Mars Ascent Vehicle Propulsion System Solid Motor Technology Plans
Andrew Prince / MAV Solid Propulsion Lead, NASA MSFC
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Summary

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• Potential Mars Sample Return Campaign
• Assumptions
• Motor Sizing
• Propellant Selection
• Nozzle and Controls
• Development and Qualification Testing
• Future Work
Potential Mars Sample Return Campaign

- Mars 2020 rover
  - Collect and cache samples

- Earth Return Orbiter (ERO)
  - Enter Mars orbit ready to receive samples and transport back to earth

- Sample Retrieval Lander
  - Places Mars Ascent Vehicle (MAV) on Mars for sample stow and launch to ERO
Currently MAV is trading between hybrid and solid propulsion with a selection to be made in September 2019

This presentation is about the methodologies and progress toward developing the solid propulsion vehicle

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**Ground Rules and Assumptions**

- Mass, length and diameter are driven by the lander.
  - Length is shared with payload, avionics and Reaction Control System (RCS).
- Landing site selection will affect low temperature requirements.
- Maximum shock will be parachute snap.

<table>
<thead>
<tr>
<th>Assumption</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum GLOM (kg)</td>
<td>400.0</td>
</tr>
<tr>
<td>Maximum Vehicle Length (m)</td>
<td>3.0</td>
</tr>
<tr>
<td>Vehicle Diameter (m)</td>
<td>0.57</td>
</tr>
<tr>
<td>Payload Length Length (m)</td>
<td>0.5</td>
</tr>
<tr>
<td>Altitude (m)</td>
<td>343,000.0</td>
</tr>
<tr>
<td>Maximum Angle of Attack (degrees)</td>
<td>4.0</td>
</tr>
<tr>
<td>Launch PBMT (°C)</td>
<td>-20 (+/-2)</td>
</tr>
<tr>
<td>Storage Temperature Min/Max (°C)</td>
<td>-70/40</td>
</tr>
</tbody>
</table>
**Design Methodology**

- **First Stage**: High initial thrust to overcome gravity losses; Burn time and throttling to minimize max Q (Boost-Sustain)
- **Second Stage**: Insensitive to burn time variation; Sensitive to $I_{sp}$ variation

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**Mission Flight Profile**

**First Stage Dynamic Pressure**

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Propellant Mass Fraction Model

- A non-dimensional relationship was derived for propellant mass fraction (pmf)
  - Like sized motors were surveyed based on pmf and propellant mass
  - A subset of boost-sustain motors yields a slightly lower curve due to added insulation for the longer burn times

\[
    f_i = f_{i_{\text{min}}} + C_{\text{ref}} \left( \frac{m_{\text{pref}}}{m_p} \right)^{2/3}
\]

\[
    \text{pmf} = \frac{1}{1 + f_i}
\]

- Where,
  - \( f_{i_{\text{min}}} \) = minimum inert mass or the limit as propellant goes to infinity
  - \( C_{\text{ref}} \) = slope of data
  - \( m_{\text{pref}} \) = a reference propellant mass driving the location of inflection
**MAV Motor Model**

- Modification to the pmf model were made to account for MAV specifics
- Additional interstage structures were accounted for by assuming 10% propellant offload
- A 25% MGA assumed for the second stage
- Additional inert mass added to the larger first stage for increased TVC
- The first stage is similar to a commercially available system allowing a 15% MGA to be assumed
Mars Ascent Vehicle Study

Motor Sizing

- **Modified COTS solution:**
  - Minimize Gross Lift Off Mass (GLOM)
  - $I_{sp}$ assigned to each motor based on Commercial Off The Shelf (COTS) motors and 3 DOF analysis
  - Propellant mass allowed to vary to meet orbital assumptions while minimizing GLOM

- **Optimum solution:**
  - GLOM limited to 400 kg
  - $I_{sp}$ allowed to move along trend as required to meet orbital assumptions

\[ y = 11.766\ln(x) + 241.81 \]
Thrust Traces for Both Solutions

- The optimum solution requires challenging $I_{sp}$ values that are above the trend of other COTS products

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$I_{sp}$, sec</th>
<th>GLOM, kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Modified COTS</td>
<td>288</td>
<td>291</td>
</tr>
<tr>
<td>Optimum</td>
<td>300</td>
<td>293</td>
</tr>
</tbody>
</table>
Propellant Selection

• A set of COTS propellants were surveyed based on a set of specific assumption
  • -70 °C/ +40 °C storage and -20 °C Operation
  • Ranked density-impulse
  • Effects of Planetary Protection procedures
    • Bio-reduction (heat or radiation)
    • Bio-barriers
    • End-of-mission procedures
  • TRL level – Similar mission histories
**Nozzle and Controls**

- With low operational temperature assumptions freezing slag is concern
  - Subsonic splitline vectorable nozzle could get entrained with slag and freeze up
  - Therefore a super sonic splitline was selected

- RCS sizing will rely on 6 DOF results when received
  - Cold gas vs hydrazine
  - Minimize mass
  - Favors minimal Q at first stage burnout
**Development and Qualification Testing Planning**

- Defining a development/qualification is important for planning purposes.
- More motors can reduce risk and increase cost requiring these to be balanced.
- A qualitative matrix of risk with varied numbers of motors was derived based on assumption parameters qualified.
- A set of 3 development and 3 qualification motors were selected by the project.
  - Flight test is considered a qualification motor in Dev/Qual Plan.

### Dev/Qual Risk Matrix

<table>
<thead>
<tr>
<th>OPTION</th>
<th>SUB-SCALE TESTING</th>
<th>FULL-SCALE TESTING</th>
<th>LIKELIHOOD</th>
<th>FINAL RISK SCORE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PLANETARY PROTECTION</td>
<td>THERMAL CYCLING</td>
<td>COLD-SOAK</td>
<td>PLANETARY PROTECTION</td>
</tr>
<tr>
<td>1</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>3 DMs + 8 QMs</td>
</tr>
<tr>
<td>2</td>
<td>2X</td>
<td>2X</td>
<td>2X</td>
<td>3 DMs + 6 QMs</td>
</tr>
<tr>
<td>3</td>
<td>3X</td>
<td>3X</td>
<td>3X</td>
<td>3 DMs + 4 QMs</td>
</tr>
<tr>
<td>4</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>3 DMs + 4 QMs</td>
</tr>
<tr>
<td>5</td>
<td>2X</td>
<td>2X</td>
<td>2X</td>
<td>3 DMs + 3 QMs</td>
</tr>
<tr>
<td>6</td>
<td>3X</td>
<td>3X</td>
<td>3X</td>
<td>2 DMs + 2 QMs</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Stage 1</th>
<th>Stage 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Development</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Qualification</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Flight Test</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Inert Mass Simulator</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Flight</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Total Motors</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

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Mars Ascent Vehicle Study

Future Work

- Refine and iterate with other subsystems
  - Trade Isp (expansion ratio) with vehicle mass (interstage)
  - Trade aero stability with flow feature mass and location and design
- Refine design models (CAD) for minimum mass

Current MAV Solid Vehicle Concept