Hydrogen Propulsion: Mission Enabling, Going Forward, Handle with Care

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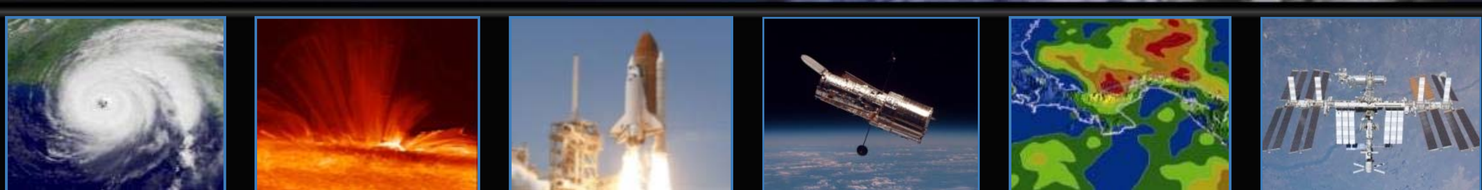


RS-25 Engine Upgrades

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

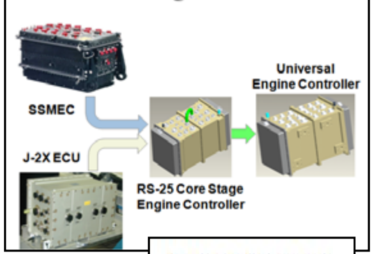
- **Lean manufacturing and assembly approach**
  - Shop layout at PWR designed for lean processing and multiple product lines
  - Engine final kitting and assembly approach based on proven lean practices

- **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

RS-25 Engine Technologies Adapted from J-2X

- **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

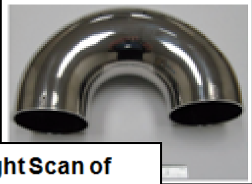
Common Engine Controller



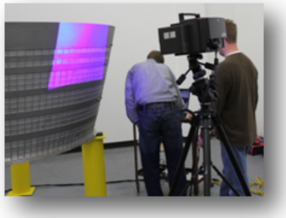
RS-25 Nozzle

J-2X HIP
Bonded MCC

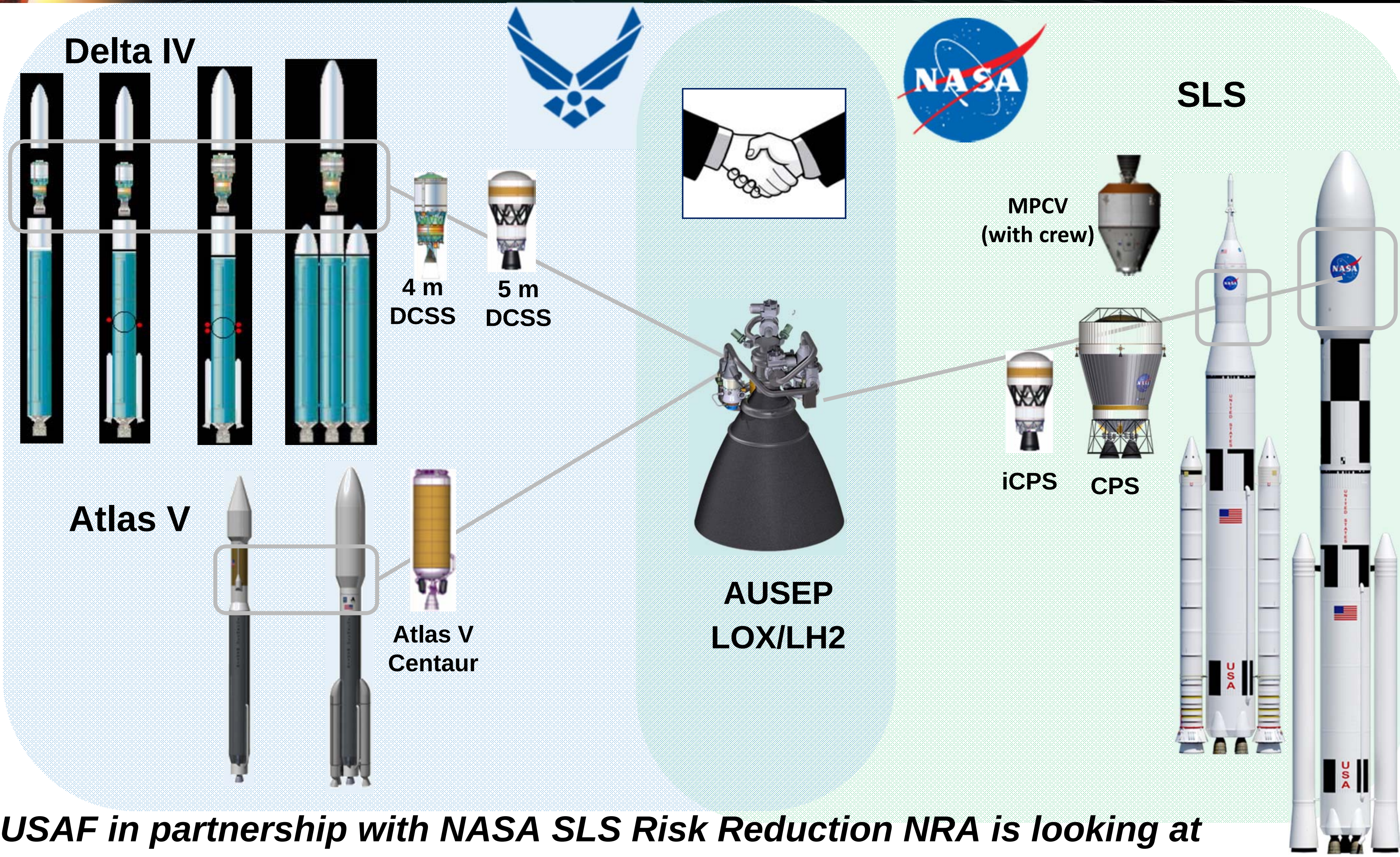
SLM Duct for J-2X
GG Hot Fire
Tested at MSFC



Structured Light Scan of
J-2X Nozzle Extension



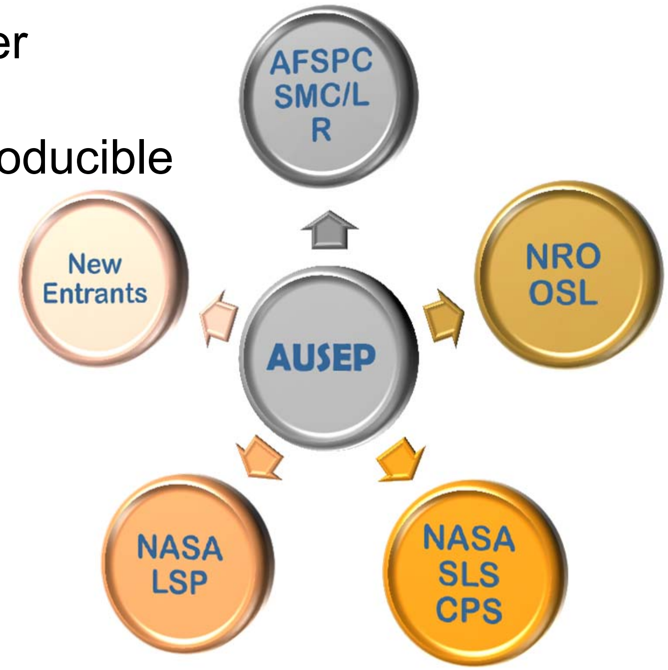
Opportunity for USAF/NASA Partnership



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)

Nuclear Cryogenic Propulsion Stage (NCPS)

Key Technology Capability Needs (Unique to NCPS)

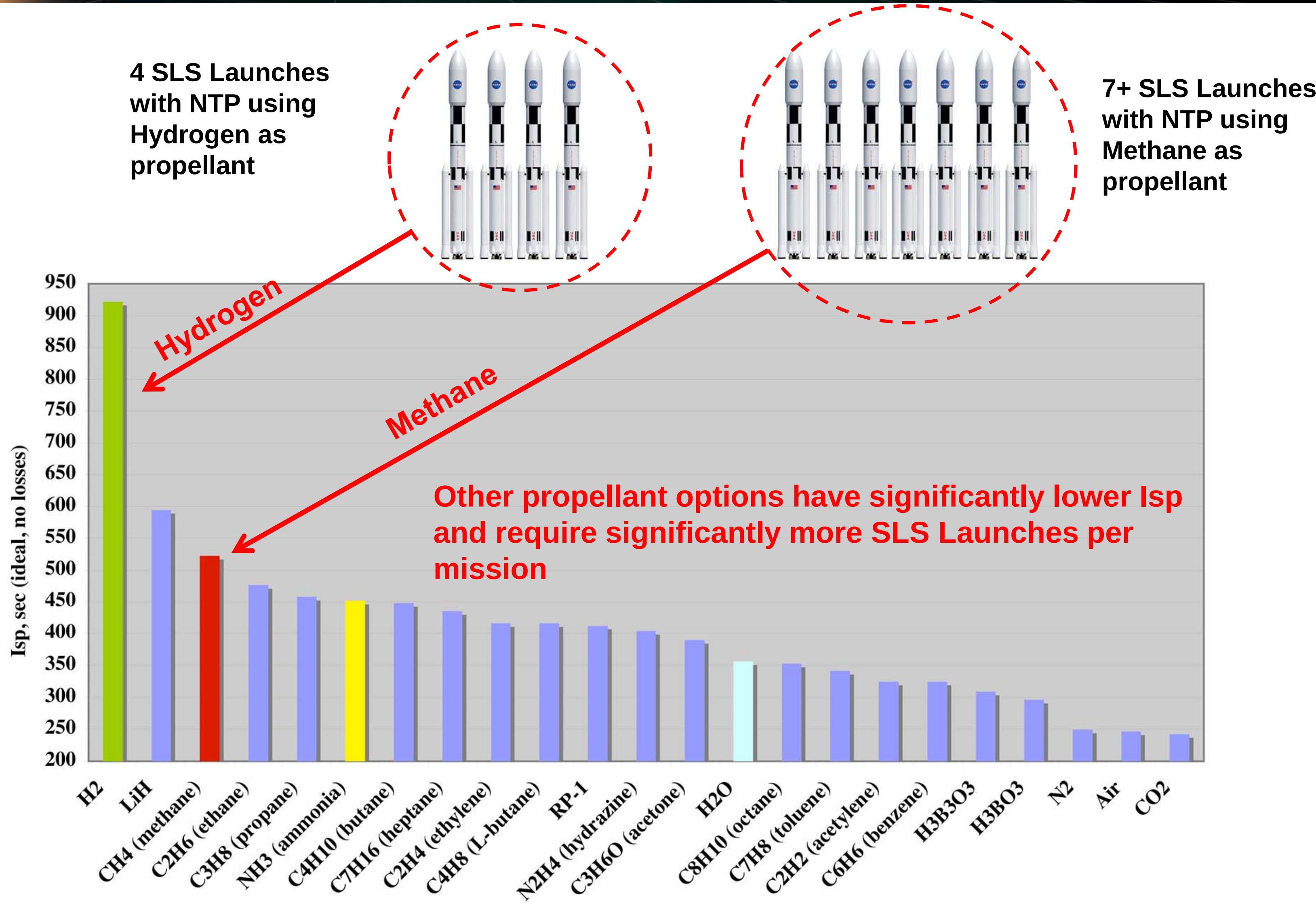
- **High Temperature NTP Fuels and Materials**
  - Nerva Derived Carbide Composite
  - Cermet
- **Affordable DDT&E approach (NTP Ground Test Facilities) that is competitive to conventional chemical propulsion systems**
  - Assessment of bore hole testing approach to hot nuclear engine system testing
  - 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



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.

OCT Chemical Propulsion Technology Needs

OCT Technology Area #	Technology	OCT Priority	Development Time to TRL 6 (Years)
1.2	Advanced, Low Cost Engine Technology for HLLV	x	4
2.1	Non-Toxic Reaction Control Engines	x	4
2.4	Unsettled Cryo Propellant Transfer	x	5
2.4	In Space Cryogenic Liquid Acquisition	Driving	5
3.1	High Strength/Stiffness Deployable 10-100 kW Class Solar Arrays	Driving	4
3.2	Regenerative Fuel Cell	Driving	5
3.2	Long Life Battery	x	5
4.5	Autonomous Vehicle Systems Management	x	8
4.5	Common Avionics	x	8
4.6	Automated/Auton. Rendez. & Docking, Prox Ops, Target Relative Nav	x	?
5.4	High Rate, Adaptive, Internetworked Proximity Communications	Driving	3
5.4	In-Space Timing and Navigation for Autonomy	x	3
5.5	Quad Function Hybrid RF/Optical Comm, Optical Ranging, RF Imaging System	x	5 – 8
12.1, 12.2	Lightweight Structures and Materials (In-Space Elements)	x	5
12.3	Mechanisms for Long Duration, Deep Space Missions	x	5
14.1	In-Space Cryo Propellant Storage	Driving	4 – 8
14.1, 2.4	LO2/LH2 Cryo Flight Demo (CPST: Cryo Propellent & Storage Transfer)	Driving	5
14.2	Thermal Control	x	9

Key Technology Demonstrations

- **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

Long Term Cryo Fluid Management

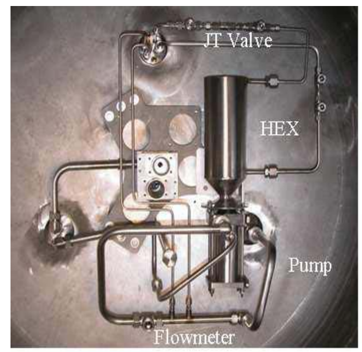
- **Cryogenic propulsion has continually proven to be the best option for space transportation elements**

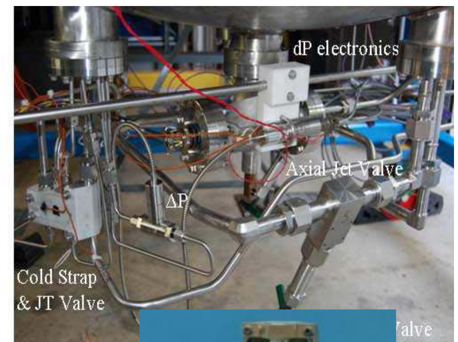
- **As mission opportunities move beyond Earth orbit, mission durations become critical driver for cryo propellants**
  - All historical human exploration missions required propellants for hours
  - Near term exploration goals need propellants for days
  - Long term exploration goals need propellants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

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

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