Presented By:
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PLUME INDUCED AERODYNAMIC AND HEATING MODELS FOR THE LOW DENSITY SUPersonic DECELERATOR TEST VEHICLE

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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)
Background

Full Scale Testing in Earth’s Stratosphere—Simulating Mars Entry

Figure Courtesy of JPL
• LDSD Test Vehicle and Trajectories (Best Equivalent)
### Background

**Orbital-ATK Star-48B Long Nozzle Solid Rocket Motor**

<table>
<thead>
<tr>
<th>Parameter</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>Ammonium Perchlorate</td>
<td>71%</td>
</tr>
<tr>
<td>Hydroxyl Terminated Polybutadiene (HTPB)</td>
<td>11%</td>
</tr>
<tr>
<td>Aluminum</td>
<td>18%</td>
</tr>
<tr>
<td><strong>Duration:</strong> 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>Parameter</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 (mean)</td>
</tr>
<tr>
<td>Propellant (Approx. % Weight)</td>
<td></td>
</tr>
<tr>
<td>Ammonium Perchlorate</td>
<td>83%</td>
</tr>
<tr>
<td>Hydroxyl Terminated Polybutadiene (HTPB)</td>
<td>9%</td>
</tr>
<tr>
<td>Aluminum</td>
<td>9%</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>5% Plasticizer</td>
</tr>
<tr>
<td><strong>Duration:</strong> 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 Al₂O₃ particles and plume gases
    - Convection from plume-air recirculation
  - Spin Motor Plume Impingement
    - Predict plume heating from convection and Al₂O₃ 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) engineering codes (MOC codes)

• CFD (induced forces and convection) - Loci-CHEM 3.3 p4
• Spin Motor Plume Particle Heating – PLIMP eng. code
• Plume Radiation (sep. series of plume solutions, Star 48)
  – RAMP2 – Gaseous and aluminum-oxide 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 5.9.9 – Surface Grids, Volume Setup
  - AFLR3 – Unstructured – Volume Grids
### 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>Spin-Down Motors</td>
</tr>
<tr>
<td>Number of Plumes Simulated</td>
<td>4 (all on) and 2 (staggered firing)</td>
<td>1</td>
</tr>
<tr>
<td>Angle-of-Attack, ( \alpha ), and Side-Slip, ( \beta ), Angles</td>
<td>( \alpha = 163^\circ, \beta = 0^\circ )</td>
<td>( \alpha = 0^\circ, \beta = 0^\circ )</td>
</tr>
<tr>
<td>Plume Chemistry</td>
<td>Frozen</td>
<td></td>
</tr>
<tr>
<td>No. Species</td>
<td>2 - Equivalent air &amp; plume gas</td>
<td></td>
</tr>
<tr>
<td>Thermodynamic and Transport Properties</td>
<td>Specific Heat, ( Cp ): Thermally perfect gas, species ( Cp ) varies with temperature, polynomial</td>
<td></td>
</tr>
<tr>
<td>Viscosity and Conduction Models</td>
<td>Transport Fit (equivalent ( \mu(T), k(T) ), per species)</td>
<td></td>
</tr>
<tr>
<td>Diffusion Model</td>
<td>Laminar-Schmidt</td>
<td></td>
</tr>
<tr>
<td>Particle Model</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>Aluminum-Oxide</td>
<td></td>
</tr>
<tr>
<td>Number of Particle Bins &amp; Sizes</td>
<td>5, 1,662 - 4,557( \mu )m</td>
<td></td>
</tr>
<tr>
<td>Turbulence Model</td>
<td>Menter's Shear Stress Transport, SST</td>
<td></td>
</tr>
<tr>
<td>Compressibility Correction</td>
<td>Sarkar</td>
<td></td>
</tr>
<tr>
<td>( U_{relax} ) (m/s)</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>( Dt_{Max} ) (sec)</td>
<td>Varied per case, generally 0.001 - 0.0001 sec</td>
<td></td>
</tr>
<tr>
<td>Accuracy</td>
<td>2nd Order, steady-state solutions</td>
<td></td>
</tr>
<tr>
<td>Surface Boundary Conditions</td>
<td>No slip, vehicle spin rate applied</td>
<td></td>
</tr>
<tr>
<td>Wall Temperatures</td>
<td>255, 973, 1773 K</td>
<td></td>
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<tr>
<td>Vehicle Spin Rate</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Internal Nozzle Wall Thermal</td>
<td>Adiabatic Wall (Carbon Phenolic)</td>
<td></td>
</tr>
<tr>
<td>Solver</td>
<td>Guass-Seidel</td>
<td></td>
</tr>
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</table>

#### Trajectory Atmospheric Conditions

<table>
<thead>
<tr>
<th>Alt (km)</th>
<th>( M_\infty )</th>
<th>( q_\infty ) (Pa)</th>
<th>( P_\infty ) (Pa)</th>
<th>( T_\infty ) (K)</th>
<th>( P_{lip} ) (psia)</th>
<th>( T_{lip} ) (K)</th>
<th>( \theta ) Press Exp Ratio</th>
<th>( \alpha_{total} ) (deg)</th>
<th>Notes</th>
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<tbody>
<tr>
<td>36.050</td>
<td>0.01</td>
<td>0.84</td>
<td>499.03</td>
<td>246.00</td>
<td>3057.00</td>
<td>70.10</td>
<td>968.52</td>
<td>163.0</td>
<td>SPIN MTR, PRE-SFDT-1</td>
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<tr>
<td>36.322</td>
<td>0.10</td>
<td>3.46</td>
<td>494.00</td>
<td>242.00</td>
<td>643.68</td>
<td>1.61</td>
<td>22.54</td>
<td>40.4</td>
<td>Post-SFDT-1, Star 48, ADB</td>
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<tr>
<td>36.390</td>
<td>0.20</td>
<td>13.71</td>
<td>489.69</td>
<td>241.88</td>
<td>643.68</td>
<td>1.61</td>
<td>22.74</td>
<td>30.0</td>
<td>Post-SFDT-1, Star 48, ADB</td>
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<tr>
<td>36.514</td>
<td>0.30</td>
<td>30.30</td>
<td>481.00</td>
<td>242.00</td>
<td>643.68</td>
<td>1.61</td>
<td>23.15</td>
<td>22.3</td>
<td>Post-SFDT-1, Star 48, ADB</td>
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<tr>
<td>36.993</td>
<td>0.50</td>
<td>78.75</td>
<td>450.00</td>
<td>244.00</td>
<td>606.29</td>
<td>1.57</td>
<td>24.01</td>
<td>17.7</td>
<td>Post-SFDT-1, Star 48, ADB</td>
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<td>37.617</td>
<td>0.70</td>
<td>141.66</td>
<td>413.00</td>
<td>244.00</td>
<td>607.40</td>
<td>1.59</td>
<td>26.46</td>
<td>17.1</td>
<td>Post-SFDT-1, Star 48, ADB</td>
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<tr>
<td>38.449</td>
<td>0.90</td>
<td>208.66</td>
<td>368.00</td>
<td>246.00</td>
<td>607.40</td>
<td>1.59</td>
<td>29.70</td>
<td>14.7</td>
<td>Post-SFDT-1, Star 48, ADB</td>
</tr>
<tr>
<td>38.682</td>
<td>0.95</td>
<td>225.53</td>
<td>357.00</td>
<td>248.00</td>
<td>607.40</td>
<td>1.59</td>
<td>30.61</td>
<td>14.4</td>
<td>Post-SFDT-1, Star 48, ADB</td>
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<tr>
<td>39.469</td>
<td>1.10</td>
<td>271.04</td>
<td>320.00</td>
<td>253.00</td>
<td>616.23</td>
<td>1.68</td>
<td>36.17</td>
<td>12.7</td>
<td>Post-SFDT-1, Star 48, ADB</td>
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<tr>
<td>49.480</td>
<td>4.23</td>
<td>1171.60</td>
<td>93.10</td>
<td>266.96</td>
<td>3057.00</td>
<td>70.10</td>
<td>5191.44</td>
<td>0.0</td>
<td>SPIN MTR, PRE-SFDT-1</td>
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</table>
INITIAL ANALYSIS

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

**Surface Contours**

- **Plume-Plume Interaction**
- **Shock Off Motor Barrel**

**Solution Plane Contours**

- **Outboard Plume**
- **Inboard Plume**
- **Reflected Shock**

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Spin Motor Analysis

• 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)
BEFORE INITIAL PLUME ANALYSIS

AFTER (MIRRORED PICTURE)

PLUME DEFLECTORS

MAST TPS

DECK SHIELDS

MOTOR BARREL BLAST SHIELDS

MOTOR BARREL SHIELD

DEFLECTOR

DECK SHIELD
FOLLOW-UP ANALYSIS

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

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

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

Reverse Angle

Shock, Flow Deflection

Impingement, Reattachment

Corner Expansion

Deck Impingement BL, Separation Region

Surfaces, Heat Flux (BTU/ft$^2$-sec)
(W/cm$^2$)
Spin Motor Results

SFDT-1 June 28, 2014
Spin-Up Motor Firings

Pre-flight Heating Contours

Post-flight Charring

TFAWS 2017 – August 21-25, 2017
• 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
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
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 ($\alpha_{total}=0°$, 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 ($\alpha, \beta = 0, 10, 20°$)
- Multiple Models – Plume w/ wout particles, hybrid RANS/LES (423M)
- Objective, predict plume induced aero. forces & moments

Pre-SFDT-2 (190 million, 2015)

- Sub, transonic cases ($M_\infty=0 - 1.2$ “larger” vol. $O \sim 1 \text{ km}^3$)
- Reconstructed trajectory subset ($\alpha, \beta = 10 – 40°$)
- Increase grid to accommodate $\geq 40°$ cases, seek grid convergence

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Star 48 Analysis

Aerodynamic Database 1.5
OVERFLOW

Loci-CHEM Runs (2015)

FUN3D
STAR48 PLUME INDUCED AERODYNAMICS

CFD, Mach = 0.7, Angle-of-Attack = 17.1°

SFDT-1 Lofting Impact
SFDT-1 Powered Phase, 0.1 \leq M \leq 1.6

Base Pressure Coefficient

Over predicted Pitching Moment
**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, $0.1 \leq M_x \leq 4.1$

\begin{align*}
\text{Axial Coefficient, } C_A \\
\text{Mach Number}
\end{align*}

SFDT-2 Base Pressure, $0 \leq M_x \leq 4.1$

\begin{align*}
\text{Static Pressure (Pa)} \\
\text{Mach Number}
\end{align*}

SFDT-2 Powered Phase, $0.1 \leq M_x \leq 1.6$

\begin{align*}
\text{Total Moment Coefficient, } C_{m,\text{Total}} \\
\text{Mach Number}
\end{align*}
Conclusions & Lessons Learned

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

• Highly under expanded plume-air 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

• Better understanding of the modelling sensitivities associated with single engine, plume induced base flow, in regards to the development of base eddy structure(s)
  • Cavity geometry provided greater base pressure recovery
  • Freestream BL separation point affected the point of impingement on Star 48 plume
  • 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

- Ambient Static Pressure, Reconstructed
- Pressure Transducer #1 Adjusted
- Pressure Transducer #1 +/- Error
- Pressure Transducer #2 Adjusted
- Pressure Transducer #2 +/- Error
- Pre-Flight Predicted, Gauge Average

Base Pressure (Pa)

Mach Number
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

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.
Back-Up

LDSD Spin-Up Motors #2 & #4 Facing
\( T_{\text{wind}} = 0^\circ \text{F} \)

**Surfaces, Heat Flux (BTU/ft}^2\cdot\text{sec)**  

\[
\begin{array}{|c|c|}
\hline
\text{Heat Flux (W/cm}^2) & \\
\text{100.00} & 113.57 \\
\text{90.00} & 102.21 \\
\text{80.00} & 90.85 \\
\text{70.00} & 79.50 \\
\text{60.00} & 68.14 \\
\text{50.00} & 56.78 \\
\text{40.00} & 45.43 \\
\text{30.00} & 34.07 \\
\text{20.00} & 22.71 \\
\text{10.00} & 11.36 \\
\text{0.00} & 0.00 \\
\hline
\end{array}
\]

**MAST CORNER HEATING**

**FIR BOX REMOVED**