Hydrogen Propulsion: Mission Enabling, Going Forward, Handle with Care
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RS-25 upgrades are focused on affordable manufacturing and assembly, manufacturing obsolescence, and expendable engine application

- RS-25 development leverages a strong culture of affordability proven by more than six years of J-2X development
  - Adapting government Design & Construction standards to industry practices
  - Lean government oversight (e.g., quality control via process-based In-Line Assessments, which reduces traditional Mandatory Inspection Points)
  - Managing in a severely constrained resource environment
  - Expendable engine considerations and constraints

- Value Stream Mapping (VSM) for affordability
  - Used extensively for J-2X lean manufacturing, assembly and test operations
  - Now being used extensively to lean down RS-25 practices

- Lean manufacturing and assembly approach
  - Shop layout at PWR designed for lean processing and multiple product lines
  - Engine final kitting and assembly approach based on proven lean practices

- Common Supply Chain across multiple product lines (RS-25, J-2X, RS-68)
  - Requires changes to RS-25 supply chain to align with more recent J-2X and RS-68
  - Common supply chain promotes industrial base stability
  - Sustain long term relationships with proven suppliers
Electronic Controller and Software design for J-2X being applied to RS-25
- Replace obsolete SSME design, and enable integration with SLS vehicle avionics
- Common “universal controller” design for RS-25 and J-2X promotes affordability
- Flight software code testing reduced via highly configurable software data set

Hot Isostatic Pressure (HIP) Bonding used to assemble J-2X and RS-68 Main Combustion Chambers will be used for RS-25 MCC
- Common process across product lines for affordability
- Eliminate SSME product-unique facilities and equipment
- Replace SSME obsolescence with state of the art bonding approach

Spin Forming process for J-2X metal nozzle extension will be applied to RS-25 nozzle jacket manufacturing (80% fewer parts and welds)

Selective Laser Melting (SLM) technology being developed
- Parts being manufactured and tested on J-2X to “mainstream” the process for RS-25 manufacturing cost savings
- Materials testing, NDE technique development, in-situ inspection techniques

“Structured Light” inspection techniques being standardized
- J-2X inspections are incorporating this technique
- Standardized technique will be applied to RS-25
USAF in partnership with NASA SLS Risk Reduction NRA is looking at Special Engine Study's to enable a better understanding of AUSEP Viability & Affordability prior to a potential program start.
Advanced Upper Stage Engine (AUSEP)

♦ Objectives
  • Ability to meet multiple users – EELV, NASA, other commercial
  • Modern manufacturing techniques & materials, producible
  • Sustainable with reduced recurring cost

♦ Common upper stage engine for EELV
  • Incorporate NSS & NASA requirements
  • Captures emerging commercial needs
  • Economy of Scale

♦ Leverage advances by AFRL/NASA tech investments
  • AFRL Upper Stage Engine Technology (USET) & NASA technology programs

♦ Benefits USAF & NASA
  • EELV payload performance margin & Orbital debris mitigation
  • Partnership with NASA’s Cryo-Propulsion Stage (CPS)
Key Technology Capability Needs (Unique to NCPS)

♦ High Temperature NTP Fuels and Materials
  • Nerva Derived Carbide Composite
  • Cermet

♦ Affordable DDT&E approach (NTP Ground Test Facilities) that is competitive to conventional chemical propulsion systems
  • Assessment of bore hole testing approach to hot nuclear engine system testing
  • Assessment of affordable methods for “scrubbing” exhaust
  • Assessment of in-space testing and demonstration options

AES NCPS project has major tasks to begin addressing these needs
Key Technology Capability Needs
(Same as Chemical Propulsion Stage - CPS)

♦ Long-Term Cryogenic Fluid Management
  • In-Space Cryogenic Propellant Transfer
  • Zero-Boiloff Cryogenic Propellant Storage
  • Cryogenic Propellant Thermal Management
  • Zero-g Cryogenic Liquid Acquisition

♦ Autonomous Vehicle System Management
  • System health monitoring
  • Autonomous orbital operation
  • Autonomous mission operations

♦ Deep-Space Spacecraft Systems
  • Highly Reliable Spacecraft Propulsion Systems and Engines
  • Spacecraft Radiation Protection (other than from reactor)
  • Long-Life High Reliability Spacecraft Systems
  • Long-Life High Reliability Spacecraft Mechanisms
Benefits of Using Hydrogen for Nuclear Thermal Propulsion for a 2033 Human Mars Mission

4 SLS Launches with NTP using Hydrogen as propellant

7+ SLS Launches with NTP using Methane as propellant

Other propellant options have significantly lower Isp and require significantly more SLS Launches per mission.

Liquid Hydrogen has a significant performance benefit over alternative propellants. While it is enhancing for NCPS it is critically enabling for more conventional chemical propulsion stages.
<table>
<thead>
<tr>
<th>OCT Technology Area #</th>
<th>Technology</th>
<th>OCT Priority</th>
<th>Development Time to TRL 6 (Years)</th>
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<td>Advanced, Low Cost Engine Technology for HLLV</td>
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<td>2.1</td>
<td>Non-Toxic Reaction Control Engines</td>
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<td>Unsettled Cryo Propellant Transfer</td>
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<tr>
<td>2.4</td>
<td>In Space Cryogenic Liquid Acquisition</td>
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<tr>
<td>3.1</td>
<td>High Strength/Stiffness Deployable 10-100 kW Class Solar Arrays</td>
<td>Driving</td>
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<tr>
<td>3.2</td>
<td>Regenerative Fuel Cell</td>
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<tr>
<td>3.2</td>
<td>Long Life Battery</td>
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<tr>
<td>4.5</td>
<td>Autonomous Vehicle Systems Management</td>
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<tr>
<td>4.5</td>
<td>Common Avionics</td>
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<tr>
<td>4.6</td>
<td>Automated/Auton. Rendez. &amp; Docking, Prox Ops, Target Relative Nav</td>
<td>x</td>
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<tr>
<td>5.4</td>
<td>High Rate, Adaptive, Internetworked Proximity Communications</td>
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<tr>
<td>5.4</td>
<td>In-Space Timing and Navigation for Autonomy</td>
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<tr>
<td>5.5</td>
<td>Quad Function Hybrid RF/Optical Comm, Optical Ranging, RF Imaging System</td>
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<td>5 – 8</td>
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<tr>
<td>12.1, 12.2</td>
<td>Lightweight Structures and Materials (In-Space Elements)</td>
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<td>5</td>
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<td>12.3</td>
<td>Mechanisms for Long Duration, Deep Space Missions</td>
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<tr>
<td>14.1</td>
<td>In-Space Cryo Propellant Storage</td>
<td>Driving</td>
<td>4 – 8</td>
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<tr>
<td>14.1, 2.4</td>
<td>LO2/LH2 Cryo Flight Demo (CPST: Cryo Propellent &amp; Storage Transfer)</td>
<td>Driving</td>
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<tr>
<td>14.2</td>
<td>Thermal Control</td>
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Long-Term Cryogenic Fluid Management
- Zero-Boiloff Cryogenic Propellant Storage
- Cryogenic Propellant Thermal Management
- In-Space Cryogenic Propellant Transfer
- Zero-g Cryogenic Liquid Acquisition

Autonomous Vehicle System Management
- System health monitoring
- Autonomous orbital operation
- Autonomous mission operations

Deep-Space Spacecraft Systems
- Highly Reliable Spacecraft Propulsion Systems and Engines
- Spacecraft Radiation Protection
- Long-Life High Reliability Spacecraft Systems
- Long-Life High Reliability Spacecraft Mechanisms
Cryogenic propulsion has continually proven to be the best option for space transportation elements.

As mission opportunities move beyond Earth orbit, mission durations become critical driver for cryo propellants:
- All historical human exploration missions required propellants for hours
- Near term exploration goals need propellants for days
- Long term exploration goals need propellants for months to years

The need to reduce or eliminate boiloff of propellants will be necessary to accomplish long term human exploration goals:
- Management of liquid oxygen to near zero boiloff conditions could be achievable with minimal technology investments
- Because of the nature of liquid hydrogen, the technology investment is greater, but considered achievable
Cryogenic Propellant Technologies

♦ Cryogenic Fluid Storage
  • Active Thermal Control (refrigeration using Tube-on-Shield heat collection)
  • Multilayer Insulation with Foam Substrate
  • Low Conductivity Structures (High strength composite struts)
  • Micro-G Pressure Control (Thermodynamic Vent System, Mixing Pumps)

♦ Cryogenic Fluid Acquisition
  • Unsettled Liquid Acquisition Devices (LADs)
  • Micro-G Transfer Line Chilldown
  • Tank Pressurization systems

♦ Cryogenic Fluid Quantity Gauging
  • Settled Mass Gauging (Cryotracker)
  • Unsettled Mass Gauging (RF gauging, PVT)

♦ Cryogenic Fluid Transfer
  • Micro-G Tank Chilldown
  • Operational Transfer Methods

♦ Instrumentation – Leak Detection
  • Automated Leak Detection

Pulse-tube cryocooler
Screen Channel Capillary LAD
## TRLs for Selected Technologies

<table>
<thead>
<tr>
<th>Cryostat Technology</th>
<th>TRL</th>
<th>Research &amp; Development</th>
<th>Test Facility Degree of Modification</th>
<th>Backup Availability</th>
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<tbody>
<tr>
<td></td>
<td>Now</td>
<td>Post Ground Test</td>
<td>Degree of Difficulty</td>
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<tr>
<td>1 Active Thermal Control: Cryocoolers w/ tube-on-shield heat collection</td>
<td>4</td>
<td>5</td>
<td>III</td>
<td>1</td>
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<tr>
<td>2 Multilayer Insulation with Foam Substrate</td>
<td>4/6</td>
<td>5/6</td>
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<tr>
<td>3 Low Conductivity Structures</td>
<td>4/6</td>
<td>5/6</td>
<td>II</td>
<td>0-1</td>
</tr>
<tr>
<td>4 Micro-G Pressure Control: Thermodynamic Vent System</td>
<td>5</td>
<td>5</td>
<td>I</td>
<td>1</td>
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<tr>
<td>5 Micro-G Pressure Control: Mixing Pumps</td>
<td>5</td>
<td>5</td>
<td>III</td>
<td>1-2</td>
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<td>6 Unsettled Liquid Acquisition Devices</td>
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<td>II</td>
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<tr>
<td>7 Micro-G Transfer Line Chilldown</td>
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<td>I</td>
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<tr>
<td>8 Pressurization Systems</td>
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<td>9 Settled Mass Gauging: CryoTracker</td>
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<td>10 Unsettled Mass Gauging: RF Gauging</td>
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<td>11 Micro-G Tank Chilldown</td>
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<td>I</td>
<td>1</td>
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<td>12 Automated Leak Detection</td>
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<td>5</td>
<td>II</td>
<td>1</td>
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</tbody>
</table>

**Note:** In some cases, backup solution is continued cryo operations with reduced performance

**Note:** TRL range indicates where there is a difference for LH2/LO2