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
BACKUP
CPS Configuration

Human Spaceflight Architecture Team

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

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

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

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 & Ariane)
- **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 in 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
## CPS Engine Options

<table>
<thead>
<tr>
<th>Requirement</th>
<th>US Engines</th>
<th>JAXA Engines</th>
<th>ESA Engines</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGE</td>
<td>J-2X</td>
<td>RL10</td>
<td>LE-5B</td>
</tr>
<tr>
<td>RL-10A4-2</td>
<td>RL-10B2</td>
<td>LE-10C-1</td>
<td>MB-60</td>
</tr>
<tr>
<td>RL-10C-1</td>
<td></td>
<td></td>
<td>LE-X</td>
</tr>
<tr>
<td>Vulcain-2</td>
<td></td>
<td></td>
<td>Vinci</td>
</tr>
</tbody>
</table>

### Cycle Type
- **Cycle Type**: TBR
- **Vacuum Thrust, lbf**: 25,000-35,000
- **Vacuum ISP, sec**: 465 or greater
- **Engine Dry Mass, lbf**: NTE 700
- **Engine Diameter, in**: NTE 73in
- **Engine Length, in**: NTE 90in
- **Mixture Ratio**: 5.5 (adjustable)
- **Chamber Pressure**: TBR 92.2 bar
- **Expansion Ratio**: TBR 92.1
- **Nozzle**: Fixed (preferred, but not required)
- **Throttle**: Throttleable down to 21,000 lbs or lower
- **Restartable**: Minimum of 4 flight starts
- **Life expectancy**: 3000 seconds or greater

### US Engines
- **Cycle Type**: Open GG, Expander
- **Vacuum Thrust, lbf**: 294000-16,800-22,300-24750-23900-30800-60000-317000-301243-40500
- **Vacuum ISP, sec**: 448-450-377-668-419-628-1302-4956
- **Engine Dry Mass, lbf**: 700-5450-419-377-668-419-628-1302-4956
- **Engine Diameter, in**: 73in-120-46-46-84-56.8
- **Engine Length, in**: 90in-185-89-89.7-163.5-87.2-111-130
- **Mixture Ratio**: 5.5 (adjustable)
- **Chamber Pressure**: TBR 92.2 bar
- **Expansion Ratio**: TBR 92.1
- **Nozzle**: Fixed (preferred, but not required)
- **Throttle**: Throttleable down to 21,000 lbs or lower
- **Restartable**: Minimum of 4 flight starts
- **Life expectancy**: 3000 seconds or greater

### JAXA Engines
- **Cycle Type**: Expander, Expander, Expander, Expander
- **Vacuum Thrust, lbf**: 447-467-432-432
- **Vacuum ISP, sec**: 465
- **Engine Dry Mass, lbf**: 628-1302-4956
- **Engine Diameter, in**: 84
- **Engine Length, in**: 130
- **Mixture Ratio**: 5.5 (adjustable)
- **Chamber Pressure**: TBR 92.2 bar
- **Expansion Ratio**: TBR 92.1
- **Nozzle**: Fixed (preferred, but not required)
- **Throttle**: Throttleable down to 21,000 lbs or lower
- **Restartable**: Minimum of 4 flight starts
- **Life expectancy**: 3000 seconds or greater

### ESA Engines
- **Cycle Type**: Expander, H2 bleed, Expander, H2 bleed
- **Vacuum Thrust, lbf**: 60000-317000-301243
- **Vacuum ISP, sec**: 432
- **Engine Dry Mass, lbf**: 4956
- **Engine Diameter, in**: 86
- **Engine Length, in**: 164
- **Mixture Ratio**: 5.5 (adjustable)
- **Chamber Pressure**: TBR 92.2 bar
- **Expansion Ratio**: TBR 92.1
- **Nozzle**: Fixed (preferred, but not required)
- **Throttle**: Throttleable down to 21,000 lbs or lower
- **Restartable**: Minimum of 4 flight starts
- **Life expectancy**: 3000 seconds or greater

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**Human Spaceflight Architecture Team**
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**

- **Minimum burn time for J-2X (during circularization burn) will not extend beyond the expected startup and shutdown transients**

<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>
<td>154.5</td>
<td>13.4</td>
</tr>
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<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**

- **Vulcain-2 and LE-X transient data not known, but behavior expected to be similar**
**Detailed Burn Times (NGE class thrust)**

<table>
<thead>
<tr>
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<th>Burn Time (sec)</th>
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</thead>
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<td>Orbit Raise from -47 x 130 nmi</td>
<td>154.5</td>
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<td>50.3</td>
<td>19.0</td>
</tr>
<tr>
<td>LEO Departure</td>
<td>2541.0</td>
<td>719.9</td>
</tr>
<tr>
<td>GEO Insertion &amp; Pl</td>
<td>1864.0</td>
<td>319.9</td>
</tr>
<tr>
<td><strong>Total Burn Time (sec)</strong></td>
<td></td>
<td>1,118.0</td>
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</tbody>
</table>

<table>
<thead>
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<th>DRM 34B Maneuver Description</th>
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<th>Burn Time (sec)</th>
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<td>Orbit Raise from -47 x 130 nmi</td>
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<td>183.8</td>
<td>102.3</td>
</tr>
<tr>
<td>Powered Earth Swingby</td>
<td>869.4</td>
<td>426.0</td>
</tr>
<tr>
<td><strong>Total Burn Time (sec)</strong></td>
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<td>798.2</td>
</tr>
</tbody>
</table>

- **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

_Human Spaceflight Architecture Team_
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