

From Paper to Production: An Update on NASA's Upper Stage Engine for Exploration

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Abstract

In 2006, NASA selected an evolved variant of the proven Saturn/Apollo J-2 upper stage engine to power the Ares I crew launch vehicle upper stage and the Ares V cargo launch vehicle Earth departure stage (EDS) for the Constellation Program. Any design changes needed by the new engine would be based where possible on proven hardware from the Space Shuttle, commercial launchers, and other programs. In addition to the thrust and efficiency requirements needed for the Constellation reference missions, it would be an order of magnitude safer than past engines. It required the J-2X government/industry team to develop the highest performance engine of its type in history and develop it for use in two vehicles for two different missions. In the attempt to achieve these goals in the past five years, the Upper Stage Engine team has made significant progress, successfully passing System Requirements Review (SRR), System Design Review (SDR), Preliminary Design Review (PDR), and Critical Design Review (CDR). As of spring 2010, more than 100,000 experimental and development engine parts have been completed or are in various stages of manufacture. Approximately 1,300 of more than 1,600 engine drawings have been released for manufacturing. This progress has been due to a combination of factors: the heritage hardware starting point, advanced computer analysis, and early heritage and development component testing to understand performance, validate computer modeling, and inform design trades. This work will increase the odds of success as engine team prepares for powerpack and development engine hot fire testing in calendar 2011. This paper will provide an overview of the engine development program and progress to date.

I. INTRODUCTION

A NASA/industry team of more than 10,000 people has been working since 2005 to develop a new architecture to replace the Space Shuttle, support the International Space Station, and renew lunar exploration as a stepping stone to exploring the rest of the Solar System as guided by national space policy. Among the inputs to the design process were: separating crew from cargo, improving safety by an order of magnitude, relying where feasible on shuttle-derived or otherwise proven technology, and seeking commonality between systems.

The Ares Projects at NASA's Marshall Space Flight Center (MSFC), is designing, building, and testing the launch vehicles to carry astronauts into low Earth orbit (LEO) and propel them to the Moon and beyond. The Ares I crew launch vehicle is designed to carry up to four astronauts to the ISS or to other missions beginning in LEO. The Ares V cargo launch vehicle is designed to carry a lunar lander into LEO and perform the Trans Lunar Injection (TLI) mission to send cargo and crew to the Moon. A single J-2X is designed to power the Ares I upper stage and will also power the Ares V EDS during ascent with modifications as needed to support the loiter and TLI phases of the Ares V mission.

The Apollo-era J-2 engine serves as the point-of-departure for the J-2X. The J-2X replaced a modified Space Shuttle Main Engine (SSME) in the original ESAS launch vehicle designs because analysis showed that it had less development risk and lower development and recurring costs than modifying the reusable SSME to be an expendable altitude start engine with re-start capability. The current J-2X configuration is shown in figure 1.

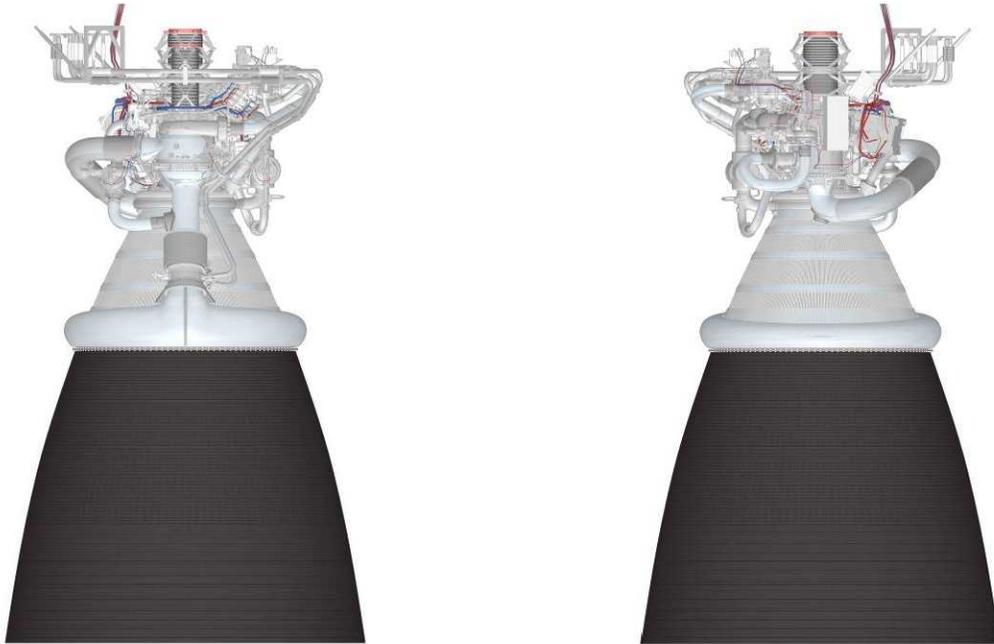


Figure 1 – Front and rear profiles of the J-2X Upper Stage Engine

In order to meet Constellation and Ares requirements, the J-2X challenge is to design an engine:

- Based on the Saturn J-2 liquid oxygen/liquid hydrogen (LOX/LH²) gas generator cycle engine
- That has 35 percent more thrust and 5 percent greater specific impulse (Isp) than the J-2
- That employs modern materials and techniques to improve safety by an order of magnitude over the SSME
- That performs two roles for two different vehicles, retaining maximum commonality.

Key requirements driving the design are a vacuum thrust of 294,000 pounds (1,307 kN), a minimum Isp 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, weight limit of 5,535 lb (2,526 kg). For the TLI phase of the Ares V mission, the J-2X design additionally must be capable of an on-orbit loiter, re-start, 500 second burn time, and a reduced mixture ratio to decrease thrust to reduce stress on the Orion/lunar lander docking interface. To accommodate the J-2X development approach with a limited number of engines for development/certification, the engine's design life is 30 starts, much greater than the planned service life of 8 starts.

The J-2X prime contractor is Pratt & Whitney Rocketdyne, Canoga Park, Ca. Flight engines will be assembled and tested at Stennis Space Center, MS, and integrated with the Ares I upper stage at Michoud Assembly Facility, LA.

II. BEHIND THE DESIGN

The J-2X is based on the J-2 engine that successfully powered the Saturn IB and Saturn V upper stages. As the design has progressed, the changes needed to achieve Constellation performance, reliability, and safety requirements were so significant that the J-2X is largely a new engine.

Obsolete materials, manufacturing methods, supplier attrition, and availability of engineers from 40 years ago make it impossible to simply rebuild the J-2. Further, Ares requirements for performance, reliability, and human rating are more demanding than those for the J-2. The Constellation design reference missions (DRMs) require a much higher delivered mass to the lunar surface, accounting for the requirement for 294,000 pounds (1,307 kN) vacuum thrust, vs. 230,000 pounds (1,023 kN) for J-2, 448

seconds Isp vs. 425 for J-2, loss of mission reliability of 1 in 1250 vs. 1 in 500 for J-2, and numerous other requirements associated with human rating that were not applied to the original J-2.

The J-2X team studied the heritage J-2 design and performed several tests of the hardware to understand and in some cases recover knowledge lost over the years regarding performance before deviating from it to improve performance and reduce risk. The development plan addresses the differences to assure NASA can achieve the Ares requirements with the J-2X design. The J-2X design heritage is shown in figure 2.

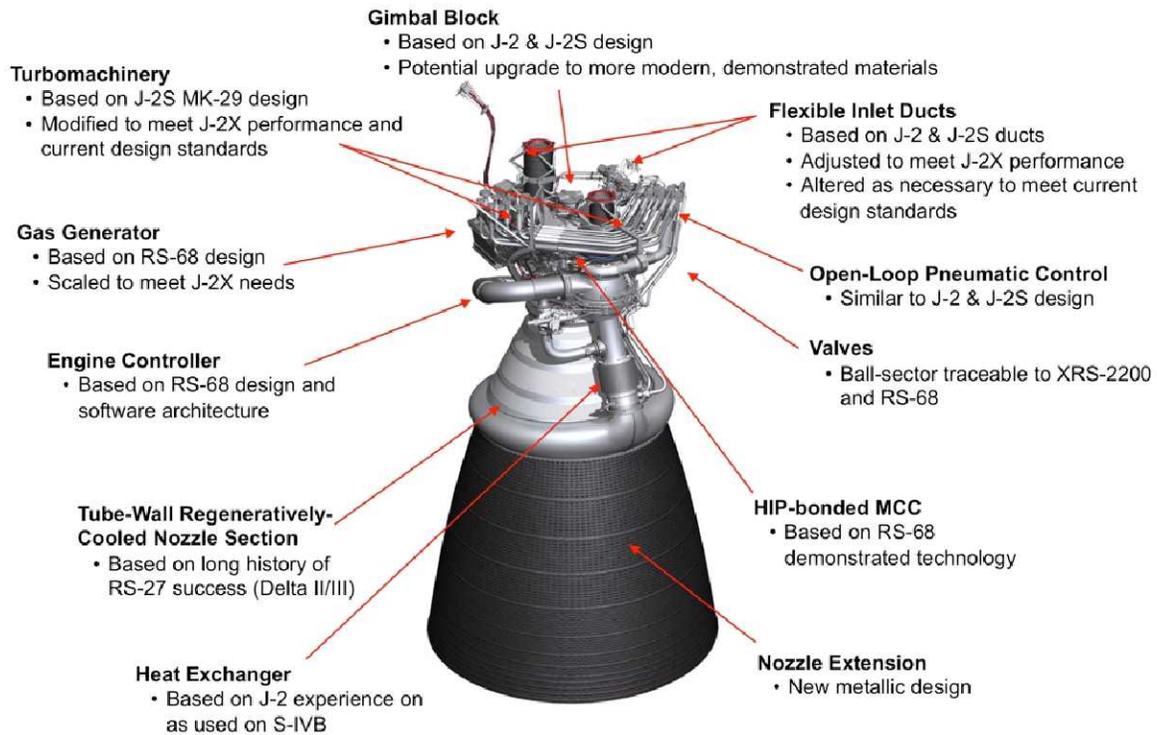


Figure 2 – The J-2X component heritage

The J-2X borrows some major design features of the J-2/J-2S engines. The J-2X uses the same series turbine gas generator power cycle in which turbine drive power is serially flowed through the fuel turbine and then the oxidizer turbine before it is dumped into the nozzle.

To perform engine throttling required for the Ares V TLI maneuver, the J-2X deviates from the J-2 oxidizer pump recirculation loop because this heritage feature would drive J-2X turbomachinery performance far outside of heritage J-2S turbomachinery experience base. Instead, the J-2X accomplishes throttling via the oxidizer turbine bypass.

J-2S/X-33 turbomachinery is modified for J-2X to the extent necessary to meet Ares thrust requirements and modern design standards including increasing design and safety margins.

Heritage designs for the J-2S turbopumps and scissors ducts were considered important enough to the evolution of the J-2X that the Powerpack 1A test hardware used this heritage hardware for a series of tests in 2007 and 2008 to replicate and augment the heritage data for operating points of importance to the J-2X evolved design for these components.

The engine team chose to make extensive use of other more recent propulsion designs which offer advantages over the 40-year-old experience with the J-2/J-2S. Technology aside, this means there are engineers in the supporting workforce with direct experience on these engines. One example of a decision to deviate from the J-2 was the decision to deviate from the heritage butterfly valves. Heritage

valves were torn down to begin reverse engineering them in early 2006 before the decision was made to use the more contemporary sector ball valve design. This also allows for flexibility to incorporate hydraulic actuator control into future upgrades. Other design solutions that resulted in J-2X deviations from J-2/J-2S, such as the gas generator design with solid propellant igniter, are derived from recent PWR experience with its current RS-68 engine.

The Ares requirement for engine Isp impulse is 448 seconds, which is only seconds short of the high performance SSMEs flown today. The SSME's staged combustion power cycle is amenable to such a performance requirement, but the J-2X uses a lower performance gas generator power cycle. In order to meet this requirement, while leveraging heritage to minimize development risk, the J-2X utilizes a high performance main injector design similar to the SSME and upgraded RS-68 as well as a new metallic nozzle extension that is cooled passively by turbine exhaust gas (TEG) injected supersonically through a manifold along the walls of the extension. The engine team carried both metallic and composite extensions through the early design cycles. Although composites had clearly superior thermal performance, the extension would have been larger than any composite nozzle to date and would have required construction of additional facilities at significant cost. The thrust chamber assembly area ratio could have been accomplished in a smaller package, but this was not done, because the chamber pressure was kept low enough to stay with the single-stage fuel turbopump design to minimize turbomachinery development risk.

These are some of the examples where the J-2X team has managed to gain the benefits of a proven design while leveraging the benefits of newer technology and knowledge. This was done to minimize development risk, translating to both cost and schedule savings.

III. HARDWARE TESTING HIGHLIGHTS

Early testing has provided critical insight into understanding the impact of design solutions on the engine system. The team has encountered several issues in the design phase, each understood and resolved with the help of component testing. Among those are oxidizer and fuel inlet duct durability, gas generator instability, nozzle extension performance/durability, oxidizer and fuel turbopump structural margins, and engine control unit (ECU) cooling margins. Many parts of the J-2X have undergone performance modeling, and have been tested in a lab environment.

Subscale Main Injector hot fire testing in 2006-2007 was used to characterize performance and select the J-2X injector element pattern for channeling propellants into the combustion chamber. The goal of testing was to find an injector element density that provides optimum performance with minimum complexity and cost. The test hardware simulated the element density but not the size of a full-scale J-2X injector. Test conditions simulated the flows, pressures, temperatures, etc. of the J-2X. Tests included 40-, 52-, and 58-element subscale injectors. The 52-element injector was chosen for the development engine. Although this element density is comparable with a SSME main injector, the J-2X main injector experiences a less severe operating environment. It has a simplified design and a proven manufacturing process. The single faceplate design has fewer welds, and it is easier to assemble and inspect. A subscale main injector test is shown in figure 3.



Figure 3 – Subscale Main Injector testing at MSFC

A heritage main injector Augmented Spark Igniter (ASI), needed for in-flight ignition, was test fired in 2007 to characterize the original design and inform the J-2X design. This test series simulated the conditions the Ares I's upper stage will experience. The series also used propellants chilled to minus 260 degrees Fahrenheit (126.6 degrees Celsius) to simulate TLI conditions within the EDS.

Another round of testing is planned in 2010 to characterize the J-2X igniter. Both the igniter and the test conditions will more closely match the development engine and flight conditions. Compared to the heritage igniter, the J-2X igniter differs in its propellant flow path, feed line materials, and the length and number of bends. The main injector exciter unit and spark igniter are redesigned. Axial separation between the J-2X ASI oxidizer injection orifices and the spark igniter ports are slightly different. Test facility changes will more closely represent flight conditions. Propellants will be delivered to the ASI similar to the way they will be delivered to the flight engine.

A Workhorse Gas Generator (WHGG), which simulates the temperatures, pressures, and flows of a flight gas generator, was used in several hot-fire series in 2008 and 2009 to characterize performance, combustion stability, and turbine inlet hot gas temperature. It was tested first in a straight discharge duct configuration. It subsequently incorporated a more flight-like elbow and U-duct connecting the WHGG to the fuel turbine inlet simulator to understand the temperature distribution of hot gas arriving at the turbine inlet. Both 61- and 43-element injectors were tested with straight and 90-degree configuration chambers. It was also tested at conditions simulating the 294,000-pound (1,307 kN) primary thrust and 240,000-pound (1,067 kN) secondary power level. Test objectives included demonstrating:

- The GG pyrotechnic igniter
- GG fuel-and oxidizer-side purge
- Injector face heating
- Injector/chamber compatibility
- Verification of temperature uniformity of GG combustion products delivered to the fuel turbopump inlet flange and turbine nozzles
- GG spontaneous and dynamic combustion stability
- Validation of the database for computational fluid dynamics (CFD) analysis of the turbine drive subsystem.

It was also used to select a gas generator (GG) chamber length and injector element pattern. As a result of these tests, a new 43-element injector was made to increase the stability margin and was tested in 2009.

The WHGG was used again in 2009 to characterize the design solution for a secondary power level combustion stability issue. The series was added to resolve combustion-stability-induced vibration issues with the original design 78-inch (198.1 cm) hot gas discharge duct connecting the GG to the fuel turbine, an issue discovered during the previous WHGG testing. In order to understand and solve the problem, five shorter duct lengths were tested. Testing also incorporated the redesigned injector referenced above. The tests included 18 tests in a straight duct/single nozzle configuration and 14 tests in a straight duct configuration with a turbine simulator. A final test was run on the leading duct length candidate in a more flight-like configuration. The data indicated the duct length chosen mitigated the vibration issue and had negligible impact on temperature uniformity. Showing no indication of elbow erosion or distress, the new, shorter duct was chosen to go forward for testing in Power Pack Assembly 2 (PPA-2) and development engine E10001. A WHGG test is shown in figure 4.



Figure 4 – Workhorse Gas Generator testing at MSFC

A final series of tests is planned for summer 2010 to verify the GG injector with the discharge duct shortened and integrated into the engine design. This series will be the final component-level test for GG performance, temperature uniformity, and stability.

The J-2X nozzle extension is critical to gaining the performance needed for the Constellation missions. At 10 feet (3 meters) in diameter at the exit plane and nearly 8 feet (2.4 m) feet in length, this extension will be among the largest passively cooled nozzle extensions. It must survive vibration and thermal stresses from inside and external to the engine. Among the most severe are nozzle side loads caused by asymmetric pressure distribution in the nozzle, particularly during engine start and shutdown. The use of hydrogen-rich TEG film cooling and thermal emissivity coatings are also significant factors in ensuring that the metallic nozzle extension's environment does not exceed the metal's performance limits.

Subscale cold flow nozzle testing with an instrumented nozzle in 2006 and 2007 was used to characterize side loads. The testing optimized the J-2X nozzle to achieve minimum loading while maintaining maximum performance. These tests also helped determine design margins that affected weight and life, as well as performance.

Additional tests in 2009 were used to predict TEG film cooling performance for the nozzle extension. Air chilled to approximately 32 degrees F (0 degrees C) was used as the coolant with static pressure measurements along the extension. The tests anchored CFD analysis for the TEG flow. However, uncertainty remains regarding TEG flow performance and nozzle extension cooling effectiveness. This risk will be carried into engine testing. The subscale cold flow nozzle test rig and details of sensor installation are shown in figure 5.

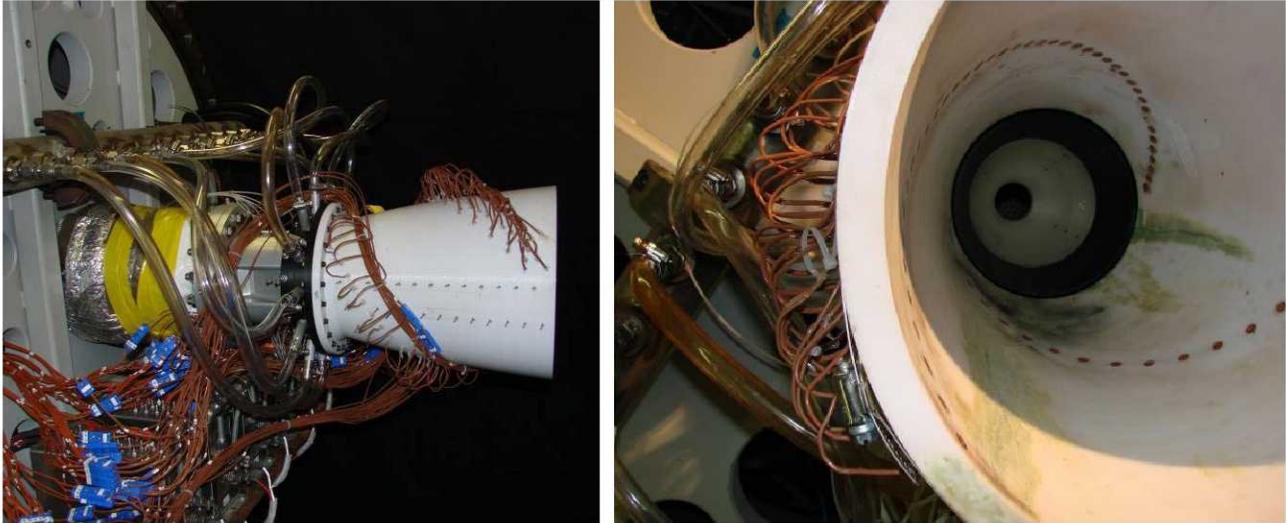


Figure 5 – Instrumented subscale cold flow nozzle test rig, left, and nozzle sensor installation, right

Thousands of hours of supercomputer time have been devoted to the design of the TEG manifold, related interfaces on the nozzle extension and their predicted performance. The heritage J-2 used turbine exhaust dumped into the regeneratively-cooled nozzle to provide some marginal cooling and efficiency. Unlike that application, turbine exhaust in the J-2X is injected supersonically via the manifold. In the design process, computational analysis was used to balance engine and manifold structural margins against cooling efficiency. The design incorporates internal flow features to better distribute the gas around the manifold. Several CFD methods were developed as the design progressed. The predicted result is a gain of 25-30 percent cooler wall temperatures and a gain of about 1 percent in Isp. While analysis continues, the ultimate validation of computer methods will be gained via full engine testing, where infrared (IR) cameras will be trained on the extension and pressure transducers will be installed on the TEG manifold itself. Figure 6 shows an image of cooling effectiveness testing from subscale cold flow testing.

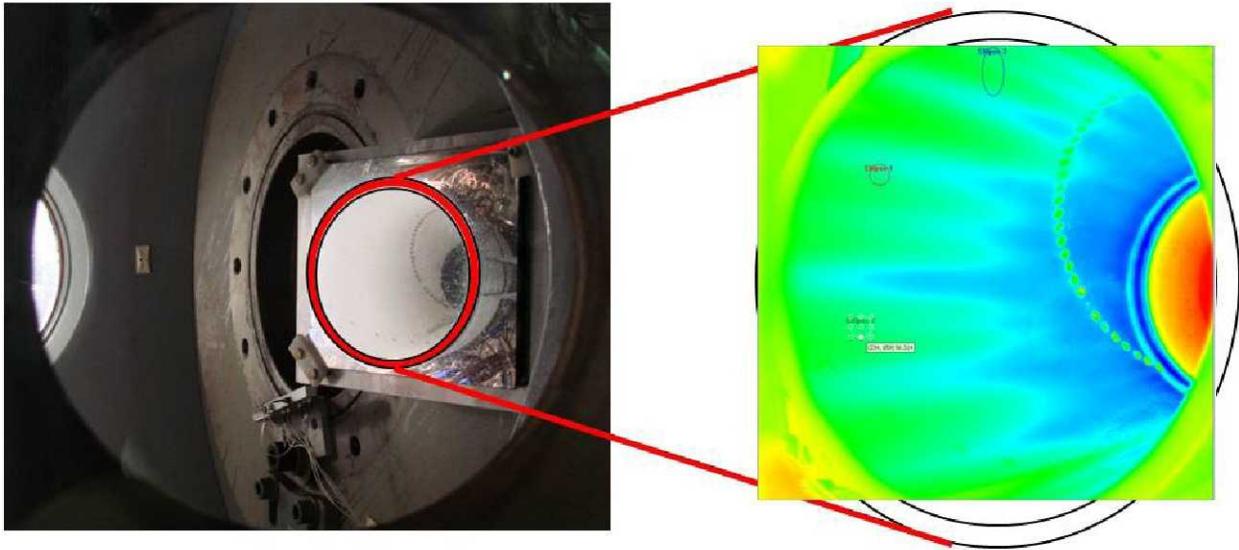


Figure 6 – Subscale cold flow TEG cooling tests showing the test article, left, and corresponding IR image, right

In addition to TEG cooling, the metal nozzle extension employs commercially-available thermal emissivity coatings on its inner and outer surfaces to withstand operating temperatures in excess of 2,000 degrees F (1,093.3 degrees C). The coating must also endure 500 seconds of operating time on Ares I and 1,000 seconds of operating time on the Ares V. Seven candidate materials were selected for testing in 2009 and 2010 to characterize their thermal performance and durability. The candidates were reduced to two for further tests in 2010, with one coating selected as the baseline design for the nozzle extension. The nozzle extension service life is 1,600 seconds and 6 starts. The required certification time is twice the rated service life, or 3,200 seconds and 12 starts. The candidate coatings were tested to show they could meet the service life, and the down-selected coatings were tested to the required certification time.

The coatings were sprayed on several 6x10-inch (15.2 x 25.4 centimeter) samples of Haynes 230 aluminum machined to the same thickness and orthogrid geometry of the full nozzle extension. During the series, different batches of coatings were applied to the panels to determine if coating performance were subject to random variables in manufacturing. A coated test panel is shown in figure 7.

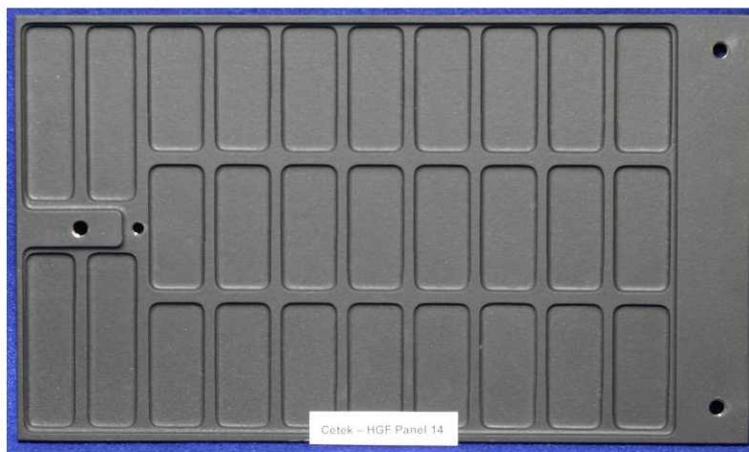


Figure 7 – Nozzle Extension thermal emissivity coating test panel

Engineers also tested the ability to repair coating defects that might occur during extension fabrication or during engine testing. Thermocouples, heat flux gauges and other high temperature instrumentation was tested as part of the emissivity series.

A separate test series on the upper stage ullage settling motors for Ares I provided an additional opportunity to subject the coatings to possible motor plume impingement. The ullage motors use solid propellant, and the exhaust plume contains relatively large, high-speed particles, essentially sand-blasting any surface that it encounters. Post-test inspection showed that the coatings survived the exposure, with no indications of erosion and no changes in pre- and post-test emissivity.

The J-2 Mk 29 turbopumps serve as the point of departure for the J-2X turbomachinery in order to minimize development risk. J-2X relies on high technology readiness level (TRL) technology with flight experience, together with high-order analyses. The J-2X design challenge has perhaps been most acute for turbomachinery for four reasons: the constrained Mk. 29 pump design baseline; the higher thrust and Isp requirements demanding higher flow rates and the resulting associated environments; contemporary design standards, such as considering alternating stresses, resulting from lessons learned in the years since the J-2 was developed; and new, more refined computer analysis techniques, not yet verified through testing.

The design of the fuel turbopump (FTP) has been perhaps the most challenging to design because it experiences a significant increase in operating environment to meet the engine needs of increased thrust and Isp requirements. The LOX pump faces a less harsh environment, but the higher fluid density places particular stress on the inducer and impeller. Design solutions in response to these increased operating requirements have been extensive. For example, CFD analysis indicated low rotordynamic stability margins in the fuel turbopump, which drove the decision to employ hydrostatic bearings, successfully tested by NASA and the Air Force but never employed in a flight engine.

With that background and those challenges in mind, the J-2X team has performed numerous tests to refine turbomachinery design and mitigate the risk of development engine testing. This section summarizes some of the more significant tests.

The heritage starting point combined with modern analytical techniques resulted in the incorporation of a new technology, hydrostatic bearings (HSB), into the J-2X design. It is the first use of hydrostatic bearings in a development engine. Based on rotordynamic analysis tools used by PWR and NASA, the design team realized at the concept design review (CoDR) there was not enough rotordynamic margin by contemporary standards on the turbine end of the heritage J-2S fuel turbopump (FTP). By floating the turbine shaft on a film of LH² injected into the bearing, vibrational modes and the resulting wear are virtually eliminated, enabling high reusability, an important benefit in this hardware-constrained development program. The addition of HSB technology to the J-2X was based largely on the Integrated Powerhead Demonstration (IPD) engine developed jointly by the Air Force and NASA and test fired nearly 30 times in 2005 and 2006. This background, verified by the J-2X development test plan, gives the design team confidence that HSBs will perform successfully in its first flight engine application.

PWR performed subscale fuel inducer water flow tests, while NASA/MSFC performed subscale LOX inducer water flow tests to assess inducer steady and unsteady performance. The heritage shrouded three-bladed inducer was tested, along with alternate configurations. As a result of testing, the LOX pump inducer design was modified to a more contemporary two-bladed un-shrouded design.

PWR also conducted "whirligig" tests of heritage J-2S fuel turbine first stage using a modified disc and heritage turbine blades to verify the fundamental modes for predicted high cycle fatigue (HCF), as well as the design for blade dampers to attenuate higher-order modes. The final damper design will be verified in whirligig testing in 2010 and the design incorporated into J-2X PPA-2 on both pumps.

Interpropellant (IP) seal testing on the LOX pump was performed at MSFC to verify the new helium buffer design and materials before selecting a new seal package to replace the obsolete design and materials. Some of the turbomachinery tests noted above are shown in figure 8.

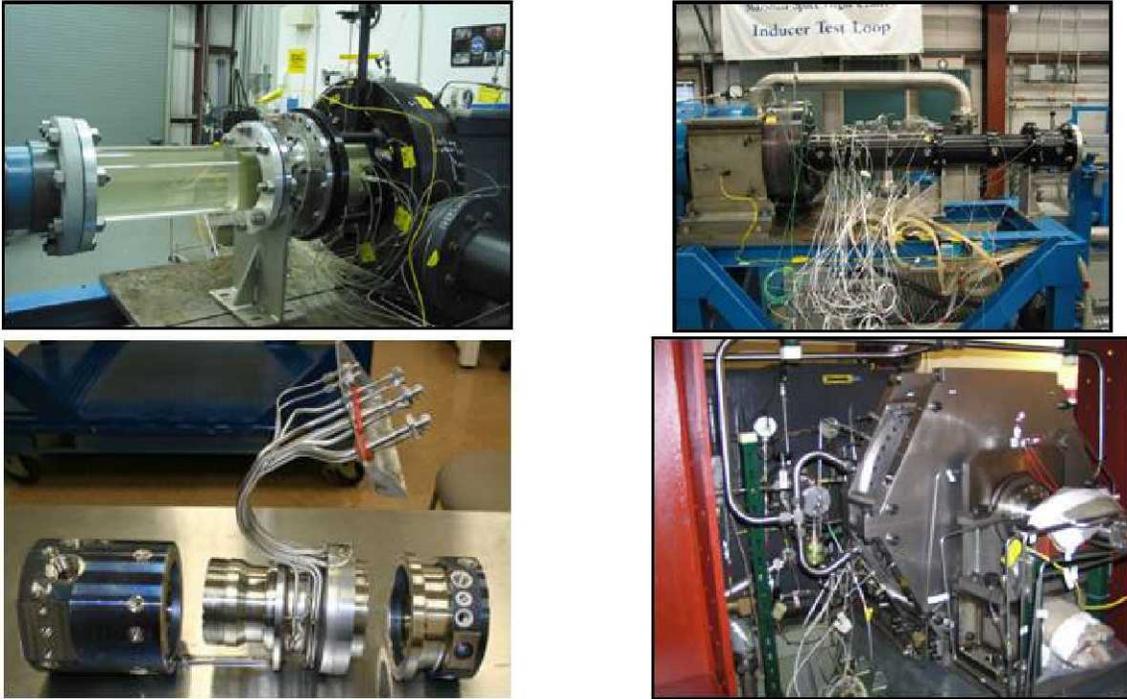


Figure 8 – Turbomachinery testing, clockwise from upper left: PWR waterflow test, MSFC waterflow test, PWR whirligig test, PWR seal tester

The Powerpack Assembly-1 (PPA-1) test series from December 2007 through May 2008 went beyond component-level testing to re-establish the baseline performance of heritage J-2 turbopumps, helium spin start, gas generator, heat exchanger, spark igniter and inlet ducts as input to the new J-2X environments. A total of six “hot-fire” tests were conducted. The government/industry engine team amassed more than 1,343 seconds of powerpack operating time at power levels up to an equivalent 274,000 pounds (1,219 kN) of thrust. The series helped resolve differences in heritage turbopump performance data and recent component-level tests. It investigated the performance of the engine inlet scissor ducts. An additional suction performance test was conducted on the oxidizer turbopump (OTP) during the last powerpack test to explore the effects of helium ingestion on the suction performance as a risk mitigation test for the pogo suppressor. That work will come full circle when PPA-2, the heart of the new J-2X engine, will be hot fired in a 25-test series planned for February 2011. PPA-1 testing is shown in figure 9.



Figure 9 – Power Pack 1A testing at Stennis Space Center

The most recent turbomachinery test series is the J-2 Heritage Fuel Airflow Turbine Test (HFATT) series in 2010. This new tool is the most heavily instrumented turbine air flow test rig NASA has ever employed. It was used to characterize turbine performance and load environments for anchoring turbine gas CFD modeling, particularly important for a constrained hardware and test budget. The test rig simulated full scale J-2 fuel heritage primary flow path, including inlet manifold and disk cavities, with emphasis on sensor installation on the first and second stage blades and rotor disks. HFATT provided steady and unsteady pressure mapping of the turbine blade environments and measured the contribution of interstage cavity pressures to turbine axial thrust. Operating conditions tested included spin start, engine start, the required 274,000 lb and 294,000 lb thrust levels, and engine shutdown. A total of 90 rotating dynamic measurements and 38 stationary dynamic measurements were collected via instruments on the two rotor stages, the backing cavity above the turbine blades, and the disc cavities. Details of HFATT sensor instrumentation are shown in figure 10.



Figure 10 – HFATT test hardware clockwise from upper left: 1st rotor blades (40 sensors), 2nd rotor blades (30 sensors), Intermediate Stator (23 sensors), Turbine Manifold (8 sensors)

While the major components discussed above are critical to the engine’s success, many smaller mechanical and electrical components must work flawlessly as well. For instance, the J-2X employs 43 valves and actuators. Also critical are engine avionics, including the Engine Control Unit, Pneumatic Control Assembly, Main Igniter Exciter Unit, Engine Data Acquisition Unit, and software.

In all cases, the challenge facing the team was designing controls/valves/instrumentation (CVI) hardware to accommodate the higher pressures and temperatures associated with the J-2X performance requirements and the larger physical dimensions of the hardware. Risk mitigation testing in the form of flow tests and cycle tests informed main valve design. Development testing started in fiscal 2010 on main valves and ancillary valves. Much of the design and testing in CVI was related to two new valves the Oxidizer Turbine Bypass Valve (OTBV) and the Helium Spin Start (HSS) valve. Neither of these valves was present in the X-33 engine hardware on which the J-2X hardware is based.

Unlike the fuel or oxidizer valves, the OTBV valves are subject to temperatures ranging from minus 400 degrees (LOX) to 750 degrees for hot exhaust gas in the span of one second. Altering the engine mixture ratio, via the OTBV is the primary means of generating the engine’s secondary thrust level driven by the Ares V TLI engine requirement. Sealing requirements, flow area versus valve position require tight tolerances. The OTBV is hit from a blast of -423 degrees F to 750 degrees F and then back to -423 F during a fuel rich shut down. It uses a new seal material, Vespel 211 by Dupont, that works well at cryogenic temperatures. The OTBV seal material testing was done mainly by PWR with molecular testing at MSFC.

The key to ensuring the operation of these devices is the new Hardware In the Loop Lab (HILL) at MSFC. It will support software validation and verification test work. It will provide a test bed for initial integration of J-2X control and monitoring hardware and software, system level testing, control system anomaly resolution, and as the propulsion component for the Upper Stage’s Systems Integration Lab/System Integration Test Facility. It also will perform system testing to verify system level requirements such as system timing and functional validation. The HILL will deploy four software test methods for ECU software testing: analog fault insertion, digital fault insertion, software trace ability, and software test patch.

Design of the 1,400 square feet facility was completed in July 2008 and construction was completed in 2009. Activation began in 2009 and is continuing in 2010. Full operating capability is planned for July

2011. Prototype hardware has been delivered for testing. Software coding is nearly complete. Software/hardware integration testing and instrumentation development testing is under way. Engine control system verification planning is also ongoing. Features of the lab are shown in figure 11.



Figure 11 – Avionics hardware undergoing tests in the HILL at MSFC

The engine team has called on best practices and used expertise and facilities wherever it was most advantageous. This included testing by Marshall Center engineers in Marshall facilities through government task agreements (GTA) with PWR. That testing, including some mentioned above has included:

- Material Testing
- Oxygen Compatibility Assessment
- High Speed Data Acquisition & Process
- Inlet Duct Heater Test
- Control System Testing
- Simulation Interface Adapter
- Pressure Test on Vented Microswitch
- Heritage Valve Testing
- Disassembly Tooling
- Air Flow Testing
- Seal Testing
- Water Flow Testing
- 40K Injector Subscale Test
- 52-Element Subscale Injector Test
- MCC Augmented Spark Igniter Test
- GG Workhorse Design Test
- Subscale Cold Flow Nozzle Side Loads Test
- Subscale Cold Flow Nozzle TEG Flow Test
- Thermal Emissivity Coating Test

IV. TEST FACILITIES

Three test stands at Stennis Space Center (SSC) will support J-2X system level development. The A1 stand was used for PPA-1 testing in 2008. It is undergoing modifications to support PPA-2 testing beginning in February 2011. Lessons learned in PPA-1 testing are being incorporated, such as the impact of flow-induced loads on facility piping that required additional support. A new thrust frame, a new thrust measurement system and an improved control system have been installed. Facility pump discharge piping and feed line designs were altered to accommodate the different test article configurations for PPA-2 and J-2X engines.

The A2 stand, which supported the Apollo Program and the SSME Program, was made available to the J-X program in April 2010 to begin refurbishing to support accelerated development of the J-2X. Propellant transfer lines to the run tanks will be replaced in 2010. A2 will perform development and certification engine testing for J-2X engines. It will provide a pseudo-altitude capability using a passive diffuser. Engine configuration is limited to the regenerative nozzle without nozzle extension or the regenerative nozzle and a lower-area-ratio “stub” nozzle extension, and no gimbal capability. Test stands A1 and A2 are shown in figure 12.



Figure 12 – Stennis test stands A2, (foreground) and A1 (background) during an SSME test

Much of the effort at Stennis remains focused on construction and activation of the new A3 test stand. This unique new national capability will support high-altitude, full-duration, full-gimbal development and certification testing of large liquid rocket engines such as the J-2X. It will support nozzle extension development and certification and engine performance verification. It can simulate altitudes of 80,000 to 100,000 feet and support operating times of up to 500 seconds. Altitude simulation is accomplished via a steam injector system in the diffuser, fed by chemical steam generators making the steam by burning isopropyl alcohol (IPA) and LOX.

The foundation and structural steel for the tower are complete, as well as stairs, platforms, handrails, and much of the lighting. The barge docks are complete. The shop building foundation is in place. The IPA unloading dock is complete. Lines and piping were being installed at the time this paper was drafted. Three LOX tanks, two IPA tanks, and six of nine planned water tanks, were installed beside the stand as of early 2010. The A3 isolation valves, test cell, diffuser and chemical steam generator (CSG) cans are in various stages of fabrication. Hydrogen transfer lines from the barge dock to the stand and the LOX and LH² facility run tanks will be installed in 2010. The stand will use nine “skids” of 3 chemical steam generator (CSG) cans each. The first skid was due to go to the E2 test complex for testing in 2010 before being moved to the stand. The thrust measurement system (TMS) is on the site awaiting installation. Gaseous nitrogen bottles to be used by the chemical steam generators also will begin installation in 2010. The 32 bottles will provide pressurization gas needed by the generators. Subscale diffuser testing in the SSC E3 complex and CSG testing in the E2 complex were completed in 2009, demonstrating the method to be used to demonstrate A3’s altitude simulation method. Construction

and activation of A3 is scheduled to be completed in late 2011, pending the outcome of space policy decisions in Washington. Progress on the A3 stand is shown in figure 13.



Figure 13 – SSC A3 test stand construction clockwise from top left: tower and barge docks; LOX, water, and isopropyl alcohol tanks; test cell door frame; and test cell head with workers

V. DEVELOPMENT ENGINE HARDWARE AND TESTING PLANS

The J-2X team has set an ambitious goal of completing the first development engine, designated 10001, by Dec. 24, 2010 and PPA-2 by January 15, 2011. The J-2X development plan calls for a total of 223 engine tests 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 HILL
- 1 control system for the Ares System Integration Lab
- Various engine support hardware, manufacturing technology demonstrators, and component test articles.

As an interesting historical note, the Saturn program had at its disposal 38 development J-2 engines through certification. There were approximately 2,600 J-2 tests, which accumulated a total of 33,579 seconds of hot fire time, according to historical records. Additionally, there were 6 development J-2S engines. They underwent 265 tests for a total duration of 21,400 seconds. Because the engine had an idle mode, an additional 6,900 seconds of test in idle mode were recorded.

J-2X development will include an order of magnitude fewer tests than original J-2 development. However, due to the J-2X heritage starting point, propulsion development since then, modern computational analysis, and PWR’s recent experience with its RS-68 development, the engine team is confident that this test program is prudent and will provide an upper stage engine fully qualified for human flight. In fact, the planned J-2X development testing is about the same as the RS-68 development test program.

VI. DEVELOPMENT ENGINE HARDWARE MANUFACTURING

The J-2X development engine program currently employs nearly 500 PWR engineers and technicians and more than 1,200 suppliers across the United States, as well as Japan and Puerto Rico. To date, approximately 100,000 pieces of hardware, mainly for PPA-2 and development engines 10001, 10002 and 10003, are completed or in various stages of manufacture to support powerpack and engine testing in 2011. Critical to the team’s goal of completing Engine 10001 by Dec, 24, 2010 and PPA-2 in January 2011, numerous major parts for both engines are in advanced stages of completion for shipment to Stennis Space Center for assembly.

Assembly of the 10001 regen nozzle assembly is under way with the forward base ring fully alloyed for braze, all three flatbands ready for plating, the turbine exhaust manifold base ring in machining, and the tubes are fully alloyed for braze. The main injector is rapidly approaching braze assembly with the interpropellant plate received, the LOX dome near complete, Lox post assemblies in stock, and ASI ready for braze. The main combustion chamber (MCC) is quickly approaching braze

assembly operations. Jacket machining is complete. The throat support halves and shear pins are ready for plating. The liner is slotted and ready for plating. Complex assembly of the FTP for Engine 10001 was under way as of late April 2010, and complex assembly of the OTP assembly was scheduled to begin within 30-60 days. Examples of major components manufactured to date for 2011 hot fire tests are shown in figure 14-16.



Figure 14 – 10001 MFV housing, 1001 MOV housing, FTP turbine manifold



Figure 15 – 10001 OTP volute, PPA-2 FTP volute, 10001 MCC jacket



Figure 16 – Two views of first development engine regeneratively-cooled nozzle tube stack

VII. CONCLUSION

NASA's Upper Stage Engine team was given some broad parameters – thrust, Isp, reliability – and a starting point – the proven J-2 and J-2S with upgrades as necessary to perform the Constellation mission for two launch vehicles. It was up to the team to fill in the details and develop a propulsion system. The engine team tested heritage hardware to recapture lost knowledge and measure the components against the new requirements. The team has made extensive use of computational analysis techniques unavailable even a few years ago, and then anchored that analysis to testing of subscale, workhorse, and candidate development components. While national leaders are now considering alternatives for the future of U.S. human space flight, the J-2X represents a capability that will be ready to serve any new direction in the human exploration of space.



From Paper to Production: An Update on NASA's Upper Stage Engine for Exploration

Space Propulsion 2010
May 3-7, 2010

Mike Kynard,
Manager
*Upper Stage Engine Element,
Ares Project Office*





J-2X Behind the Design



◆ Mission:

Common upper stage engine for Ares I and Ares V

◆ Key Features:

- LOX/LH₂ GG cycle
- Series turbines with throttle capability through Lox turbine bypass
- Open loop, pneumatically actuated valves
- On-board engine controller and health monitoring
- Tube-wall regen nozzle/large passively-cooled nozzle extension, turbine exhaust gas boost/cooling
- Helium spin start – with on-orbit restart capability

◆ Development Philosophy:

Evolved hardware and mature technology where possible, aggressive schedule, early risk reduction testing, 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 Flow

- 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 Design Heritage



MK 72 Turbomachinery

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

Gas Generator

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

Engine Controller

- Based directly on RS-68 design and software architecture

Tube-Wall Regeneratively-Cooled Nozzle Section

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



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



Component and Subscale Testing



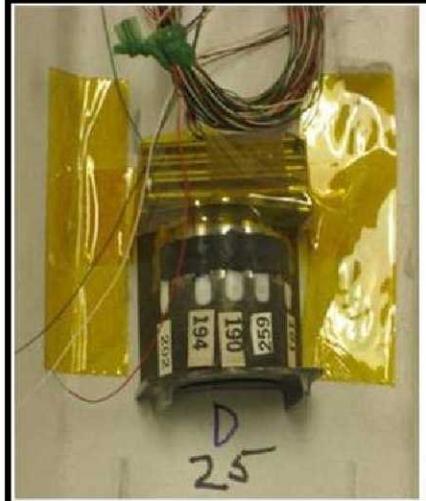


Powerpack 1 Testing at Stennis Space Center





Turbomachinery Testing



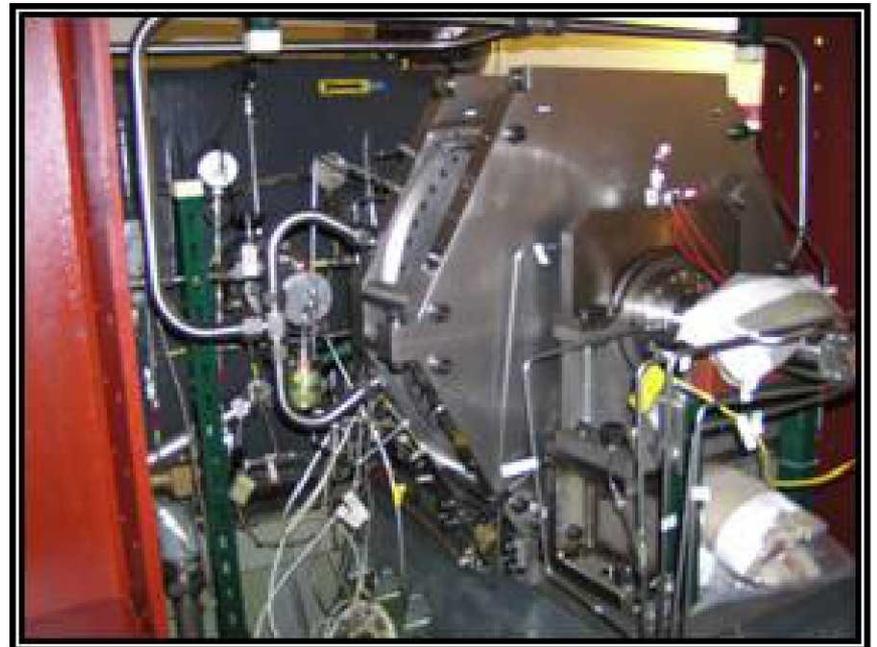
Bearing Tester



Intermediate Seal Tester



Turbomachinery Testing (cont'd)





Subscale Main Injector Testing, MSFC



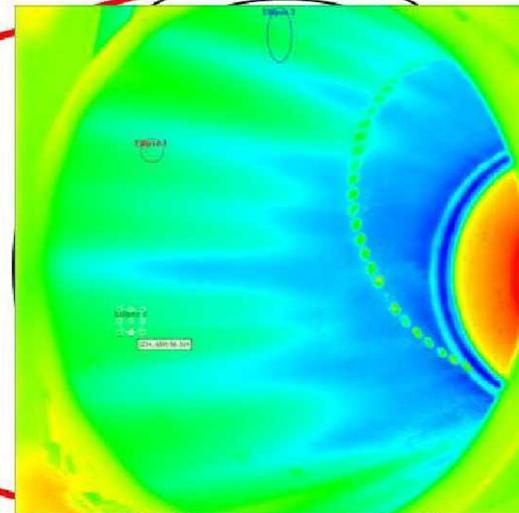
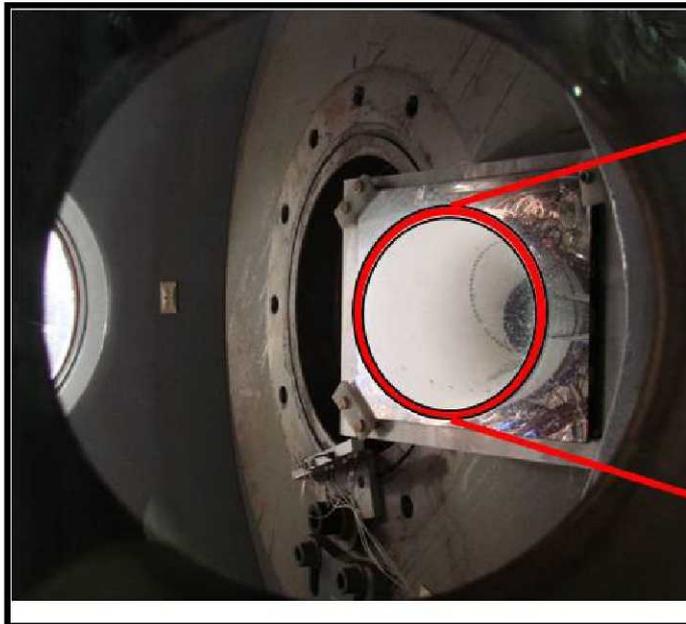
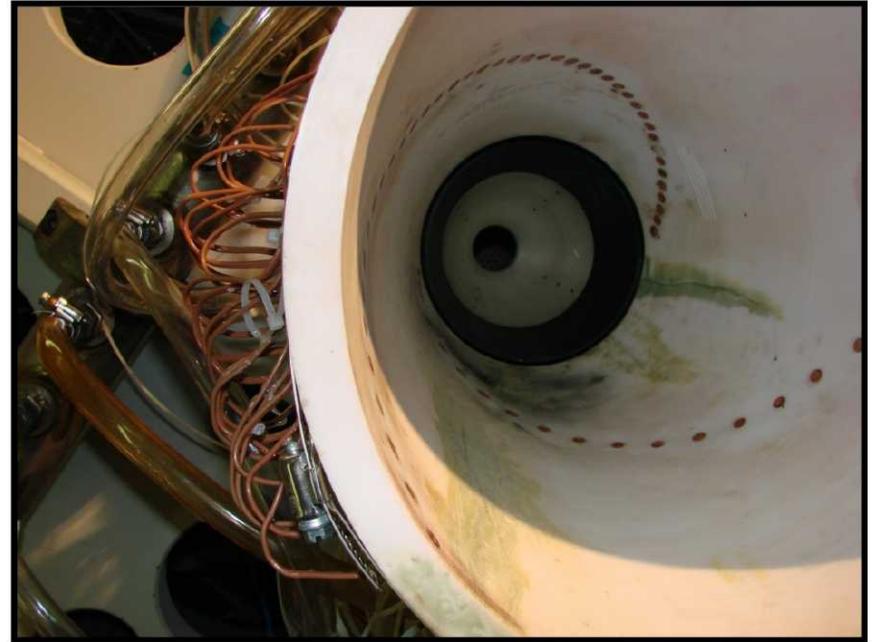
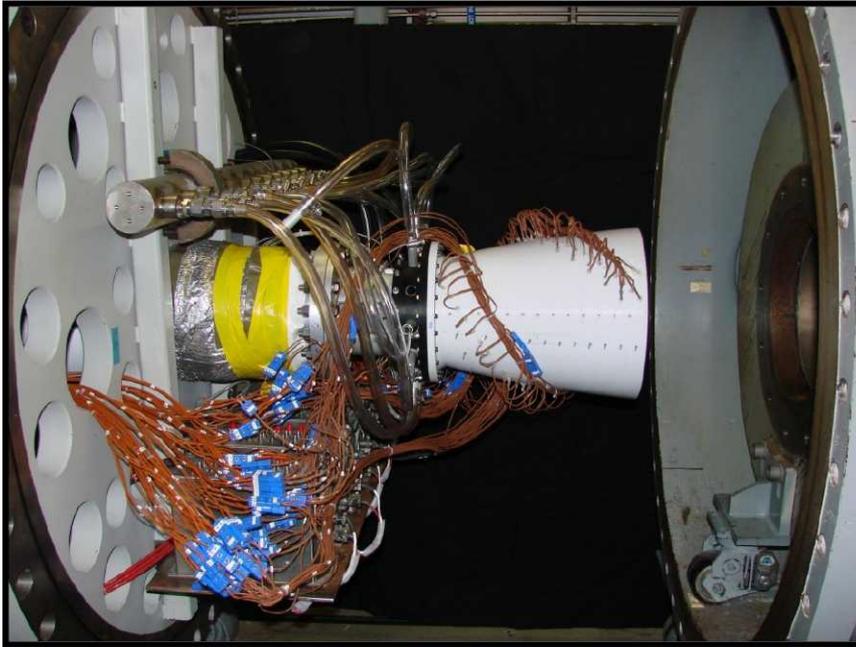


Workhorse Gas Generator Testing at MSFC





Nozzle Extension Testing at MSFC



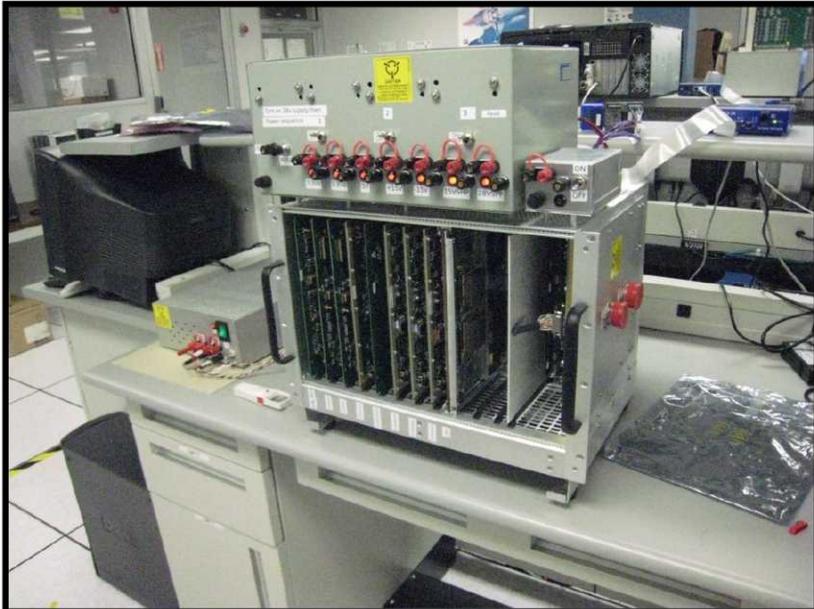


Nozzle Extension Thermal Emissivity Coating Tests at MSFC





Hardware In the Loop Lab (HILL)



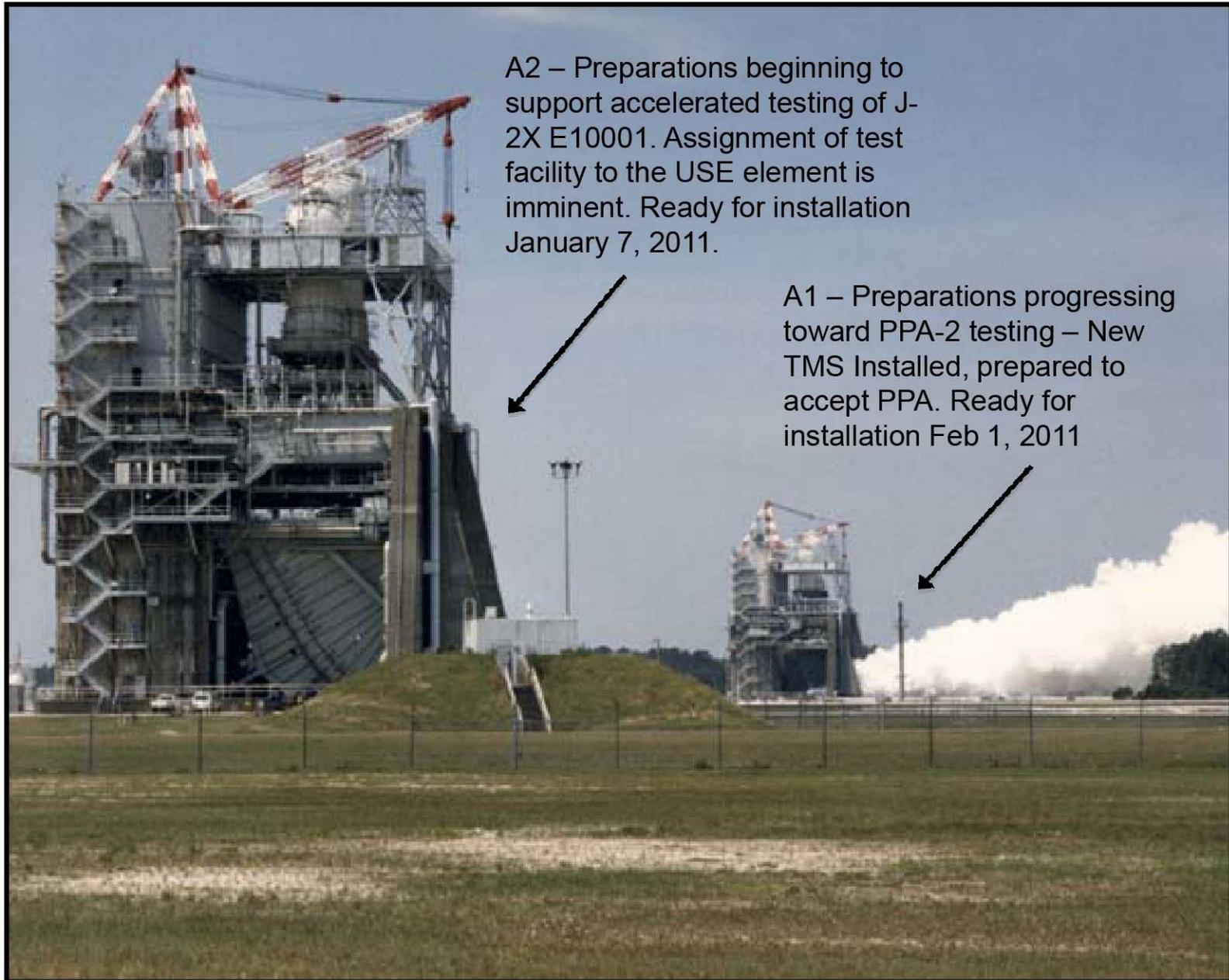


Large Scale Test Facility Readiness





A1 & A2 Test Stands (SSC)



A2 – Preparations beginning to support accelerated testing of J-2X E10001. Assignment of test facility to the USE element is imminent. Ready for installation January 7, 2011.

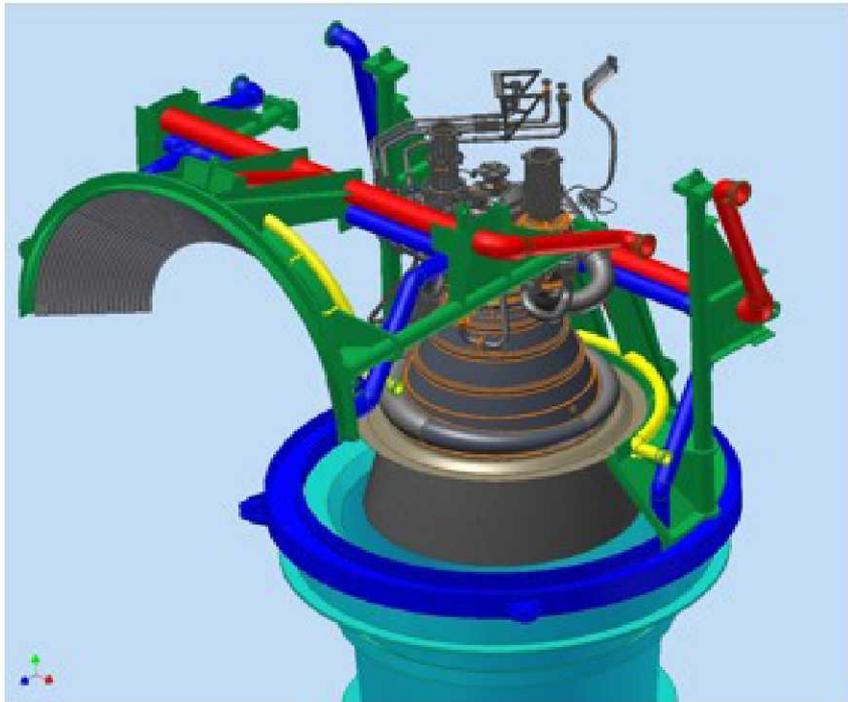
A1 – Preparations progressing toward PPA-2 testing – New TMS Installed, prepared to accept PPA. Ready for installation Feb 1, 2011



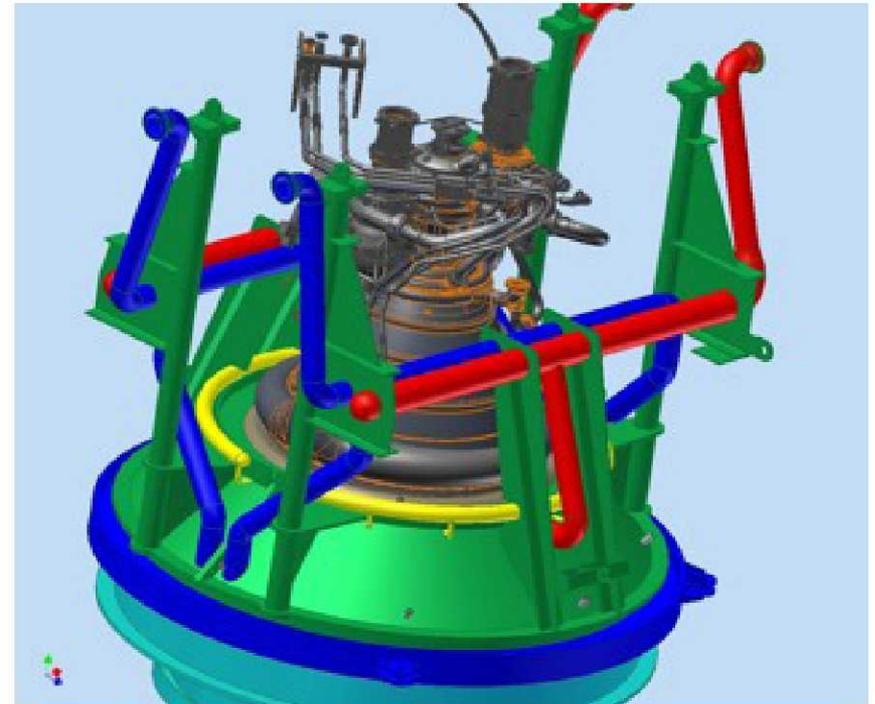
Test Facilities: A2 Clamshell Modifications



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



Open



Closed

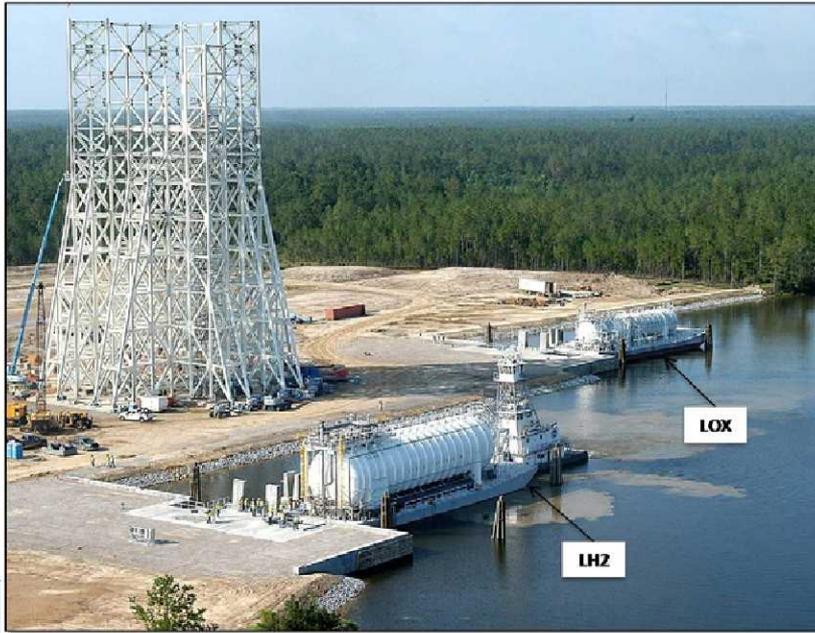


A3 Test Stand





Test Facilities: A3 Construction





Hardware Manufacturing Progress





Engine Hardware – Established at CDR 2008



◆ 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 Hardware in the Loop Laboratory

◆ 1 Control System for Ares SIL

◆ Engine Support Equipment

◆ Manufacturing Technology Demonstrators

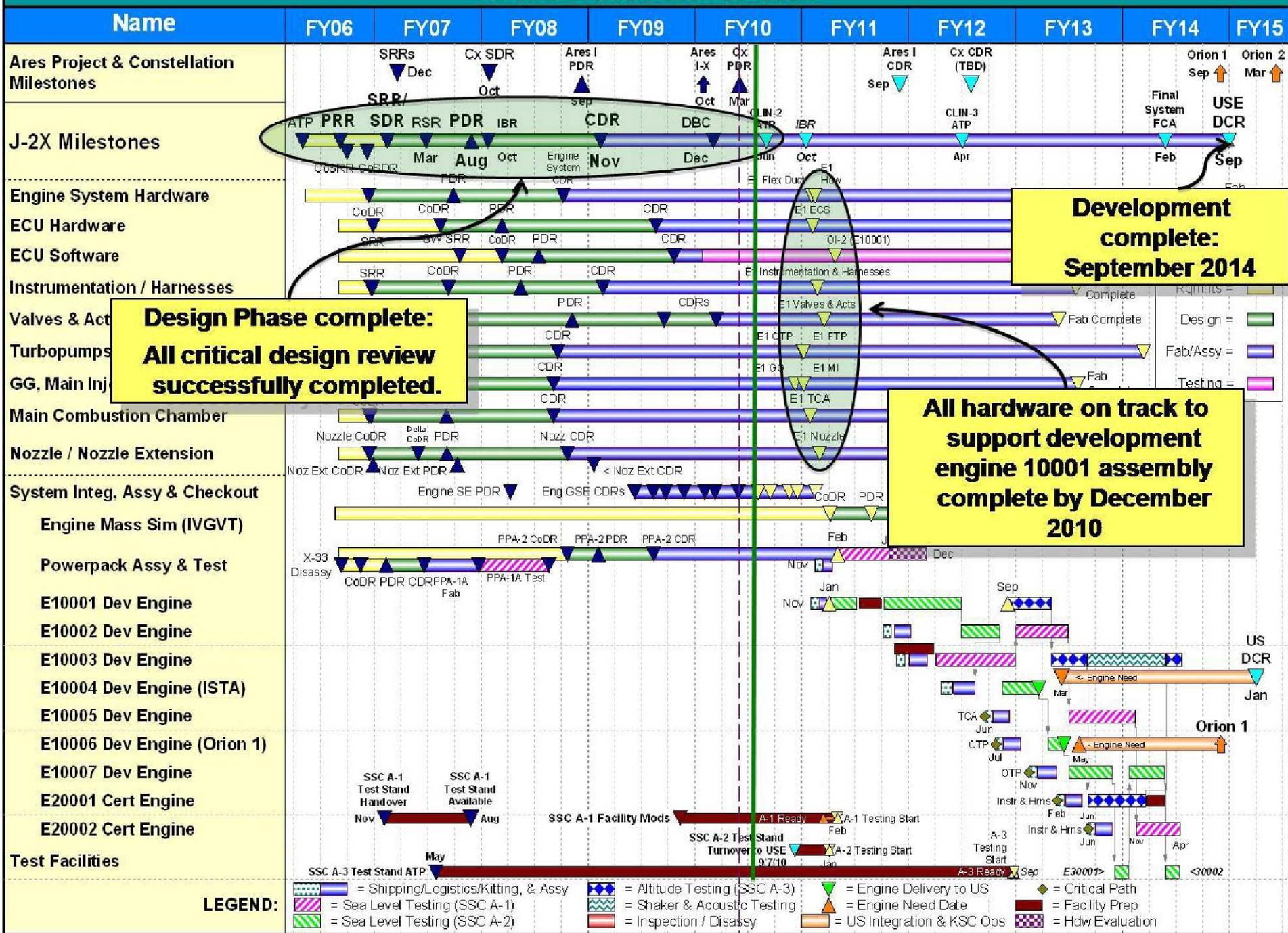
◆ Component Test Articles

Total 223 engine tests as follows:

- 132 development tests
- 32 certification tests
- 7 tests/flight - first Ares I test flight
- 15 tests as a part of Upper Stage Integrated Stage Test Article
- 17 contingency tests
- 20 rework tests

Ares Upper Stage Engine (J-2X) DDT&E Major Milestones Summary Schedule (As of 4/8/10)

Hardware Acceleration Schedule



**Design Phase complete:
All critical design review
successfully completed.**

**Development
complete:
September 2014**

**All hardware on track to
support development
engine 10001 assembly
complete by December
2010**

- LEGEND:**
- [Blue hatched] = Shipping/Logistics/Kitting, & Assy
 - [Green hatched] = Sea Level Testing (SSC A-1)
 - [Red hatched] = Sea Level Testing (SSC A-2)
 - [Blue diamond] = Altitude Testing (SSC A-3)
 - [Green wavy] = Shaker & Acoustic Testing
 - [Red wavy] = Inspection / Disassy
 - [Green triangle] = Engine Delivery to US
 - [Orange triangle] = Engine Need Date
 - [Red triangle] = Facility Prep
 - [Green diamond] = Critical Path
 - [Red triangle] = Facility Prep
 - [Red wavy] = Hdw Evaluation



Complex Hardware Work at PWR: MCC, GG, & Valves



10002 jacket forging now machined and ready for EB weld to manifolds



10001 MCC Jacket Assembly – finish machined and ready for HIP prepping



10001 MOV housing during high speed rough machining via ceramic inserts



10001 MOV housing in final machining operation



10001 MCC Throat Support Halves - ready for plating



10001 MCC Jacket ready for etch and pent of EB welds



10002 MCC Jacket ready for VTMC final machining



10001 MFV Housing during rough machining – now ready for final machining



10003 MCC FWD Manifold in machining



10001 MCC Jacket – note the machined coolant holes



10001 MCC Throat Support Shear Pins – plating in process (5 of 12 complete)



10001 MOV housing in final machining



Complex Hardware Work at PWR: Turbomachinery



**10001 FTP Turbine Manifold –
clean and heat treat**



**10001 OTP Volute – final
machined, in deburr, next to
clean, dim inspect, pent**



**10001 Volute- final
machined, pressure test
completed awaiting Pent**



**10001 OTP Turbine Manifold –
ready for torus welding**



**PPA-2 OTP Volute casting –
beginning detailed machining**



**PPA-2 FTP Volute – Finish
machining on VTMC**



**PPA-2 OTP Turbine Manifold
– x-ray of nozzle EB weld,
then machine torus weld
preps**



Complex Hardware Work at PWR: Regen Nozzle



**Strongback fwd section –
final machining**



**Trimming pressure bags for
strongback braze tool**



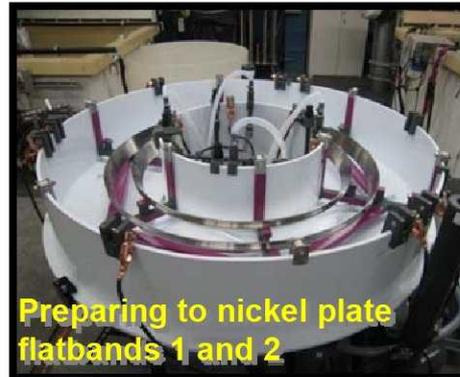
Nozzle tube stack complete



**Strongback mid-section –
final machining**



**Preparing to nickel plate
flatbands 1 and 2**



**FWD base ring
fully alloyed**



Flatband 3 ready for plating





Major Components: Nozzle Extension



Ares I Upper Stage Engine (J-2X) Assembly & Test Summary Schedule

USE Hardware Acceleration Schedule (As of 4/8/10)

