, vehicle spin rate applied</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>255, 973, 1773 K</td>
<td></td>
</tr>
<tr>
<td>Vehicle</td>
<td>Spin Rate</td>
<td>0</td>
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<tr>
<td>Spin Rate</td>
<td></td>
<td>50 (RPM)</td>
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<tr>
<td>Solver</td>
<td></td>
<td></td>
</tr>
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<td></td>
<td>Adiabatic Wall (Carbon Phenolic)</td>
<td></td>
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<tr>
<td></td>
<td>Guass-Seidel</td>
<td></td>
</tr>
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</table>

#### Spin-Up Motor Surface Mesh

(Final Iteration, 174M)

#### STAR 48 SFDT-2 & Spin Motor Case Conditions

<table>
<thead>
<tr>
<th>Trajectory Atmospheric Conditions</th>
<th>Chamber Conditions</th>
<th>Vehicle Attitude</th>
<th>Notes</th>
</tr>
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<tbody>
<tr>
<td>Alt (km)</td>
<td>Po (psia)</td>
<td>( \theta_{\text{Press Exp Ratio}} )</td>
<td>( \alpha_{\text{Total (deg)}} )</td>
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<tr>
<td>36.050</td>
<td>0.01</td>
<td>0.84</td>
<td>499.03</td>
</tr>
<tr>
<td>36.322</td>
<td>0.10</td>
<td>3.46</td>
<td>494.00</td>
</tr>
<tr>
<td>36.390</td>
<td>0.20</td>
<td>13.71</td>
<td>489.69</td>
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<tr>
<td>36.514</td>
<td>0.30</td>
<td>30.30</td>
<td>481.00</td>
</tr>
<tr>
<td>36.993</td>
<td>0.50</td>
<td>78.75</td>
<td>450.00</td>
</tr>
<tr>
<td>37.617</td>
<td>0.70</td>
<td>141.66</td>
<td>413.00</td>
</tr>
<tr>
<td>38.449</td>
<td>0.90</td>
<td>208.66</td>
<td>368.00</td>
</tr>
<tr>
<td>38.682</td>
<td>0.95</td>
<td>225.53</td>
<td>357.00</td>
</tr>
<tr>
<td>39.469</td>
<td>1.10</td>
<td>271.04</td>
<td>320.00</td>
</tr>
<tr>
<td>49.480</td>
<td>4.23</td>
<td>1171.60</td>
<td>93.10</td>
</tr>
</tbody>
</table>
Spin Motor Analysis

INITIAL ANALYSIS

SPIN-UP – 120 Kft (36.6 km), $P_\infty = 0.72$ PSIA (499 Pa) - ALL SPIN-UP MOTORS “ON”

Surface Contours

Solution Plane Contours

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• Initial Spin Motor Plume Impingement Summary
  – Motor casings, bridle coverings - severe heating areas, peak heat rates in excess of 500 BTU/ft\(^2\)/sec (568 W/cm\(^2\))
  – Camera mast, peak heat rates in excess of 200 BTU/ft\(^2\)/sec (170 W/cm\(^2\))

• Thermal and Operational Design Impacts
  – Two week “Tiger Team” to provide thermal protection options
  – Added plume deck blast shields, motor barrel shields and deflectors
    • Restricted height to prevent potential entanglement with chute brid. lines
  – Thermal protection (TPS) increased on camera mast (thin cork)
  – Staggered firing configurations (driven by flight dynamics, flight-ops as well)
Spin Motor Analysis

BEFORE INITIAL PLUME ANALYSIS

AFTER (MIRRORED PICTURE)

- Plume Deflectors
- Motor Barrel Blasts Shields
- Deck Shields
- MAST TPS

DEFLECTOR
DECK SHIELD
MOTOR BARREL SHIELD
FOLLOW-UP ANALYSIS

SPIN-UP – 120 Kft (36.6 km), $P_\infty = 0.72$ PSIA (499 Pa) – STAGGERED FIRINGS

Deck Impingement

BL, Separation Region

Corner Expansion

Impingement, Reattachment

Shock, Flow Deflection

Reverse Angle

Surfaces, Heat Flux (BTU/ft²·sec) (W/cm²)

Clip Plane, Mach Number

LDSD Spin-Up Motors #1 & #3 Firing
$T_{wall} = 0^\circ F$

LDSD Spin-Up Motors #2 & #4 Firing
$T_{wall} = 0^\circ F$

Surfaces, Heat Flux
• Pre-SFDT-1 Star 48 plume induced heating environments
  – Predicted radiation rates approximately a factor of 4 less than initial
  – Predicted base pressure coefficient always negative, predicted convective heat rates generally <1 BTU/ft²/sec
  – No thermal issues, very benign, highest temperatures were recorded on the Star 48 motor case (282 C, driven by internal environment)
SFDT-1 flight reconstruction revealed the test vehicle overshot the targeted altitude approximately 10Kft

- No chamber pressure measurements, no distinct way to accurately decoupling thrust and drag (challenge on determination of $C_A$)
- Thrust reconstruction analysis revealed slightly over performing solid and over prediction of plume induced drag
- Over predicted total moment (pitch-yaw) coefficient, resulting in the vehicle lofting more than expected
Star 48 Analysis

- LDSD plume induced base flow field is different than “traditional” launch vehicles and missiles
  1. Blunt body - Realm of historical launch vehicles and missiles have a large slenderness ratio, where there is considerable running length to allow the development of a thick boundary layer that enters the base
  2. Ratio of base-to-nozzle exit area – free stream expansion angle entering the base, relative base eddy scale. Aft cavity provides recovery volume that affects the base environment
  3. Variation in total alpha due to spin/flight dynamics

![Graph showing LDSD plume induced base flow field](image)

Figure Courtesy of Clara O'Farrell, JPL

![Static Pressure (Pa) vs. Mach Number](image)

SFDT-2 Base Pressure, $0 \leq M_\infty \leq 4.1$

$M_\infty = 0.200$

$\alpha = 30.0^\circ$

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Grid Evolution – Star 48

Initial Grids, Pre-SFDT-1 Heating (41 - 90 million cell, 2013)

*Predominantly supersonic cases, 1.1 < \( M_\infty < 4.3 \), need higher \( q_\infty \) for recirculation*

Simple geometry & trajectory (\( \alpha_{\text{total}}=0^\circ \), small vol. \( O \sim 0.1 \text{ km}^3 \))

*Primary objective, resolve forward shock, plume induced base recirc. (avg heating)*

Post-SFDT-1 (90, 136 million, 2014)

Sub, transonic cases (\( M_\infty= 0.5 - 1.2 \), “larger” vol. \( O \sim 1 \text{ km}^3 \))

Two geometries, reconstructed traj. subset (\( \alpha, \beta = 0, 10, 20^\circ \))

Multiple Models – Plume w/wout particles, hybrid RANS/LES (423M)

Objective, predict plume induced aero. forces & moments

Pre-SFDT-2 (191 million, 2015)

Sub, transonic cases (\( M_\infty=0 - 1.2 \) “larger” vol. \( O \sim 1 \text{ km}^3 \))

Reconstructed trajectory subset (\( \alpha, \beta =10 – 40^\circ \))

Increase grid to accommodate \( \geq 40^\circ \) cases, seek grid convergence

<table>
<thead>
<tr>
<th>Type</th>
<th>Grid Cells (M)</th>
<th>Mach</th>
<th>( \alpha ) (deg)</th>
<th>CA</th>
<th>%CA_{\text{abs}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium</td>
<td>136</td>
<td>0.5</td>
<td>20</td>
<td>1.1086</td>
<td>0.32%</td>
</tr>
<tr>
<td>Fine</td>
<td>192</td>
<td>0.5</td>
<td>20</td>
<td>1.1027</td>
<td>0.54%</td>
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<tr>
<td>Medium</td>
<td>136</td>
<td>0.9</td>
<td>20</td>
<td>1.2662</td>
<td>0.32%</td>
</tr>
<tr>
<td>Fine</td>
<td>192</td>
<td>0.9</td>
<td>20</td>
<td>1.2703</td>
<td>0.32%</td>
</tr>
</tbody>
</table>
Star 48 Analysis

Aerodynamic Database 1.5
OVERFLOW

Figures Courtesy of John Van Norman, LaRC

Loci-CHEM Runs (2015)
STAR 48 Analysis

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

CFD, Mach = 1.2, Angle-of-Attack = 11.5°

Base Pressure Coefficient

SFDT-1 Lofting Impact
SFDT-1 Powered Phase, 0.1 ≤ M ≤ 1.6

Over predicted Pitching Moment

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Star 48 Analysis

\[ M=0.100 \quad \alpha = 40.8^\circ \]
\[ M=0.200 \quad \alpha = 30.0^\circ \]
\[ M=0.300 \quad \alpha = 14.7^\circ \]

\[ M=0.500 \quad \alpha = 17.7^\circ \]
\[ M=0.700 \quad \alpha = 17.1^\circ \]
\[ M=0.900 \quad \alpha = 14.7^\circ \]

\[ M=0.950 \quad \alpha = 14.4^\circ \]
\[ M=1.10 \quad \alpha = 12.7^\circ \]
\[ M=1.20 \quad \alpha = 11.5^\circ \]
**Flight Instrumentation**

- Star 48 chamber pressure, Kulite pressure transducer
  - Star 48 performance, thrust reconstruction
- Tavis (2) pressure transducers (0-0.137 psia)
  - Base pressure, aero model CFD validation
Impacts & Results

SFDT-2 Powered Phase, $0.1 \leq M_{\infty} \leq 4.1$

- Best Equivalent Trajectory
- $\pm 3\sigma$
- Aerodynamic Database Ver. 1.7
- MSFC, Loci-CHEM 3.3 CFD, Pre-Flight

SFDT-2 Powered Phase, $0.1 \leq M_{\infty} \leq 1.6$

- Best Equivalent Trajectory
- $\pm 3\sigma$
- Aerodynamic Database Ver. 1.7
- MSFC, Loci-CHEM 3.3 CFD, Pre-Flight

SFDT-2 Base Pressure, $0 \leq M_{\infty} \leq 4.1$

- Base Pressure Transducer #1
- Base Pressure Transducer #2
- MSFC, Loci-CHEM 3.3, Pre-Flight Predicted
- Ambient Pressure, Reconstructed

Avg. 9% over-prediction mean gauge pressure

SFDT-2 Powered Phase, $0.1 \leq M_{\infty} \leq 1.6$

- Best Equivalent Trajectory
- Aerodynamic Database Ver. 1.6.3
- MSFC, Loci-CHEM 3.3 CFD, Pre-Flight

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Conclusions & Lessons Learned

- Plume induced environments - all thermal requirements met\(^2\), robust thermal design validated, Star 48 power-on aerodynamic data base updated (ready for potent. SFDT-3)

- Highly under expanded plume interactions can be significant
  - Degree of expansion, plume size, can lead to a variety of consequences!
  - Observed similar plume induced environment issues with sep. motors
  - Get plume modeling involved early in the analysis cycle

- Better understanding of the modelling sensitivities associated with single engine, plume induced base flow, in regards to the development of base eddy structure
  - Cavity geometry provided greater base pressure recovery, recirc. vortex interaction with base (similarly observed in base eddy studies)
  - Forward BL separation point, affects the point of impingement on Star 48 plume, momentum transfer interaction between base eddy and BL
  - Angle of attack, relative exposed plume area to the freestream
  - Match all nozzle exit conditions as best as possible
Questions?
SFDT-2 Base Pressure, Powered Phase

SFDT-2 Base Pressure Coefficient, Powered Phase

Av. 9% over-prediction mean gauge pressure

Back-Up
Temperature Response

Figure 34. Spin Motor temperatures Pre Drop.

Figure 35. Spin Motor temperatures Post Drop.

Figure 36. Star 48 Main Motor temperatures Pre Drop. AFT violation observed near nozzle during ascent.

Figure 37. Star 48 Main Motor experienced soak back heating post engine burn up to a peak temp of 282°C.
Temperature Response$^{24}$

Figure 30. PDD and SSRS Canister temperatures. Inflation Aid within PDD canister likely at 44°C prior to deployment.

Figure 31. Heat Shield inner facesheet, Heat Shield Water Recovery Aid (WRA), and Balloon Fitting temperatures.

Figure 32. Core structure top deck outer facesheet temperatures.

Figure 33. Core structure rib temperatures in vicinity of Star 48 Main Motor adaptor mounting ring.
References

1. Muppidi, S., SFDT1_5p6_trajout_aero_ekf.mat, file received via email correspondence, Jul. 21, 2015.