

TESTING FOR THE J-2X UPPER STAGE ENGINE

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ABSTRACT

NASA selected the J-2X Upper Stage Engine in 2006 to power the upper stages of the Ares I crew launch vehicle and the Ares V cargo launch vehicle. Based on the proven Saturn J-2 engine, this new engine will provide 294,000 pounds of thrust and a specific impulse of 448 seconds, making it the most efficient gas generator cycle engine in history. The engine's guiding philosophy emerged from the Exploration Systems Architecture Study (ESAS) in 2005. Goals established then called for vehicles and components based, where feasible, on proven hardware from the Space Shuttle, commercial, and other programs, to perform the mission and provide an order of magnitude greater safety. Since that time, the team has made unprecedented progress. Ahead of the other elements of the Constellation Program architecture, the team has progressed through System Requirements Review (SRR), System Design Review (SDR), Preliminary Design Review (PDR), and Critical Design Review (CDR). As of February 2010, more than 100,000 development engine parts have been ordered and more than 18,000 delivered. Approximately 1,300 of more than 1,600 engine drawings were released for manufacturing. A major factor in the J-2X development approach to this point is testing operations of heritage J-2 engine hardware and new J-2X components to understand heritage performance, validate computer modeling of development components, mitigate risk early in development, and inform design trades. This testing has been performed both by NASA and its J-2X prime contractor, Pratt & Whitney Rocketdyne (PWR). This body of work increases the likelihood of success as the team prepares for testing the J-2X powerpack and first development engine in calendar 2011. This paper will provide highlights of J-2X testing operations, engine test facilities, development hardware, and plans.

I. Introduction

"Space operations" encompass a wider technical discipline than the name itself implies. The subject of this paper is testing plans, hardware, and operations to support development of a new upper stage engine for NASA's Ares I and Ares V launch vehicles. The Ares vehicles support NASA's Constellation Program. Constellation was formulated in 2005 to respond to national space policy goals to retire the Space Shuttle fleet and develop its successor, support International Space Station operations, and resume human exploration of the solar system, beginning with a permanent and expanded presence on the Moon. Those plans are currently under review by national leaders. However, work continues on the Ares vehicles until a future course of action is finalized.

The Ares I and the Ares V are being designed to provide safe, reliable, sustainable space transportation systems built on a foundation of proven technology and technical expertise amassed from nearly 50 years of human space flight, including the Shuttle, Saturn, and more recent programs such as the X-33 and the Evolved Expendable Launch Vehicle (EELV) programs.

For Ares I, the J-2X will ignite after the first stage is discarded and powers the upper stage and Orion crew vehicle into low Earth orbit (LEO). For Ares V, the J-2X ignites after booster and core stage separation to place the Earth departure stage (EDS) and payloads, such as a lunar lander, into LEO. A planned kitted modification will allow it to re-ignite following a loiter phase to perform trans lunar injection (TLI) to send the EDS and its payload toward lunar orbit. The current Constellation program-of-record architecture is shown in figure 1.

Our Exploration Fleet *What Will the Vehicles Look Like?*

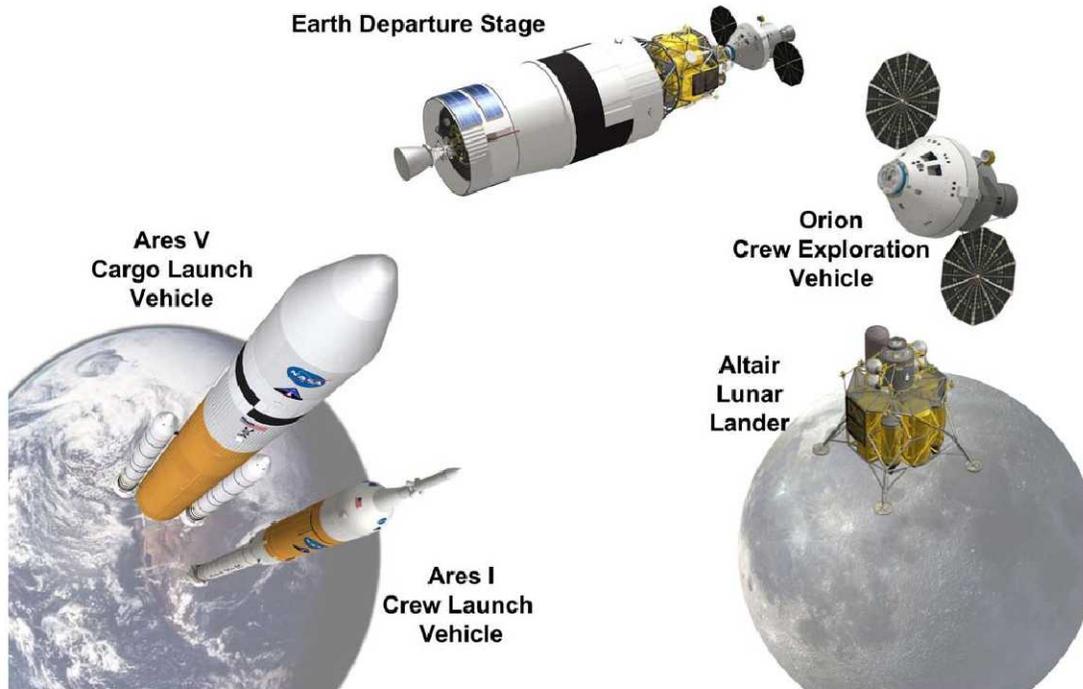


Figure 1 – Constellation architecture components

II. J-2X Requirements Description

The J-2X engine is a gas generator cycle selected to enable component testing and leverage flight-proven liquid oxygen/liquid hydrogen (LOX/LH₂) gas generator cycle J-2 and RS-68 engine capabilities. Key requirements driving the design are a vacuum thrust of 294,000 pounds (1,307 kN), specific impulse (I_{sp}) of 448 seconds, 5.5:1 mixture ratio, run duration on Ares I of 500 seconds, an operational life of 8 starts and 2,600 seconds, and a weight goal of 5,450 lb (2,472 kg). It uses a HIP-bonded main combustion chamber (MCC) and a tube wall regeneratively-cooled nozzle. To achieve stage combustion-range efficiency, the J-2X employs a passively-cooled metallic nozzle extension with an area ratio of 92:1. An overall key to the J-2X ability to meet Constellation requirements has been the use of contemporary technology and experience such as valves, MCC, engine controller and gas generator based on the modern RS-68 engine used by the Boeing Delta IV launch vehicle.

For the TLI phase of the Ares V mission, the J-2X must be kitted to be capable of on-orbit re-start, 500 second burn time, and a reduced mixture ratio to decrease thrust to reduce stress on the Orion/lunar lander docking interface. Engine throttling is achieved by changing propellant mixture ratio from 5.5 to 4.5. Engine operating life requirements cover cumulative starts and hot fire time to account for engine acceptance testing, stage green run testing, altitude start and in-space restart. The J-2X prime contractor is PWR, Canoga Park, CA. which developed both the J-2 and the RS-68 that provide the technical base for much of the engine. Engines will be assembled and tested at Stennis Space Center, MS, and integrated with the Ares I upper stage at Michoud Assembly Facility, LA. The component heritage of the J-2X engine is shown in figure 2.

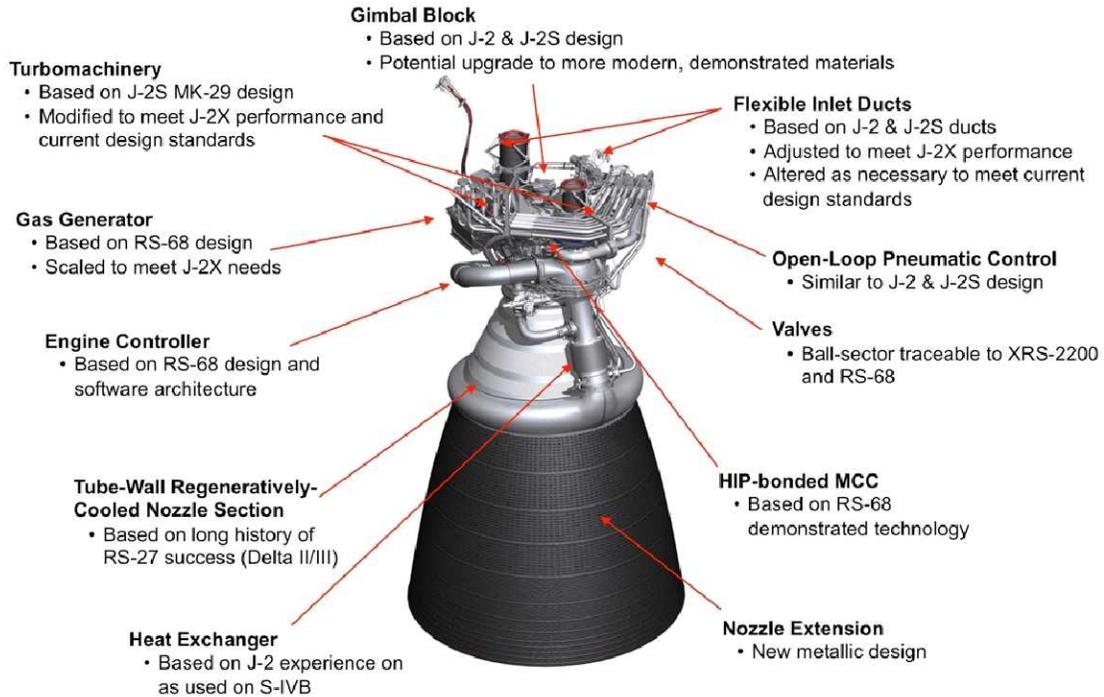


Figure 2 – The J-2X hardware heritage

Propulsion systems are historically the most technologically challenging area of any space vehicle development because of the high operating pressures, temperatures, and other performance requirements. The J-2X is no different, despite the decision to design an engine based on the proven Saturn J-2. Thrust exceeds the heritage J-2 by nearly 28 percent. Specific Impulse (I_{sp}) is more than 5 percent higher. Loss of mission reliability is in excess of an order of magnitude higher. Changes were made where necessary to meet these performance requirements. In some cases, heritage materials and suppliers no longer existed. As a result, while the J-2X retains the heritage gas generator cycle, and the turbomachinery is based on the heritage Mk 29, the J-2X is essentially a new engine. Conscious of the interactions between so many new components and the dramatically higher performance requirements, the J-2X team at the outset built the program around a detailed risk reduction strategy. Elements of that strategy were:

- Early requirements definition and management
- Early risk reduction testing
- Incorporating lessons learned from the J-2 heritage programs
- Initiating long-lead procurement items before the PDR
- Incorporating design features for anticipated EDS requirements.
- Identifying facilities for sea-level and altitude testing
- Starting ground support equipment and logistics planning at an early stage

III. Component Testing

The J-2X team has employed testing as a way to understand the heritage J-2 point-of-departure and the component and system level because much of the detailed engine knowledge no longer exists. It also has used testing as a way to select technologies and component details for the new engine. While computational methods have made a major contribution to the J-2X design, hardware tests have been used to anchor computational tools. Key tests in the J-2X development are discussed briefly in this section.

Subscale Main Injector firing tests (figure 3) in 2007 and 2008 allowed the team to characterize performance and select the J-2X injector element pattern. Test hardware simulated the flight element density but not the size of a full-

size J-2X injector. Test conditions mimicked flows, pressures, and temperatures in tests of 40-, 52-, and 58-element subscale injectors. The 52-element injector was subsequently selected for the development engine program. This injector is less complex than the Space Shuttle Main Engine (SSME) injector, yet provides optimum efficiency and operability for the J-2X.



Figure 3 – Subscale Main Injector testing at MSFC

Subscale Main Injector hot fire testing in 2006-2007 was conducted to characterize performance and select the J-2X injector element pattern. Main Injector Augmented Spark Igniter hot fire testing in 2007 helped characterize the heritage igniter, and in 2010 it will be used again to characterize the J-2X igniter.

Workhorse Gas Generator (GG) testing (figure 4) in 2008-2009 was employed to evaluate combustion stability and turbine inlet hot gas temperature uniformity. A new round of GG testing in 2010 will verify the redesign of the hot gas duct to resolve a combustion stability issue.



Figure 4 – Workhorse Gas Generator testing at MSFC

The passively-cooled metallic engine nozzle extension has been the subject of extensive testing. Subscale nozzle cold flow testing in 2009 was used to characterize nozzle side loads, as well as the effectiveness of supersonic turbine exhaust gas (TEG) film cooling (figure 5). A variety of tests were also conducted to characterize the thermal emissivity and durability of several candidate coatings for the inside and outside of extension. One coating passed the 3,200-second certification time and was down-selected in 2010 for use on the development engine.

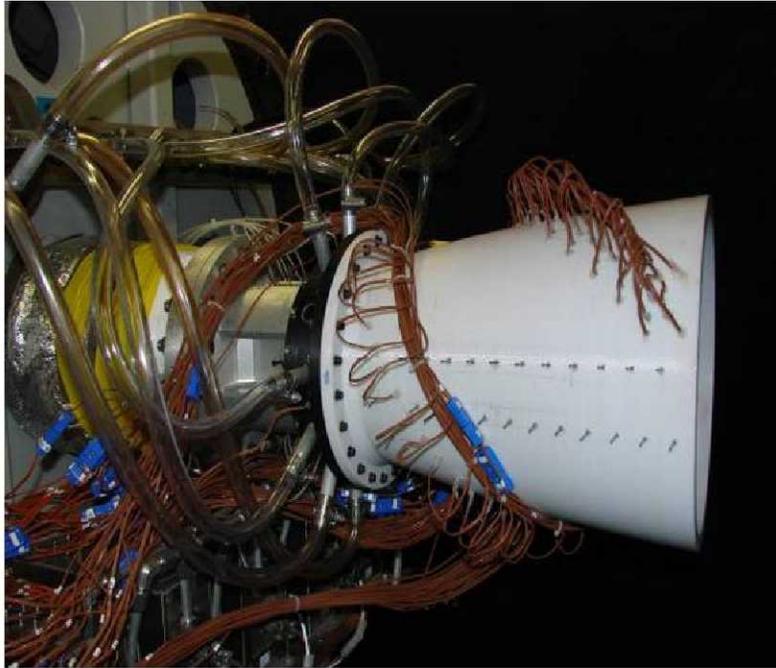


Figure 5 – Supersonic film cooling effectiveness testing at MSFC

Testing to support the design of the liquid hydrogen and liquid oxygen turbopumps began with tests of the original Mk. 29 J-2 pumps. Subscale inducer water flow testing was conducted in 2008-2009 to help select the J-2X inducer designs. Fuel turbine blade damping whirligig testing in 2008-2010 was used to characterize dynamic damping and to select turbine damper design. Oxidizer turbopump seals were tested in 2009 to characterize seal endurance and performance. J-2 Heritage Turbine Air Flow Testing in 2010 characterized turbine dynamics for anchoring turbine gas computational fluid dynamics modeling. This notably included the first use of an on-rotor and on-blade sensor and data collection system.

Development and qualification testing for main propellant valves and actuators, ancillary valves and pneumatic control assemblies was conducted in 2009-2011. Development and flight software configurations for the engine control system engine valves and actuators began testing in 2009 and will continue through 2011. A key capability added to support this testing is the new Hardware in the Loop Lab (HILL), which, when complete, will verify the performance of the engine controller, valves, actuators, and software.

Additional tests conducted by MSFC under agreements with PWR include: material testing, oxygen compatibility assessment, high speed data acquisition and process tests, control system testing, simulation interface adaptor testing, pressure tests on a vented microswitch, and disassembly tooling.

IV. Engine System Testing

The first engine system tests in support of J-2X development occurred early in the program with a series of tests on the heritage J-2S powerpack (figure 6). Powerpack Assembly-1A (PPA-1) included the turbopumps, inlet ducts, and gas generator. Conducted on the A1 test stand at NASA's Stennis Space Center, the goal was to recapture precise performance data lost since the J-2 was developed and provide a baseline for J-2X development. A total of six hot-fire tests were conducted between February and May 2008, accumulating more than 1,300 seconds of operating time at power levels equivalent to 274,000 pounds of thrust.

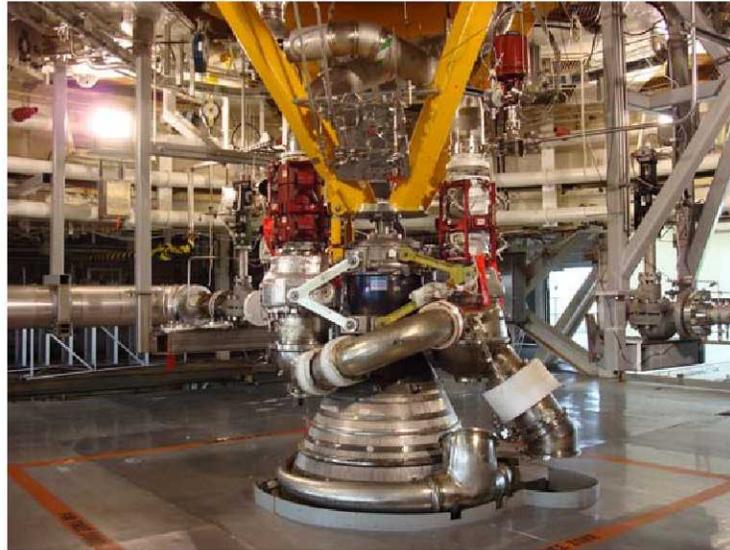


Figure 6 – PPA-1 in the A1 test stand at Stennis Space Center

Based on the success of heritage J-2 tests and development component hardware tests, J-2X development is now only a year away from the first development engine system tests. The J-2X team has set an ambitious goal of completing assembly of the first development engine, designated 10001, by Dec. 24, 2010 and the PPA-2 by January 15, 2011. The first J-2X engine test would follow by Jan. 31, 2011, and powerpack testing would begin in February 2011. J-2X development incorporates 223 engine tests laid out as follows:

- 132 development tests
- 32 certification tests
- 7 development/flight tests for the engine to be flown on the first Ares I test flight
- 15 tests of the engine with the Ares I Upper Stage Integrated Stage Test Article
- 17 contingency tests
- 20 rework tests

Engine development hardware finalized at CDR includes:

- 9 development engines, including one for the first Ares I/Orion test flight, Orion launch, 1 for ISTA, and 2 for engine certification testing
- 2 powerpack assemblies, consisting primarily of turbomachinery and gas generator, for characterization of the heritage engine and early testing of J-2X hardware
- 4 long-lead hardware sets
- 1 unassembled spare engine
- 1 engine mass simulator

- 7 full nozzle extensions and two “stub” length extensions for testing on the A-2 and A-3 test stands
- 1 set of spare fuel and oxidizer turbopumps
- 1 set of hardware/software for the Hardware in the Loop Lab
- 1 control system for the Ares SIL
- various engine support hardware, manufacturing technology demonstrators, and component test articles.

In support of development engine testing, three major test stands at NASA’s Stennis Space Center, MS, are being renovated or built. The A1 test stand is now undergoing modifications to support PPA-2 testing as well as later engine systems development testing. The A1 thrust takeout structure, thrust measurement system, and an improved control system have been installed. PPA-2 pump capture systems are being redesigned to eliminate flow-induced vibration problems experienced during PPA-1A. The PPA-2 series will involve 25 tests of the development engine turbomachinery and gas generator.

The A2 stand is scheduled to be turned over to J-2X this year to support development and certification engine testing. Propellant transfer lines to the run tanks are scheduled for replacement this year as part of those changes. A2 can provide pseudo-altitude testing with a passive diffuser. It is limited to testing a shortened “stub” nozzle extension, and it cannot provide gimbaling capability. However, it represents a much-needed overlapping capability to move both development and flight engines through testing. A2 will host testing of the first development engine, E-10001.

Significant work has been completed on the new A3 altitude test stand since site clearing began in spring 2007 (figure 7). The A3 stand will be first capable of testing large liquid rocket engines for full duration at full simulated altitude with full gimbaling capability. Using steam created by the combustion of isopropyl alcohol to evacuate the atmosphere from the test cell, A3 can simulate altitudes of 80,000 to 100,000 feet. The future status of the A3 stand is currently under review by an internal NASA team as a result of 2011 budget guidance. However, much of the stand is now completed. Foundation and structural steel for the tower and barge docks are complete. Installation of the stand’s LOX, IPA, and water tanks were continuing in 2010. The stand’s chemical steam generator system was in various stages of completion following separate subscale tests to validate the system. The test site as it appears now is shown in Figure 8, with manufacturing details of the altitude test cell shown in figure 9.



Figure 7 – A view of the SSC A3 test site in May 2007 before construction began



Figure 8 – The A3 test site as it appeared in March 2010, including tower and barge docks

5.2.4.1

Test Cell Diffuser TO 1

-Test Cell; Diffuser; Test Cell Door; Floor



Figure 9 – Photos showing A3 diffuser test cell, floor, and dome in fabrication

V. Conclusion

While based on a heritage design, the J-2X is effectively a new engine designed to respond to significantly greater performance and safety requirements. While modern design techniques contribute to the design team's confidence as the J-2X prepares for its first tests in 2011, testing has played a vital role in verifying original J-2 performance, analyzing problems, verifying optimum design solutions, and anchoring computational modeling techniques. The J-2X has successfully passed several major design reviews, and the design has moved into production. More than 100,000 parts have been manufactured or are in-process. A nationwide team is working to assemble the first development engine by Dec. 24, 2010 and hot-fire test it by Jan. 31, 2011. The engine team is confident that its carefully chosen testing at the heritage and component levels will lead to successful engine testing to provide the nation with an engine capable of supporting any new direction in human space exploration.

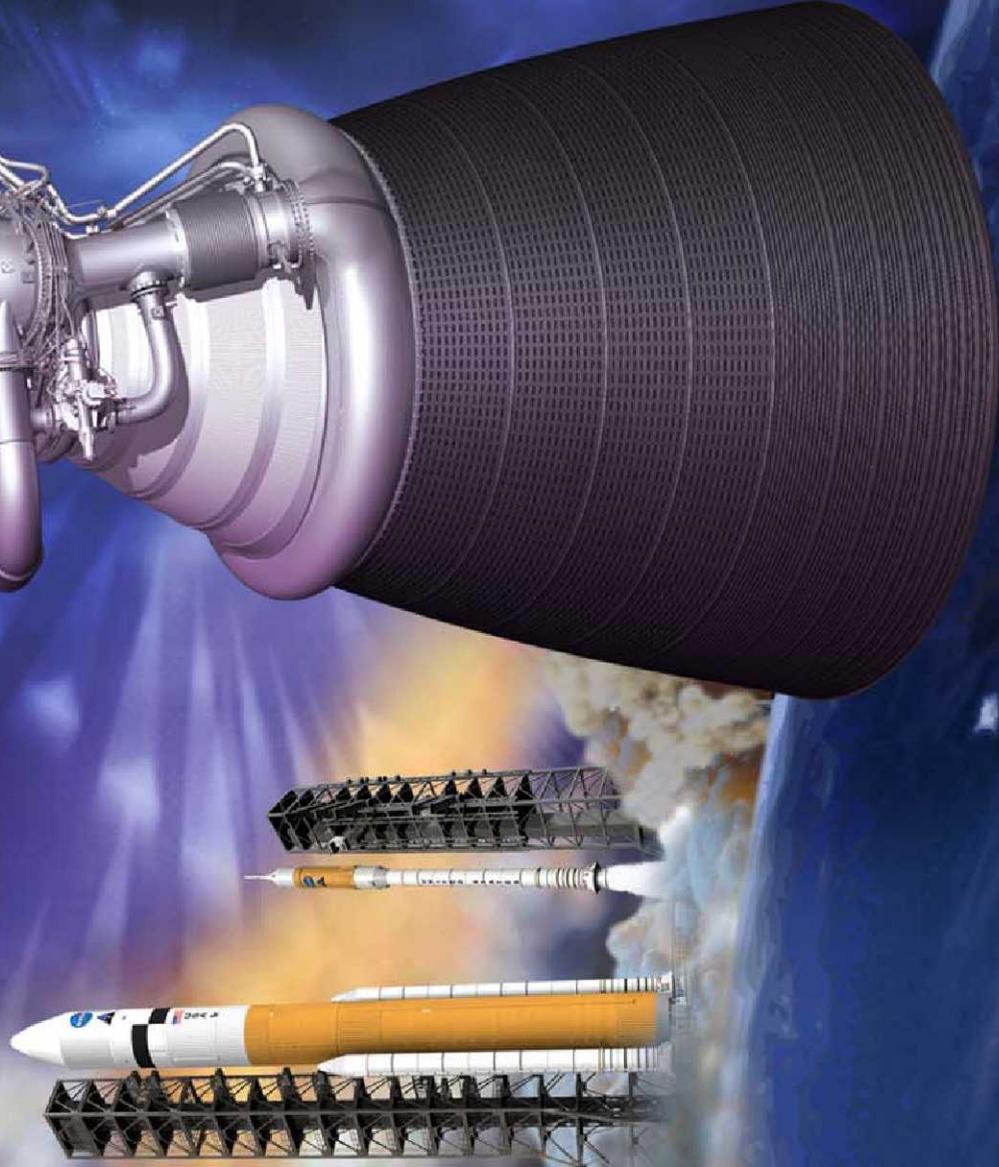


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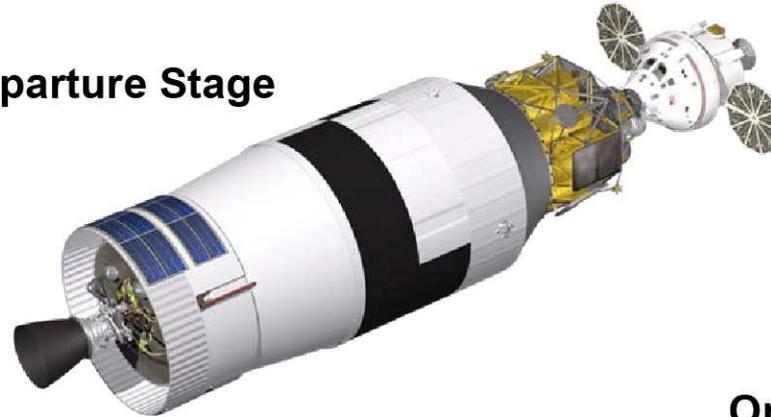




Program of Record Architecture



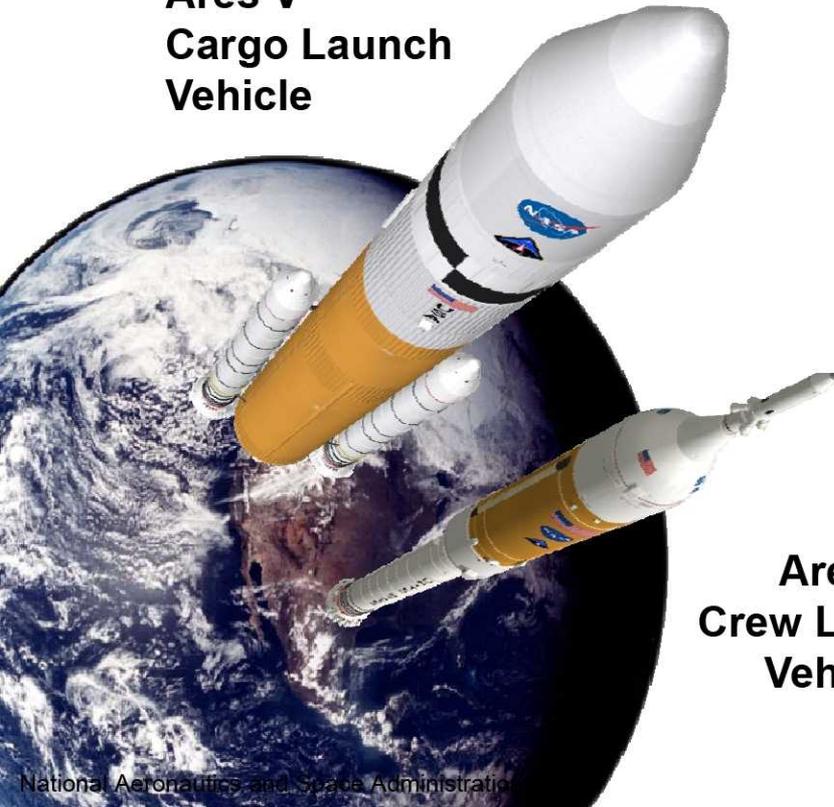
Earth Departure Stage



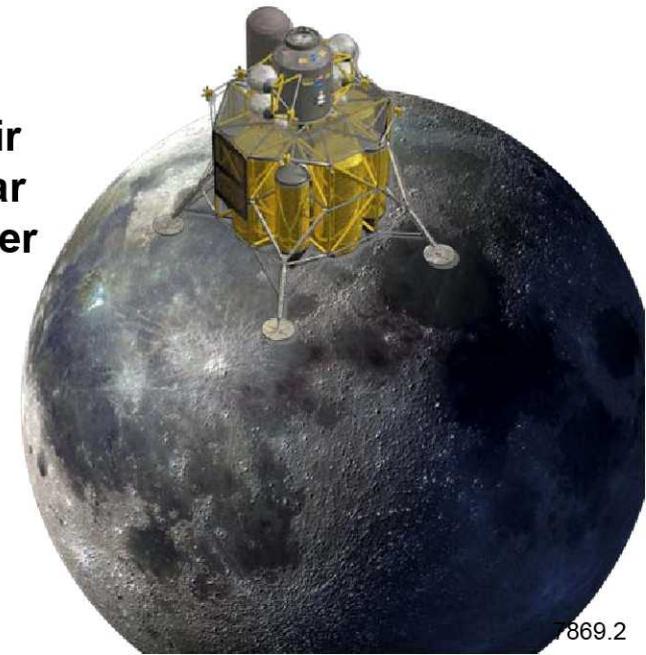
**Orion
Crew Exploration
Vehicle**



**Ares V
Cargo Launch
Vehicle**



**Altair
Lunar
Lander**



**Ares I
Crew Launch
Vehicle**



J-2X at a Glance



◆ Mission:

Common upper stage engine for Ares I Upper Stage and Ares V Earth Departure Stage

◆ Challenge:

Use proven technology from Saturn, X-33, RS-68 to develop the highest Isp GG cycle engine in history for 2 missions

◆ Key Features:

LOX/LH₂ GG cycle, series turbines (2), HIP-bonded MCC, pneumatic ball-sector valves, on-board engine controller, tube-wall regen nozzle/large passively-cooled metallic nozzle extension, TEG boost/cooling

◆ Development Philosophy:

proven hardware, aggressive schedule, early risk reduction, requirements-driven



◆ USE Key Requirements

- Vacuum Thrust: 294,000 lbf (1307 kN)
- Specific impulse: 448 sec (min)
- Mixture ratio: 5.5
- Run duration: 500 seconds
- Weight: 5,535 (2,516 kg)
- Size: 120" dia x 185" long
- Life: 8 starts / 2600 sec
- Ares V specific: on-orbit restart, 82% thrust (4.5 mixture ratio)

◆ Major Hardware Ops

- Production – Pratt & Whitney Rocketdyne, Canoga Park, CA
- Engine assembly – SSC, MS, Bldg 9101
- Test – SSC, MS, Stands A1, A2, A3
- Stage integration – MAF, LA



J-2X Major Elements



Turbomachinery

- Based on J-2S MK-29 design
- Modified to meet J-2X performance and current design standards

Gimbal Block

- Based on J-2 & J-2S design
- Potential upgrade to more modern, demonstrated materials

Gas Generator

- Based on RS-68 design
- Scaled to meet J-2X needs

Engine Controller

- Based on RS-68 design and software architecture

Tube-Wall Regeneratively-Cooled Nozzle Section

- Based on long history of RS-27 success (Delta II/III)

Heat Exchanger

- Based on J-2 experience on as used on S-IVB

Flexible Inlet Ducts

- Based on J-2 & J-2S ducts
- Adjusted to meet J-2X performance
- Altered as necessary to meet current design standards

Open-Loop Pneumatic Control

- Similar to J-2 & J-2S design

Valves

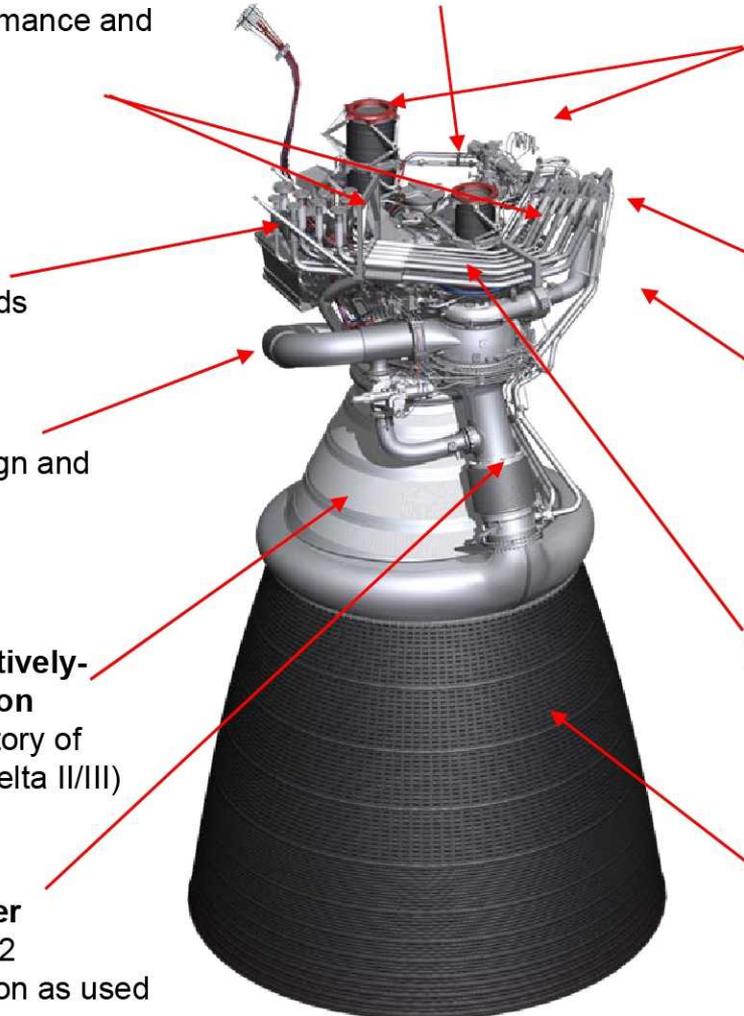
- Ball-sector traceable to XRS-2200 and RS-68

HIP-bonded MCC

- Based on RS-68 demonstrated technology

Nozzle Extension

- New metallic design





MSFC Hot Fire Testing



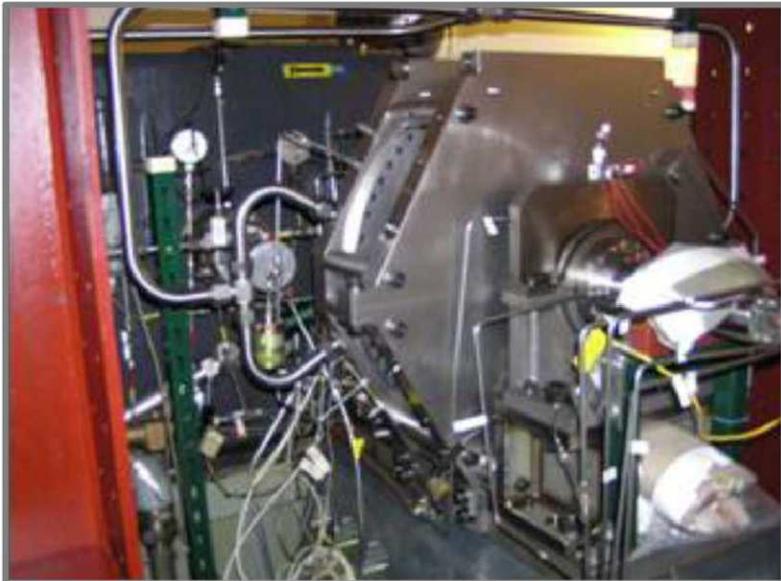
Subscale Main Injector



Workhorse Gas Generator



Turbomachinery Testing

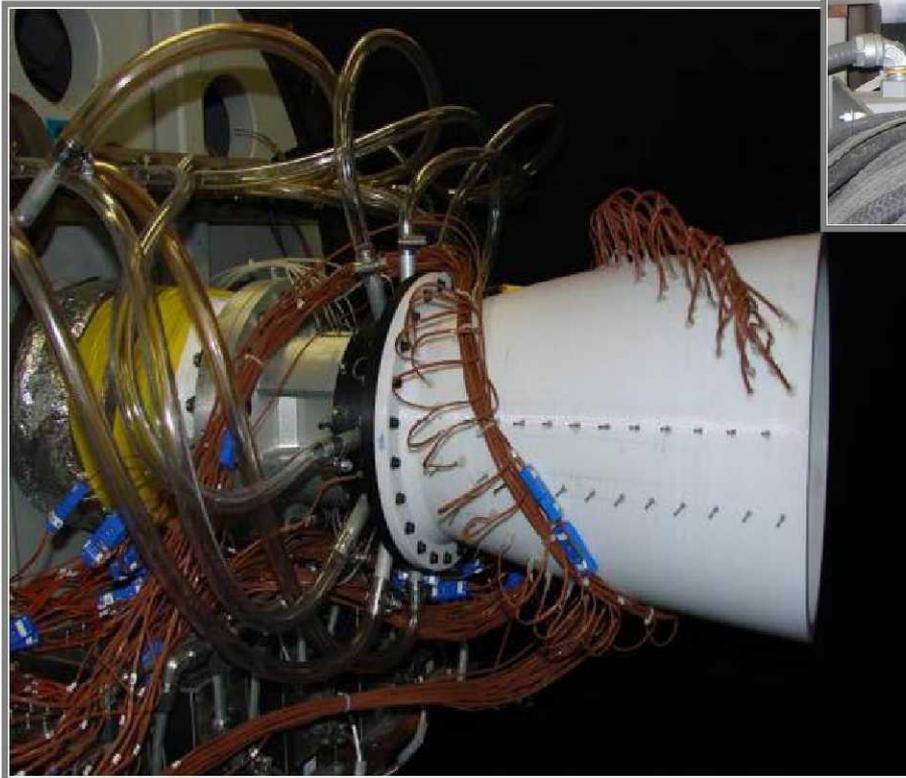
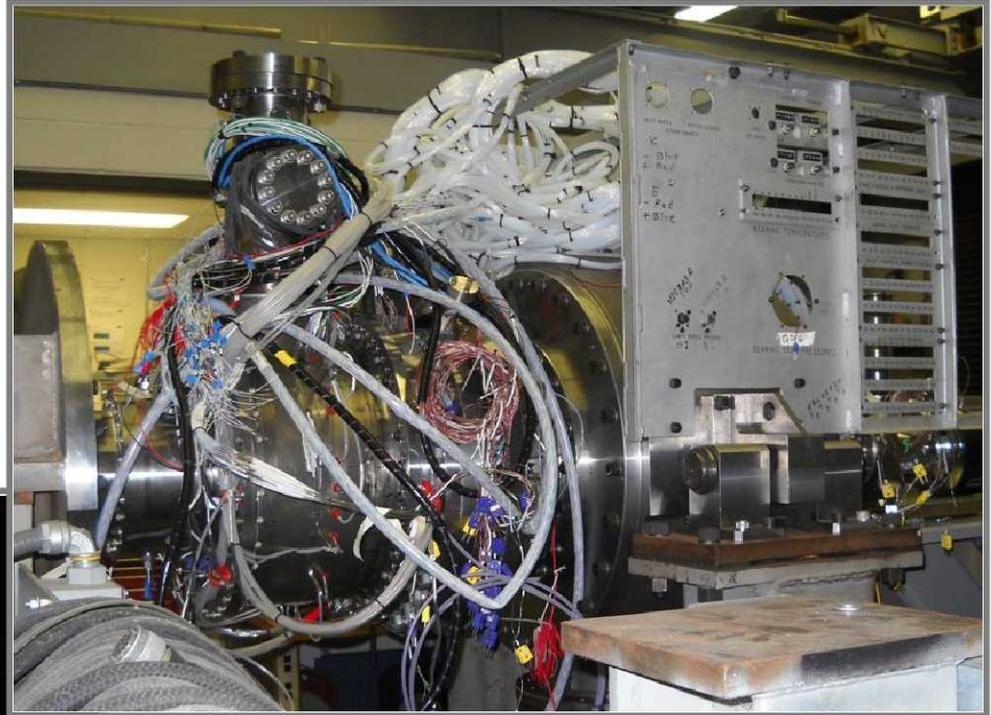




Cold Flow Testing at MSFC



Heritage Fuel Air Turbine Testing



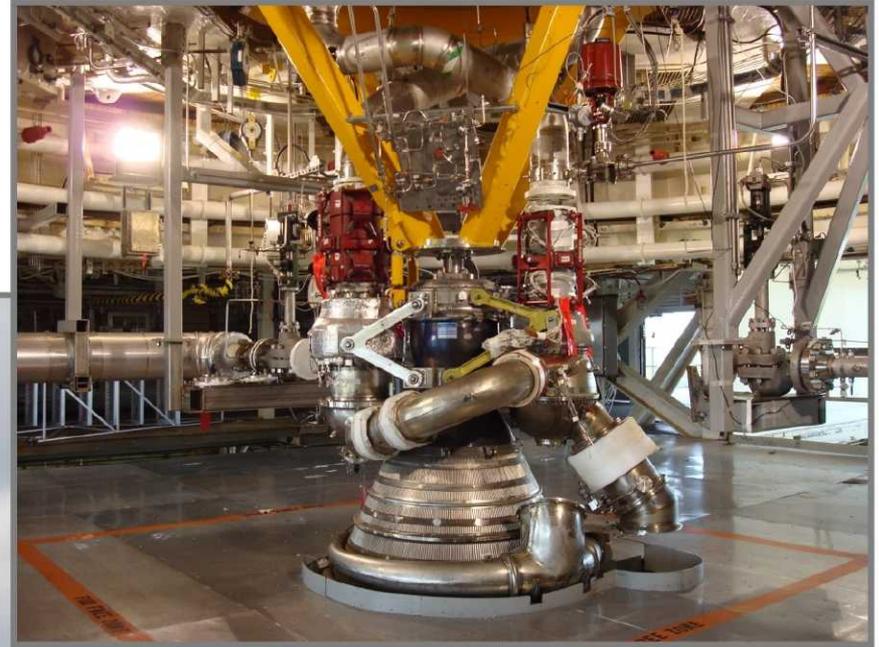
Super Sonic Film Cooling Effectiveness Testing



Powerpack Assembly 1 (PPA-1) Testing



- 6 hot-fire tests
- Feb. 15 – May 8, 2008
- 1,343 seconds of operation

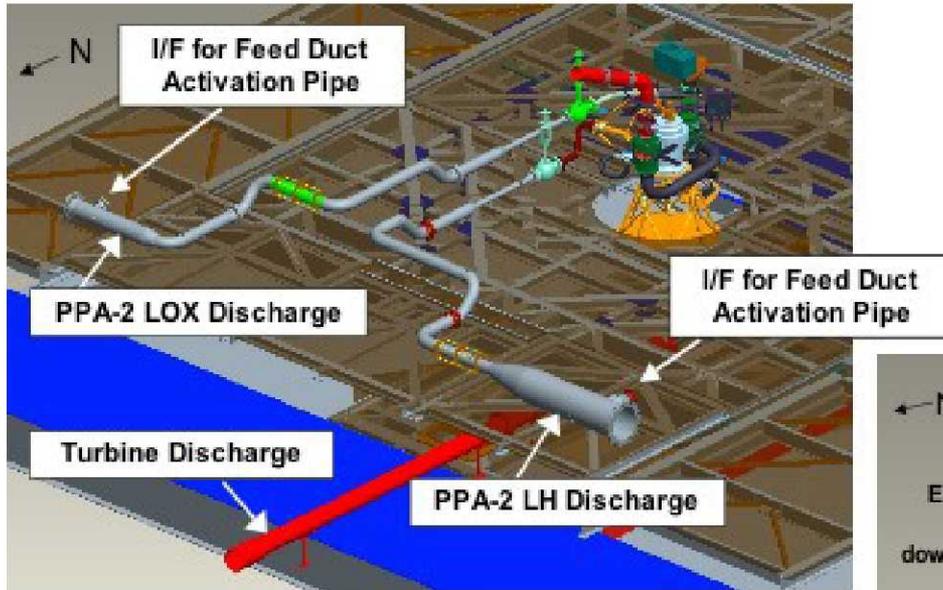




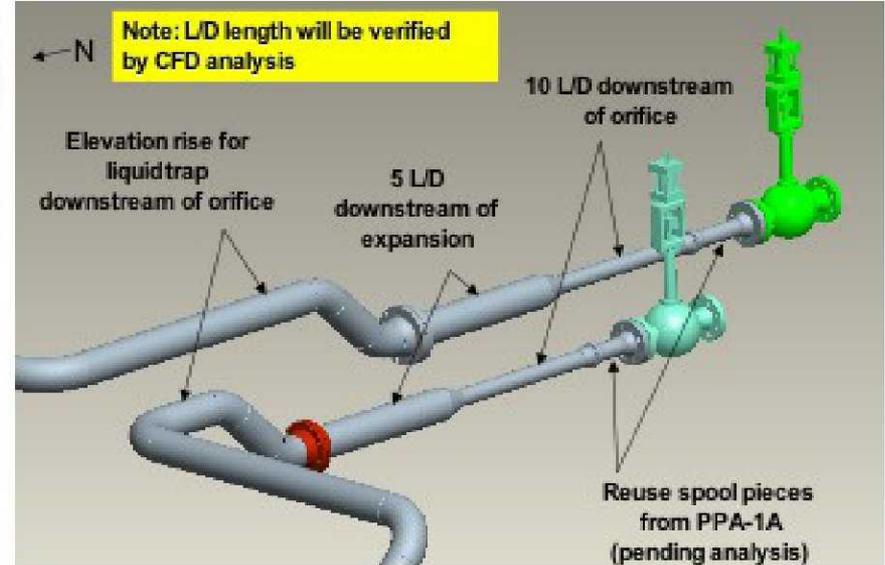
A-1 Test Stand PPA-2 Modifications



- ◆ The A-1 PPA-2 pump capture systems are being redesigned to eliminate PPA-1A flow-induced vibration problems



Layout



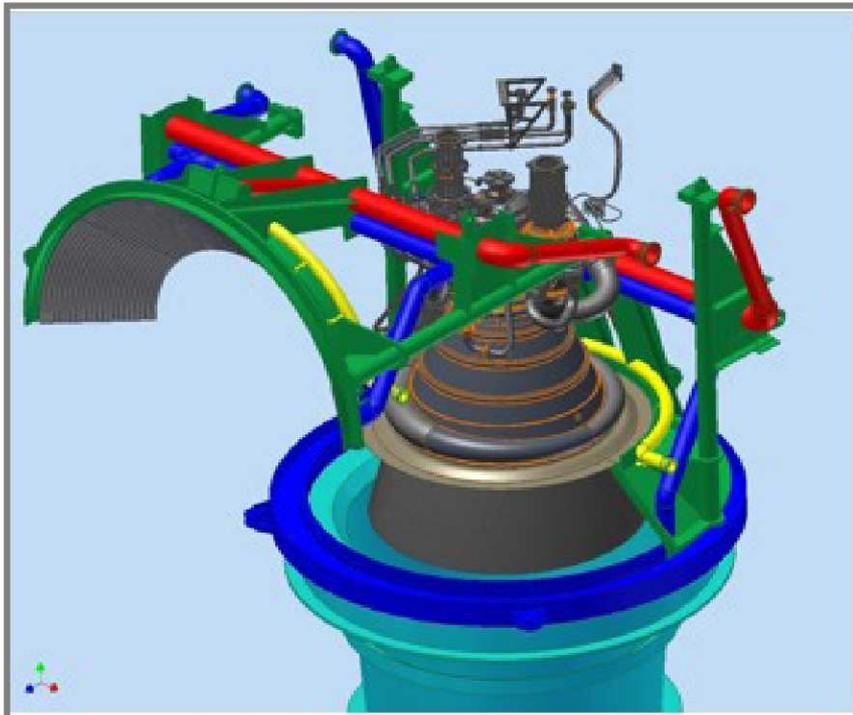
PPA-2 Interface Detail



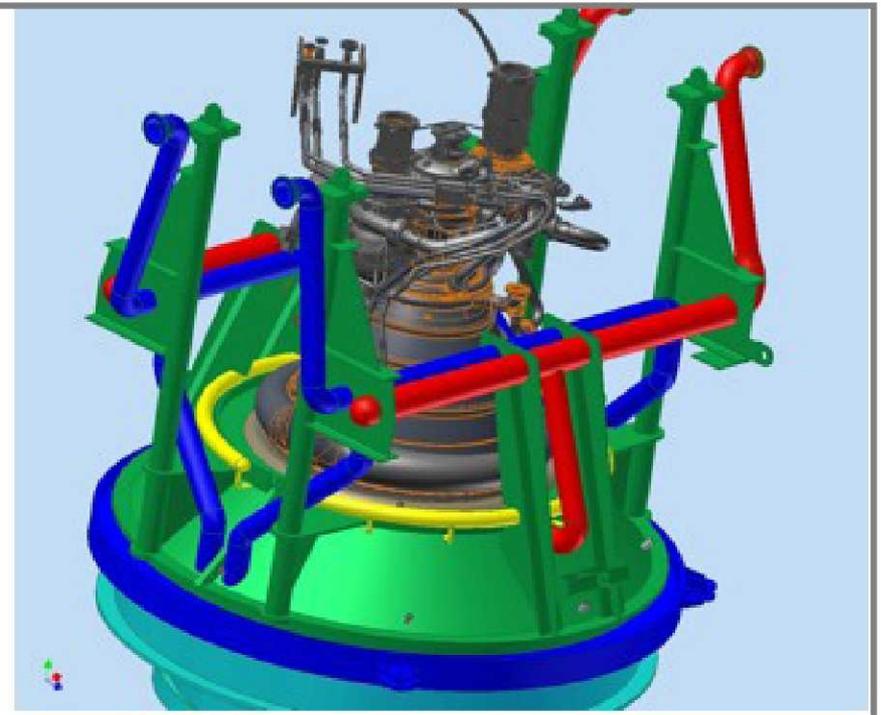
A-2 Test Stand Modifications - Clamshell



- ◆ A new clamshell design will be used with the existing diffuser to test J-2X at secondary power level on A2



Open



Closed



A3 Altitude Test Stand Progress





A3 Diffuser, Test Cell, Floor, and Dome Fabrication



5.2.4.1

Test Cell Diffuser TO 1

-Test Cell; Diffuser; Test Cell Door; Floor





J-2X Test Program



◆ 232 Development Engine Tests

- 132 Development Tests
- 32 Certification Tests
- 7 Flight Engine Development/Flight Tests
- 15 ISTA Tests
- 17 Contingency Tests
- 20 Rework tests



Development Engine Test Hardware



◆ 10 DDT&E Engines

- Development ground test engines (5)
- Certification ground test engines – (2)
- Upper Stage ISTA ground test engine – (1)
- Orion 1 flight test engine – (1)
- Full unassembled engine (1)

◆ 2 Powerpack Assemblies

- Heritage J-2/J-2S Powerpack – (1)
- J-2X Powerpack – (1)

◆ 4 Long Lead Hardware Sets

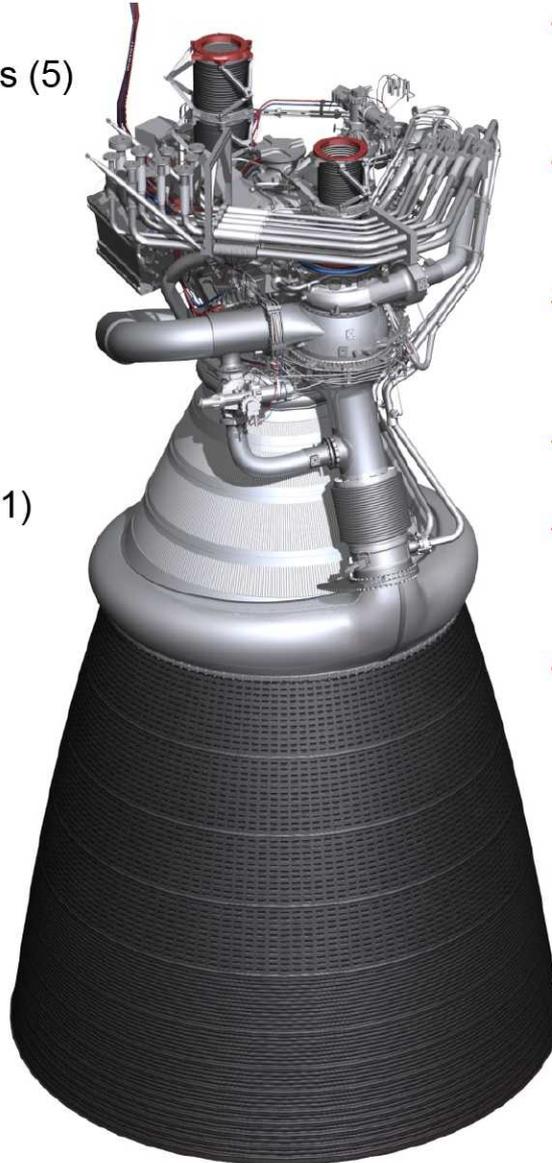
- Represents first 18 months of engine manufacturing

◆ 1 Engine Mass Simulator

- IVGVT

◆ 9 Nozzle Extensions

- Full Length – (7)
- Stub Length for SSC A2/A3 – (2)



◆ 1 Set Spare Fuel and Oxidizer Turbopumps

◆ 1 Set Hardware/software for J-2X HILL

◆ 1 Control System for Ares SIL

◆ Engine Support Equipment

◆ Manufacturing Technology Demonstrators

◆ Component Test Articles