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The J-2X Upper Stage Engine: From Heritage to Hardware

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Abstract

NASA's Global Exploration Strategy requires safe, reliable, robust, efficient transportation to support sustainable operations from Earth to orbit and into the far reaches of the solar system. NASA selected the Ares I crew launch vehicle and the Ares V cargo launch vehicle to provide that transportation (Figure 1). These launch vehicles, along with the Orion crew exploration vehicle and the Altair lunar lander, will carry out the national policy goals of succeeding the Space Shuttle fleet, renewing and expanding lunar exploration, and eventually sending humans to Mars. Ares I will begin its initial operating capability of flying up to six astronauts to the International Space Station (ISS) no later than 2015. Ares V is scheduled to be operational in the 2020 timeframe to support lunar missions.

Figure 1. The Ares V Cargo Launch Vehicle (left) and Ares I Crew Launch Vehicle (right) will form the backbone of America's new space fleet. (NASA artist's concept)

Guiding principles in creating the architecture represented by the Ares vehicles were the maximum use of heritage hardware and legacy knowledge, particularly Space Shuttle assets, and commonality between the Ares vehicles where possible to streamline the hardware development approach and reduce programmatic, technical, and budget risks. The J-2X exemplifies those goals. It was selected by the Exploration Systems Architecture Study (ESAS) as the upper stage propulsion for the Ares I Upper Stage and the Ares V Earth Departure Stage (EDS).

For Ares I, the J-2X is designed to start at altitude and burn for 500 seconds to put the Orion spacecraft in orbit. For Ares V, the J-2X will start at altitude, operate roughly 500 seconds to put the EDS in orbit, shut down, loiter for up to 95 days, restart in orbit on command, operate for roughly 300 seconds in secondary mode at reduced thrust level for the trans-lunar injection (TLI) to send the EDS/Orion/Altair combined spacecraft toward a lunar orbit, and then shut down safely.

The J-2X is an evolved version of the historic J-2 engine that successfully powered the second stage of the Saturn I launch vehicle and the second and third stages of the Saturn V launch vehicle. The J-2X employs the J-2's flight-proven LH_2/LOX, gas generator cycle. Several major components, including the turbomachinery, trace their origin to the post-Apollo J-2S engine development and the XRS-2200 engine program for the X-33 program in the late 1990s. Several components are derived from the RS-68 engine design, currently in operation on the Delta IV Evolved Expendable Launch Vehicle (EELV). The nozzle extension is similar to a design flown on the RL-10B-2 engine.

The Constellation architecture, however, requires performance greater than its predecessor. The new architecture calls for larger payloads delivered to the Moon and demands greater loss of mission reliability and numerous other requirements associated with human rating that were not applied to the original J-2. As a result, the J-2X must operate at much higher temperatures, pressures, and flow rates than the heritage J-2, making it one of the highest performing gas generator cycle engines ever built, approaching the efficiency of more complex stage combustion engines such as the Space Shuttle Main Engine. Pratt & Whitney Rocketdyne, designer of the original J-2, is under a six-year design, development, test and evaluation (DDT&E) contract to develop this new engine.

The heritage Saturn Apollo J-2 provided 230,000 pounds-force (lbf) of thrust at a specific impulse of 425 seconds. Using a LH_2/ LOX propellant combination, the J-2X gas generator power cycle is designed to produce 294,000 pounds-force (lbf) of thrust at a minimum vacuum specific impulse of 448 seconds. It can be operated at two thrust levels, called "primary" and "secondary" mode. The primary mode mixture ratio is 5.5, while secondary mode uses a mixture ratio of 4.5 to deliver roughly 82% of primary mode thrust. Primary mode thrust will be used for the ascent burn on both Ares I and Ares V. Secondary thrust mode is for the TLI burn on Ares V due to load limitations on the Orion-to-Altair docking system.

Ares I requirements drive the J-2X thrust requirement, while Ares V requirements drive the engine's specific impulse performance. Both must be balanced against schedule, cost, weight and volume limitations. Other changes reflect contemporary manufacturing techniques and materials, as well as post-Apollo engine design and analysis techniques.

For the critical turbomachinery, NASA mitigated schedule risk by starting design work with the J-2S Mk 29 turbopump as its point of departure. The single-stage fuel turbopump design limits the main combustion chamber pressure and throat area, which, in turn, sets the nozzle exit area to attain the area ratio necessary to achieve 448 seconds specific impulse. The resulting nozzle exit area and length drives the need to add a radiatively-cooled nozzle extension onto the regeneratively-cooled nozzle.

In the process of designing the J-2X to meet these requirements, virtually every component of the heritage J-2 and J-2S was modified or replaced altogether. But the engine avoids the risk associated with a typical "new development" engine due to lessons learned in the 40 years since the J-2 was designed, as well as new materials and new manufacturing methods. The government/industry design team is deviating from the heritage J-2 only as needed and has a development plan that addresses the differences. The baseline J-2X design underwent several major changes. Plans for a 274,000-pound-thrust engine were canceled as confidence grew in the ultimate 294,000 pound design. More heritage J-2 components were replaced by RS-68 designs scaled down to the J-2X, including the main injector and gas generator. A tube-wall regeneratively-cooled nozzle similar to the J-2 was selected. A turbine exhaust gas manifold was also added to the nozzle design to provide cooling of the forward joint region of the nozzle extension, as well as extra specific impulse. Despite higher development costs, composites were selected for the nozzle extension because of their significantly higher temperature margin and lower weight.

Development is focused on early risk mitigation, component and subassembly test, and engine system test. The development plans include testing engine components, including the subscale injector, main igniter, powerpack assembly (turbopumps, gas generator and associated ducting and structural mounts), full-scale gas generator, valves, and control software with hardware-in-the-loop. Aware of the development times associated with new propulsion hardware, the J-2X Element office began testing with heritage J-2 hardware at Marshall Space Flight Center less than six months after the organization's inception, and the Element continues to press forward to mature the design ahead of other elements of the Ares vehicle because of the need to perform approximately 200 engine system hot-fire tests in 2010-2012. Testing in 2006 focused on injector and valve hardware. Testing expanded in 2007, accompanied by the refinement of the design through several key milestones. This paper will present a discussion of those 2007 tests and milestones, as well as an update on key developments in 2008.