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ABSTRACT INFORMATION

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The J-2X Upper Stage Engine (USE) will be the first new human-rated upper stage engine since the Apollo program of the 1960s. It is designed to carry the Ares I and Ares V into orbit and send the Ares V to the Moon as part of NASA's Constellation Program. This paper will provide an overview of progress on the design, testing, and manufacturing of this new engine in 2009 and 2010. The J-2X embodies the program goals of basing the design on proven technology and experience and seeking commonality between the Ares vehicles as a way to minimize risk, shorten development times, and live within current budget constraints. It is based on the proven J-2 engine used on the Saturn IB and Saturn V launch vehicles. The prime contractor for the J-2X is Pratt & Whitney Rocketdyne (PWR), which is under a design, development, test, and engineering (DDT&E) contract covering the period from June 2006 through September 2014. For Ares I, the J-2X will provide engine start at approximately 190,000 feet, operate roughly 500 seconds, and shut down. For Ares V, the J-2X will start at roughly 190,000 feet to place the Earth departure stage (EDS) in orbit, shut down and loiter for up to five days, re-start on command and operate for roughly 300 seconds at its secondary power level to perform trans lunar injection (TLI), followed by final engine shutdown. The J-2X development effort focuses on four key areas: early risk mitigation, design risk mitigation, component and subassembly testing, and engine system testing. Following that plan, the J-2X successfully completed its critical design review (CDR) in 2008, and it has made significant progress in 2009 and 2010 in moving from the drawing board to the machine shop and test stand. Post-CDR manufacturing is well under way, including PWR in-house and vendor hardware. In addition, a wide range of component and sub-component tests have been completed, and more component tests are planned. Testing includes heritage powerpack, turbopump inducer water flow, turbine air flow, turbopump seal testing, main injector and gas generator, injector testing, augmented spark igniter testing, nozzle side loads cold flow testing, nozzle extension film cooling flow testing, control system testing with hardware in the loop, and nozzle extension emissivity coating tests. In parallel with hardware manufacturing, work is progressing on the new A-3 test stand to support full duration altitude testing. The Stennis A-2 test stand is scheduled to be turned over to the Constellation Program in September 2010 to be modified for J-2X testing also. As the structural steel was rising on the A-3 stand, work was under way in the nearby E complex on the chemical steam generator and subscale diffuser concepts to be used to evacuate the A-3 test cell and simulate altitude conditions.

TESTING TO TRANSITION THE J-2X FROM PAPER TO HARDWARE

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ABSTRACT

The J-2X Upper Stage Engine (USE) was selected in 2006 to power the Ares I Upper Stage and the Ares V Earth Departure Stage as part of NASA's Constellation Program. 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 launchers, and other programs to perform the Constellation reference missions and provide an order of magnitude greater safety. It required the J-2X government/industry team to develop the highest performance engine of its type in history, develop it faster than any similar engine in the past, and to use it for two vehicles with two different missions, retaining as much commonality as possible. 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 experimental and development engine parts are completed or are in various stages of manufacture. Approximately 1,300 of more than 1,600 engine drawings were released for manufacturing. A major factor in the J-2X development approach is testing 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's prime contractor, Pratt & Whtiney Rocketdyne (PWR), and by NASA engineers under government task agreements (GTAs) with PWR. This body of work together increases the likelihood of success as the team prepares for powerpack and development engine hotfire testing in calendar 2011. This paper will discuss the J-2X development philosophy and provides top-level information on testing to support design and manufacture.

1.0 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. Among the guiding principles for that development 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.

As part of NASA's Constellation Program, the Ares Projects, managed by NASA's Marshall Space Flight Center (MSFC), is designing, building, and testing the launch vehicles to put explorers in 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. The J-2X is designed to power the Ares I and Ares V upper stages during ascent, with kitting modifications as needed to support the loiter and TLI phases of the Ares V mission.

The expendable J-2X is based on the Apollo-era J-2 engine. It replaced a modified Space Shuttle Main Engine (SSME) as the upper stage engine of choice for the Ares vehicles because a study showed that it had less development risk and a lower development and recurring costs than modifying the reusable SSME to be an expendable altitude start engine. The current J-2X configuration is shown in figure 1.

Figure 1 – The J-2X Upper Stage Engine artist's concept.

The J-2X challenge is to use proven technology as feasible from the Saturn, X-33, RS-68, and other contemporary programs to develop an engine based on a gas generator operating cycle that is relatively less complex and expensive than a staged combustion engine such as the SSME, yet still approaches staged combustion efficiency. It must generate 35 percent more thrust than its proven predecessor. It must use modern construction standards to improve overall safety by an order of magnitude over the SSME. Further, the team must develop it in record time with finite resources.

The J-2X is a liquid oxygen/liquid hydrogen (LOX/LH2) engine. It uses series turbines, a HIP-bonded main combustion chamber (MCC), pneumatic ball-sector valves, on-board engine controller, a tube-wall regeneratively cooled tube-wall nozzle, and a large, metallic nozzle extension controlled thermally by a commercial thermal protection coating inside and out and by turbine exhaust gas (TEG) injected around the inner walls.

Key requirements driving the design are a vacuum thrust of 294,000 pounds (1,307 kN), specific impulse (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 goal of 5,535 lb (2,526 kg). For the TLI phase of the Ares V mission, the J-2X design will be capable of 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.

Due to the limited number of development/certification engines budgeted for the J-2X, the design life for the engine is 30 starts, much greater than the operational 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.

Recognizing that the longest, most difficult part of any new vehicle development historically is the propulsion system, NASA made J-2X development a priority. In addition to using proven hardware where feasible, the design philosophy also calls an aggressive development schedule, strict adherence to requirements, and early risk reduction analysis and testing.

2.0 BALANCING REQUIREMENTS AND RISK

The J-2X is based on the proven J-2 upper stage engine that successfully powered the Saturn IB and Saturn V upper stages. However, the magnitude of the changes to achieve the J-2X performance effectively constitutes a new development program. An off-the-shelf J-2 could not be built today due to the obsolete materials, manufacturing methods, supplier attrition, and availability of engineers from 40 years ago. In addition, Ares requirements for performance, reliability, and human rating are all more demanding than those for the J-2. The Constellation reference mission calls for a much higher delivered mass to the lunar surface, accounting for the requirement for 294,000 pounds vacuum thrust, vs. 230,000 pounds for J-2, 448 seconds specific impulse 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 design team understands the deviations from J-2 and has methodically studied the heritage J-2 design for its applicability to J-2X needs, and has deviated from heritage J-2 only as needed to meet requirements and mitigate 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.

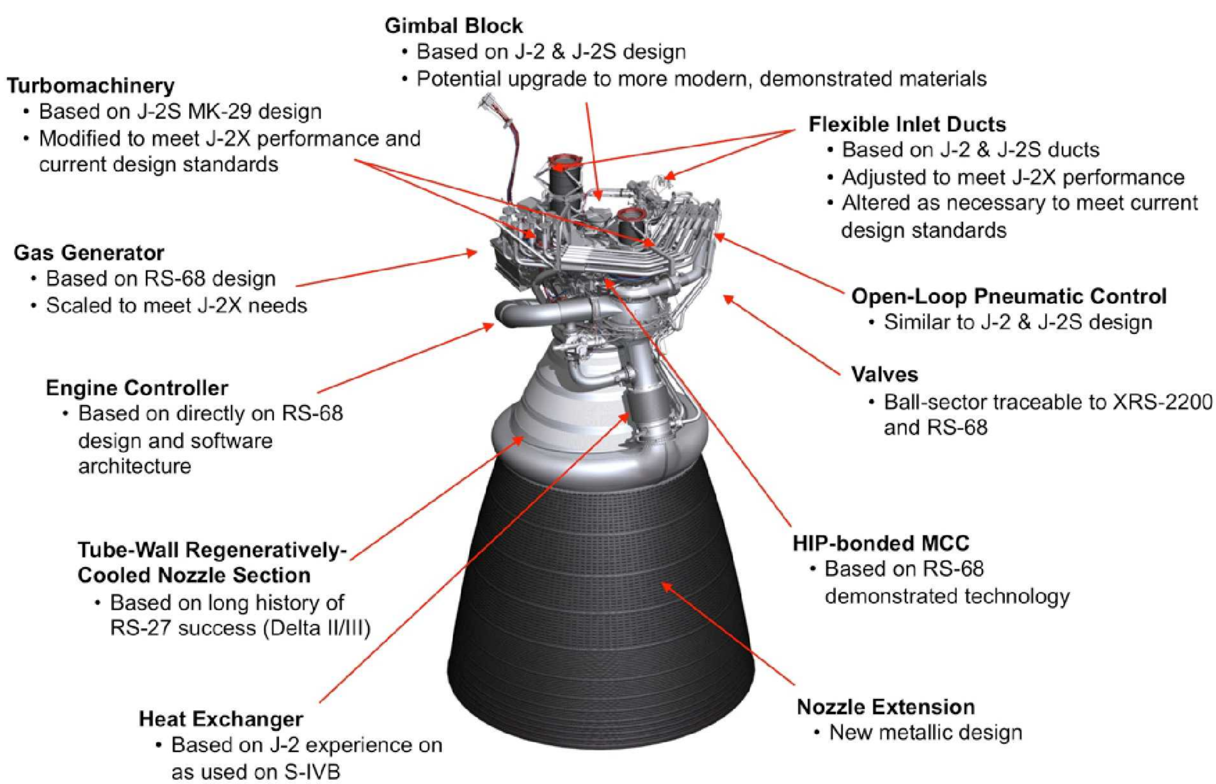

Figure 2 – The J-2X component heritage

The J-2X has strong links to major design features of the J-2/J-2S engines. The J-2X utilizes the same power cycle as J-2, which is a series turbine gas generator cycle in which turbine drive power is serially flowed through the fuel turbine and then the oxidizer turbine before dumping into the nozzle.

To achieve engine throttle mode for the Ares V TLI thrust limitation requirement, 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. To stay closer to the turbomachinery experience base, J-2X accomplishes throttling via the oxidizer turbine bypass.

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

J-2X uses heritage J-2/J-2S turbopump inlet scissors ducts, to be modified only relative to hydrogen duct insulation. To use essentially the same duct design, the fuel and oxidizer duct inlets use the same diameters as the heritage design. This approach requires considerable assessment of duct flow characteristics utilizing computational fluid dynamics to assure the heritage ducts can be used with the considerably higher flow rates required to meet the J-2X thrust requirement.

Heritage designs for the J-2S turbopumps and scissors ducts were considered important enough to the evolution of the J-2X that Powerpack 1A utilized 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 design.

J-2X has extensively leveraged experience with other engines, all of which offer more recent experience than the 40 year old experience of the J-2/J-2S. Accordingly, there are available engineers in the workforce today with direct experience on these engines. True adherence to J-2/J-2S heritage design would require significant reverse-engineering to determine many details, unavailable today, of how those engines were designed, although significant data has been recovered for the J-2/J-2S heritage design and utilized for J-2X.

One example of the need to deviate from the heritage design is the heritage butterfly valves. PWR's lack of available experience with those heritage valves was quickly realized, although heritage valves were torn down to begin reverse engineering in early 2006, before the sector ball valve design was chosen from experience that includes the X-33 engine.

Several of the necessary J-2X deviations from J-2/J-2S, such as the gas generator design with solid propellant igniter, are evolved from recent PWR experience with the RS-68 engine. The Ares requirement for engine specific impulse is 448 seconds, which is only four 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 much lower performance gas generator power cycle. So to meet this requirement while leveraging heritage to minimize development risk, the J-2X utilizes a high performance injector design leveraged the RS-68, and a nozzle extension leveraged from recent RL-10B2 experience. The nozzle extension diameter could have been reduced to approximately the RL-10B2 diameter, but this was not done because the chamber pressure was kept low enough to stay with the heritage single stage J-2S fuel turbopump design to minimize turbomachinery development risk.

Overall, then, true clean-sheet design has been kept to an absolute minimum, while leveraging proven engine technology to the maximum. This is done so development risk can be minimized, which is a necessity for both cost containment and development schedule for Ares to minimize the gap in human space flight after Shuttle retirement. Development risk is a strong function of design experience and development experience, and leveraging previous engine programs, including J-2, J-2S, X-33, RS-68, SSME, MBXX, IPD, RL-10, Fastrac, COBRA, RS-83, RS-84 and other engines is key to the J-2X development risk strategy.

3.0 TESTING TO INFORM DESIGN

Despite an overall effort to use the current knowledge base to develop a new engine, J-2X development has demonstrated the complex interactions that result when many well-understood components tailored to other engines are adapted and assembled into a single new engine design. The team has encountered several design issues, none unexpected in an engine design effort. 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. This section discusses selected component test highlights that have anchored computational modeling.

3.1 SUBSCALE MAIN INJECTOR TESTING

Subscale Main Injector (MI) hot fire testing in 2006-2007 was used to characterize performance and select the J-2X injector element pattern, critical to metering the flow of fuel and oxidizer into the main combustion chamber. The goal of testing was to find an injector 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. Compared to a SSME main injector, the J-2X MI sees less severe operating environment, it has a proven manufacturing process, and it has a simplified design featuring a single faceplate, a reduced number of welds, and greater inspectability and ease of assembly. A subscale main injector test is shown in figure 3.

Figure 3 – Subscale Main Injector testing at MSFC

3.2 MAIN INJECTOR AUGMENTED SPARK IGNITER TESTING

A heritage main injector Augmented Spark Igniter (ASI) was test fired in 2007 to characterize the original design. The ASI is needed for in-flight ignition. This test series simulated the conditions the Ares I's upper stage will experience when activated in low-Earth orbit. The series also used propellants chilled to minus 260 degrees Fahrenheit, simulating conditions prior to injection between Earth and the Moon, where the J-2X will be used to power the Ares V upper stage, called the Earth Departure Stage (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 has different propellant flow paths. Feed line materials, length and the number of bends are different. 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. Small, low-pressure liquid propellant tanks will simulate a "tank-head" start. The set pressures on the small tanks will be varied within the engine start box.

3.3 WORKHORSE GAS GENERATOR TESTING

A Workhorse Gas Generator (WHGG), which simulates the temperatures, pressures, and flows of a flight gas generator, was used in several series in 2008 and 2009 to characterize performance, combustion stability, and turbine inlet hot gas temperature. It was tested in both a straight-duct configuration, then incorporating the elbow and U-duct connecting the WHGG to the fuel turbine simulator per the flight configuration 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 240,000 pounds secondary power level and 294,000 pounds primary power level of thrust. Among its objectives were demonstration of GG pyrotechnic igniter, GG fuel-and oxidizer-side purge, injector face heating, injector/chamber compatibility, down-select of a GG chamber length and injector element pattern, verification of temperature uniformity of GG combustion products delivered to the fuel turbopump inlet flange and turbine nozzles, GG spontaneous and dynamic combustion stability, and validation of the database for computational fluid dynamics (CFD) analysis of the turbine drive subsystem. 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 vibration issues with the heritage 78-inch hot gas duct from the WHGG to the fuel turbine. Five shorter duct lengths were tested. Testing also incorporated a redesigned injector. The series 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 optimum length duct in a more flight-like configuration. The data indicated the duct had negligible impact on stability and 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). A WHGG test is shown in figure 4.

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.

Figure 4 – Workhorse Gas Generator testing at MSFC

3.4 NOZZLE EXTENSION TESTING

The J-2X nozzle extension is key to achieving the performance needed for the Ares V lunar mission. It will be the world's largest passively cooled nozzle extension. It faces both vibration and thermal stresses from inside and outside 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 turbine exhaust gas film cooling and emissivity coatings are also significant factors in ensuring that the metallic nozzle extension does not exceed its thermal limit.

Subscale cold flow nozzle testing in 2006 and 2007 was used to characterize side loads. The testing optimized the truncated ideal contour (TIC) nozzle with minimum loading and maximum performance. These tests also helped determine design margins that affected weight and life, as well as performance.

Another round of tests in 2009 was used to predict turbine exhaust gas TEG film cooling performance. It retained the test nozzle base and added a new nozzle extension and scale manifold simulating J-2X. Air cooled to approximately 32 degrees F 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.

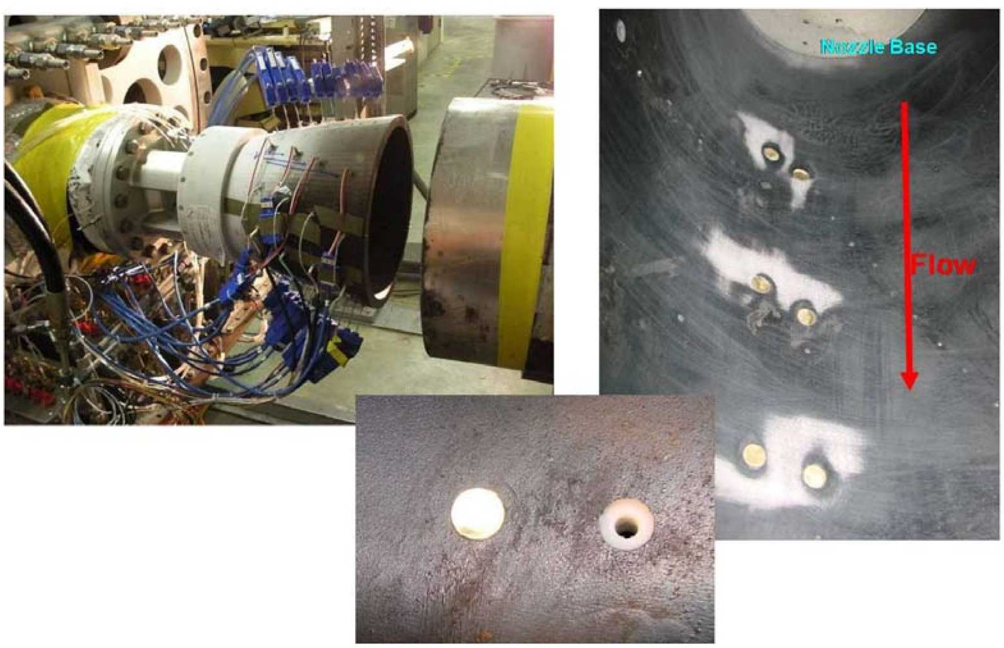

Figure 5 – Subscale Cold Flow Nozzle testing at MSFC

In addition to TEG cooling, the metal nozzle extension also relies on thermal emissivity coatings on its inner and outer surfaces to survive temperatures in excess of 2,000 degrees Fahrenheit that could otherwise cause it to fail. This coating must survive 500 seconds of operating time on Ares I and 1,000 seconds of operating time on the Ares V. Seven off-the-shelf candidate materials were selected for testing in 2009 and 2010 to characterize their thermal performance and durability. Most are commonly used in industrial furnaces, power generation, the steel industry, or the petroleum/natural gas industry. The field was narrowed to two candidates, which were tested in early 2010. One coating was down-selected as the baseline design for the nozzle extension.

The nozzle extension service life is 1,600 seconds and six starts. The required certification time is 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 show they could meet the certification time.

In the tests coating samples were applied to several 6x10-inch 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 see if the coatings were sensitive to manufacturing variables. A coated test panel is shown in figure 6.

Figure 6 – Nozzle Extension thermal emissivity coating panel test at MSFC

Engineers also tested the ability to repair coating defects that might occur during extension fabrication or during engine testing. The series was used to develop and evaluate high temperature instrumentation such as thermocouples and heat flux gauges that could be used to measure the full scale extension environments. One sample met the requirements and was selected for scale-up to a full nozzle extension.

Another series was also used to test the effects of Ares I upper stage ullage settling motors impingement on the coatings. The motors use solid propellant, and the exhaust plume contains relatively large, high-speed particles, essentially grit-blasting any surface that it encounters. Post-test inspection showed that the coatings were still adhered to the aluminum test panels, with no indications of erosion and no changes in pre- and post-test emissivity.

3.5 TURBOMACHINERY TESTING

The J-2X turbopumps are based on the J-2 heritage Mk 29 turbopumps as a point of departure, with changes as necessary to meet the higher Constellation requirements. The plan for design and testing was 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 due to four key factors: the constrained J-2 Mk. 29 pump design baseline; the higher thrust and Isp requirements involving greater flow, temperature, pressure, etc.; contemporary design standards, such as alternating stress, resulting from lessons learned in the years since the J-2 was developed; and new detailed analytical techniques, not yet anchored to testing, which, notably, raised questions about even the proven J-2 design.

Perhaps most challenging has been the fuel turbopump (FTP) design, which sees the harshest environments in the engine due to the 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.

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.

PWR performed subscale fuel inducer water flow tests, while 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 performed "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 heritage design and materials.

The Powerpack Assembly-1 (PPA-1) test series from December 2007 through May 2008 allowed engineers 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 improvements. 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 of thrust. The series helped resolve differences in heritage turbopump performance data and recent component-level tests. It investigated the performance of the engine 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 2011. Some of the turbomachinery tests noted above are shown in figure 7.

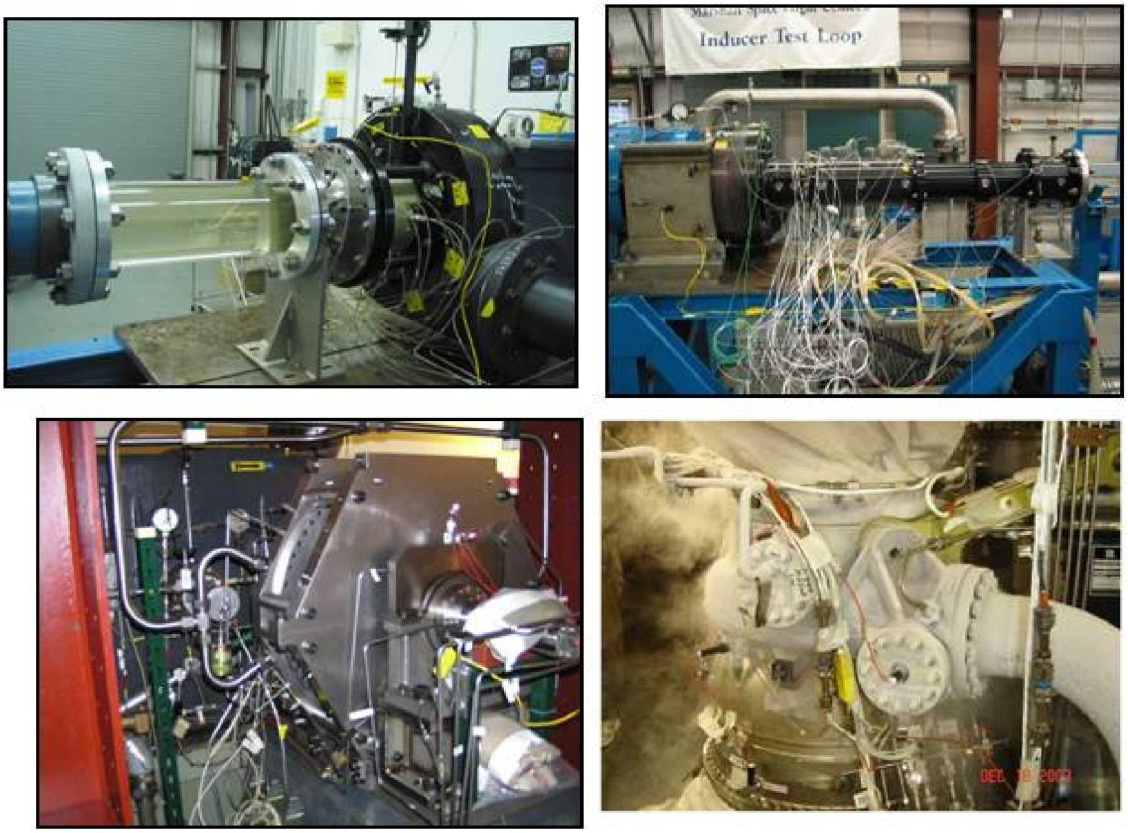

Figure 7 – Turbomachinery testing, clockwise from upper left: PWR waterflow test, MSFC waterflow test, PPA-1 OTP, PWR whirligig test.

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. Its main use is to characterize turbine performance and load environments for anchoring turbine gas computational fluid dynamics 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 instrumenting 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 8.

Figure 8 – 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)

4.0 TEST STANDS

Three test stands at Stennis Space Center (SSC) will support J-2X development work. The A1 stand hosted PPA-1 testing in 2008, and it is undergoing modifications to support PPA-2 testing beginning in 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 feedline designs were altered to accommodate the different test article configurations for PPA-2 and J-2X engines.

On the A2 test stand, 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 low-area-ratio “stub” nozzle extension, and no gimbal capability.

Much of the effort at Stennis remains focused on 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 burning isopropyl alcohol (IPA) and LOX.

On the A3 stand, 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 LH 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 9.

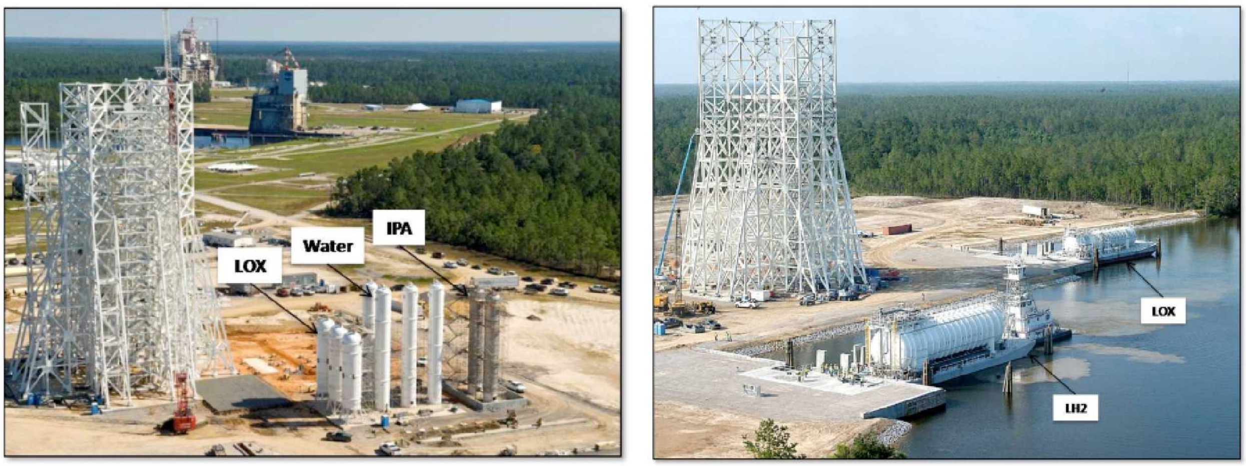

Figure 9 – SSC A3 test stand construction showing LOX, water, and isopropyl alcohol tanks, top, and LH2 and LOX barrage positions, bottom.

5.0 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 the 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-2 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
- and 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. Planned J-2X development testing is about the same as the RS-68 development test program.

6.0 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. Examples of major components manufactured to date are shown in figure 10.

Figure 10 – Manufactured engine components for PPA-2 and E-10001 include, clockwise, from upper left, FTP turbine manifold, GG injector body, MCC liner, regen nozzle tube stack, FTP volute

7.0 CONCLUSION

NASA's J-2X team has developed new analysis techniques and a new national rocket engine test facility capability in the process of developing a simplified, high-performance liquid engine. While based on proven hardware, the J-2X upper stage engine represents the development of essentially new engine, updating a heritage design for vastly improved performance and safety by selectively employing contemporary knowledge, design, analysis, and materials. More than 100,000 parts are in various stages of manufacturing, representing the work of thousands of private manufacturers across the country. Component-level and other risk mitigation testing has played a major role in bringing this new engine successfully through a series of technical review cycles ahead of the other elements of NASA's Constellation Program and to the brink of testing in 2011. While national leaders are now considering alternatives for the future of U.S. human space flight, the J-2X represents a capability critical to any new direction in human exploration beyond Earth orbit.