Cryogenic Propulsion Stage

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The CPS is an in-space cryogenic propulsive stage based largely on state of the practice design for launch vehicle upper stages.

- However, unlike conventional propulsive stages, it also contains power generation and thermal control systems to limit the loss of liquid hydrogen and oxygen due to boil-off during extended in-space storage.

The CPS provides the necessary ΔV for rapid transfer of in-space elements to their destinations or staging points (i.e., E-M L1).

The CPS is designed around a block upgrade strategy to provide maximum mission/architecture flexibility

- Block 1 CPS: Short duration flight times (hours), passive cryo fluid management
- Block 2 CPS: Long duration flight times (days/weeks/months), active and passive cryo fluid management
Cryo-Propulsion Stage – Block 1, Block 2

Block 1 LOX/LH2 Cryo Stage:
- Passive Boil-Off Control
- 12 t inert mass
- 67 t propellant
- 2X 30,000 lbf NGE

Block 2 LOX/LH2 Cryo Stage:
- Zero Boil Off Control
- 21.4 t inert mass
- 47 t propellant
- 30.8% Offloaded

Commonality:
- Main Propulsion Tanks
- Main Engine
- Primary Structure
- Reaction Control System
- Avionics
Engine Sensitivity Assessment

◆ Using HAT Cycle B DRMs, assess implications of using various engine options
  • High Thrust vs. Low Thrust (>200k vs <35k lbf)
  • International Engines (JAXA & ESA)

◆ Top level CPS implications were assessed
  • Propellant Mass Impacts
  • Burnout Mass Impacts
  • Burn Time – total mission run time and minimum burn time
  • Stack Acceleration – both maximum and minimum values

◆ Assessment highlights the compilation of several efforts
  • Thrust Range for CPS: J-2X vs RL10 “classes”
  • International Partnerships
  • Commonality
  • NGE Requirements
Engine Assessment Summary

- Higher thrust engines are not the preferred solution for CPS to meet the current HAT DRM requirements
  - Integrated stack accelerations greater than current HAT element limits
  - Burn times occur within known engine transients
  - Engines not currently designed for required number of restarts
  - Lower Isp results in CPS growth

- Lower thrust engines fit the current HAT DRM requirements better due to higher Isp and lower integrated stack accelerations

- Results of this assessment are preliminary
  - Any engine chosen will need a more in depth assessment to capture detailed system impacts
Current CPS Activities

- Continued effort to meet HAT mission goals and objectives
- Continued refinement of stage design and related sensitivities to drive out top level requirements
  - Block 1 Duration Trade Studies
    - Power options
    - Boil-off verification/predictions
  - Continued investigation on long duration cryogenic fluid management
    - Reduced boil-off
    - Zero boil-off
  - Propulsion Trades
    - Main Propulsion
    - Reaction Control System
CPS Configuration

Fwd Assembly Structure/Payload Adapter
- Sized for payloads up to 40mt at launch

Reaction Control System:
- MMH/NTO
- 8x 110 lbf lateral thrusters for attitude control
- 8x 900 lbf axial thrusters for MCC & disposal

Main Propulsion System:
- LOX/LH2 (66,900kg capacity)
- 2x NGE
  - 30,000 lbf Thrust
  - 465 sec minimum ISP

Power System:
- Block 1: Li-Ion Batteries
- Block 2: 2x UltraFlex Arrays with Secondary Batteries

Thermal System:
- Block 1: SOFI/MLI Passive System
- Block 2: Broad Area Cooler Active System & Block 1 Passive System

Aft Assembly Structure
- Sized for thrust loads up to 75,000 lbf

Stage Characteristics:
- Diameter: 7.5 meters
- Length: 13 meters
- Array Diameter: 9.5 meters
- Array Power: ~22kW

Block 2 Configuration Shown
Engine Implications

J2-X, LE-X, & Vulcain-2 (> 200 klbf)

♦ J2-X & Vulcain-2 is a Gas Generator cycle
  • Isp: 438 - 448 second Range
  • Application: Boost & orbit insertion (Eg SaturnV & Arianne)
♦ High stack accelerations major issue for HAT DRM elements
♦ Short burn times for small maneuvers for large engines
  • Delta-V errors can be expected due to the majority of short maneuvers occurring within expected engine transients
  • Does not allow for engine steady state operation
    • Resulting increase in shutdown variability causes larger residuals and thrust dispersions
♦ Restart capability also a potential issue with this engine class, 5 starts needed
  • J-2X specification allows for two ignitions
    • Without redundancy 4 starts possible (Gas generator currently uses 2 of 4 cartridges per ignition)
  • 5 starts would require new ignition system
  • Vulcain-2 is a sea level engine not a space engine
    • Requires soft goods, start transients, and re ignition system investigation/development
    • Significant development and testing may be necessary to qualify this engine for multi in space restart
  • LE-X not developed (specifications unknown)
♦ Long term mission survivability risk
  • J-2X specification does allow for space environments
  • Driving CPS duration approximately 530 days

NGE, RL10, Vinci, MBXX, LE-5B (< 30klbf)

♦ RL10 and Vinci are Closed Expander cycle
  • Isp: 450 - 465 second range
  • Application: Orbit insertion & transfer In-space (Eg Centaur)
  • Derivatives include Expander Bleed & Augmented Expander
    • Allows for Higher Isp without large nozzle extension
    • Allows for Higher Thrust as it is not heat transfer limited
♦ Higher Isp reduce propellant mass & burnout mass
  • Repeatable discreet transients due to simplicity & inherent power limits of cycle
♦ Low accelerations reduce integrated stack loads for other architecture elements
  • Throttling may be required for burns w/ SEP arrays deployed
  • Expander throttle control within previous NASA experience
♦ Acceptable burn times are for these class of engines
  • Engines less than 30k lbf thrust require more than two engines
♦ Top level analysis shows multiples of all low thrust engine options fit within CPS OML
  • Closed expander engines require nozzle extension to reach high Isp
    • Extension criticality & reliability human rating complication
    • Stack length considerations not yet addressed
    • Advanced Expander engine cycles (eg NGE & MBXX) enable high Isp within smaller real estate
♦ Class of engines Designed & Qual’d for space environments & space coast
  • Including wider inlet conditions and boost phase vibe stability

Human Spaceflight Architecture Team
## CPS Engine Options

<table>
<thead>
<tr>
<th>Cycle Type</th>
<th>US Engines</th>
<th>JAXA Engines</th>
<th>ESA Engines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Requirement</td>
<td>NGE</td>
<td>RL10</td>
<td>J-2X</td>
</tr>
<tr>
<td>Requirement</td>
<td>TBR</td>
<td>Open GG</td>
<td>Expander</td>
</tr>
<tr>
<td>Vacuum Thrust, lbf</td>
<td>25,000-35,000</td>
<td>294000</td>
<td>16,800</td>
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<tr>
<td>Vacuum ISP, sec</td>
<td>465 or greater</td>
<td>448</td>
<td>450</td>
</tr>
<tr>
<td>Vacuum ISP, sec</td>
<td>NTE 700</td>
<td>5450</td>
<td>419</td>
</tr>
<tr>
<td>Vacuum ISP, sec</td>
<td>NTE 73in</td>
<td>120</td>
<td>46</td>
</tr>
<tr>
<td>Vacuum ISP, sec</td>
<td>NTE 90in</td>
<td>185</td>
<td>89</td>
</tr>
<tr>
<td>Vacuum ISP, sec</td>
<td>5.5 (adjustable)</td>
<td>5.5</td>
<td>5.35</td>
</tr>
<tr>
<td>Chamber Pressure</td>
<td>TBR</td>
<td>92.2 bar</td>
<td>~300 psia</td>
</tr>
<tr>
<td>Expansion Ration</td>
<td>TBR</td>
<td>92.1</td>
<td>84</td>
</tr>
<tr>
<td>Nozzle</td>
<td>Fixed (preferred, but not required)</td>
<td>Gimbal</td>
<td>Fixed</td>
</tr>
<tr>
<td>Throttle</td>
<td>Throttled down to 21,000 lbs or lower</td>
<td>Two throttle settings</td>
<td>Fixed</td>
</tr>
<tr>
<td>Restartable</td>
<td>Minimum of 4 flight starts</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Life expectancy</td>
<td>3000 seconds or greater</td>
<td>1400</td>
<td>2000</td>
</tr>
</tbody>
</table>
Obvious trend shows that lower Isp engines require additional propellant

Additional architecture analysis necessary to determine CPS propellant load that breaks current HAT DRMs
- Burnout mass differences scale with propellant load
- Minimal impacts due to engine mass
  - Currently only primary engine mass included, secondary engine hardware not modeled
- Differences in propellant load bigger mass driver than burnout mass
To maintain acceptable single burn times and minimum stack accelerations, the following engine quantities were assumed:

- J-2X, Vulcain-2, MB-60 and LE-X use only one engine
- Vinci, NGE and LE-5B assume two engines
- Non-human rated RL-10 variants use three engines
- Human Rated RL-10 uses four engines

Total run times need to be verified against engine lifetime requirements, data not currently available for all engines.
Detailed Burn Times (J-2X thrust class)

<table>
<thead>
<tr>
<th>DRM 32A Maneuver Description</th>
<th>ΔV (m/sec)</th>
<th>Burn Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit Raise from -47 x 130 nmi</td>
<td>154.5</td>
<td>13.9</td>
</tr>
<tr>
<td>Circularization to 220 nmi</td>
<td>50.3</td>
<td>4.4</td>
</tr>
<tr>
<td>LEO Departure</td>
<td>2541.0</td>
<td>166.4</td>
</tr>
<tr>
<td>GEO Insertion &amp; PC</td>
<td>1864.0</td>
<td>72.6</td>
</tr>
</tbody>
</table>

Total Burn Time (sec) 257.2

<table>
<thead>
<tr>
<th>DRM 34B Maneuver Description</th>
<th>ΔV (m/sec)</th>
<th>Burn Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit Raise from -47 x 130 nmi</td>
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<td>13.4</td>
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<td>Circularization to 220 nmi</td>
<td>50.3</td>
<td>4.3</td>
</tr>
<tr>
<td>EM L1 Departure</td>
<td>320.3</td>
<td>39.9</td>
</tr>
<tr>
<td>Powered Lunar Swingby</td>
<td>183.8</td>
<td>21.6</td>
</tr>
<tr>
<td>Powered Earth Swingby</td>
<td>869.4</td>
<td>89.5</td>
</tr>
</tbody>
</table>

Total Burn Time (sec) 168.6

- Minimum burn time for J-2X (during circularization burn) will not extend beyond the expected startup and shutdown transients
- Vulcain-2 and LE-X transient data not known, but behavior expected to be similar
### Detailed Burn Times
(NGE class thrust)

#### DRM 32A Maneuver Description

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<td>50.3</td>
<td>19.0</td>
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<tr>
<td>LEO Departure</td>
<td>2541.0</td>
<td>719.9</td>
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<tr>
<td>GEO Insertion &amp; Pl</td>
<td>1864.0</td>
<td>319.9</td>
</tr>
</tbody>
</table>

Total Burn Time (sec) 1,118.0

#### DRM 34B Maneuver Description

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<td>Circularization to 220 nmi</td>
<td>50.3</td>
<td>19.7</td>
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<td>188.7</td>
</tr>
<tr>
<td>Powered Lunar Swingby</td>
<td>183.8</td>
<td>102.3</td>
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<tr>
<td>Powered Earth Swingby</td>
<td>869.4</td>
<td>426.0</td>
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</tbody>
</table>

Total Burn Time (sec) 798.2

◆ **Single burn time requirement extends just beyond typical RL10 performance for GEO mission**
  - 700 sec single burn for RL10

◆ **Single burn time requirements may necessitate additional engines for the lower thrust class engines**
  - RL10 variants, LE-5B, Vinci, and MB-60
Stack acceleration values over 1 g occur for all engines with greater than 200,000 lbf thrust
  - Does not drive CPS design, currently assuming launch loads of 5 g’s

High acceleration levels significantly impact current HAT DRMs
  - Currently expected to need accelerations less than 0.25 g for EM L1 departure to reduce impact on SEP arrays
    - SEP arrays could need this acceleration to be as low as 0.1 g
  - MPCV Arrays currently designed to a maximum of 2.5 g accelerations

Minimum accelerations remain high enough for all maneuvers to prevent excessive gravity loss

All accelerations calculated at 100% throttle level: lower throttle levels have not yet been assessed