

System Engineering and Technical Challenges Overcome in the J-2X Rocket Engine Development Project

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Abstract

Beginning in 2006, NASA initiated the J-2X engine development effort to develop an upper stage propulsion system to enable the achievement of the primary objectives of the Constellation program (CxP): provide continued access to the International Space Station following the retirement of the Space Station and return humans to the moon. The J-2X system requirements identified to accomplish this were very challenging and the time expended over the five years following the beginning of the J-2X effort have been noteworthy in the development of innovations in both the fields for liquid rocket propulsion and system engineering.

1. Introduction

The J-2X system is being developed for NASA by the Pratt & Whitney Rocketdyne (PWR) company to satisfy the propulsion needs of two very dissimilar launch vehicles: the manned Ares-I and the Ares-V. Accomplishing the missions of both vehicles required very aggressive performance requirements for the J-2X engine, most notably high thrust, high specific impulse, multiple thrust levels, and extended in-orbit loiter and restart. This is in addition to pursuing the usual imperatives of safety, reliability, maintainability, and cost. In addition to the difficult technical requirements demanded by the Ares vehicles, the J-2X development effort was further challenged by limited funding, a compressed schedule, supporting the development and element integration of the Ares vehicles, and supporting the programmatic needs of the Constellation program. Since the initiation of development in early 2006, innovations in system design and engineering practices have facilitated the engine design to evolve to enable the initiation of system testing of the first development test article, engine E10001.

The J-2X Upper Stage Engine/Earth Departure Stage Engine (USE/EDSE) is a pump-fed rocket engine system using liquid oxygen (LO₂) and liquid hydrogen (LH₂) propellants in a proven gas generator (GG) power cycle. It is based upon the heritage of the J-2 rocket engine used during the Apollo era. The primary differences between J-2X and the original J-2 are design changes for increasing reliability, implementation of human-rating requirements, increased performance (see Table 1), optimized vehicle integration, increased producibility, and overcoming obsolescence issues. Ares-V mission requirements for the J-2X engine include the following: start at altitude (i.e., vacuum), operate at either of two power levels, shutdown for disposal or loiter on orbit for up to 100 days, restart on command, operate with sufficient impulse for earth departure and shutdown. The J-2X engine requirements for the Ares-I mission are a subset of those identified for the Ares-V mission. The J-2X produces 294,000 lbf of thrust at a nominal specific impulse of 448 seconds in vacuum and can be operated at two thrust levels called “primary” and “secondary” mode.

Table 1: Evolution of J-2X Requirements with J-2 and J-2S

Requirement	J-2	J-2S	J-2X
Thrust, vacuum (klbf)	230	265	294
Specific Impulse, vacuum (sec)	425	436	448
Mass, dry (lb)	3492	3800	5535

Although the J-2X was designed to operate on the Ares launch vehicles, the replacement of the CxP with the Space Launch System (SLS) will produce a new suite of challenges. A clear understanding of these challenges will rely heavily on systems engineering discipline to conduct a thorough gap analysis between the CxP and SLS vehicle

propulsion requirements and assess the propulsion needs of the SLS vehicle and compare those against what the J-2X system can provide.

1.2 The Beginning of J-2X - ESAS and Constellation

The J-2X engine development effort was initiated as a result of the Exploration Systems Architecture Study (ESAS) study conducted at the beginning of the CxP. The Ares vehicles defined by the ESAS study each utilized the J-2X engine to enable the accomplishment of the mission objectives of propelling the Ares-I Upper Stage to the International Space Station (ISS) and conducting the trans-lunar injection burn for the Ares-V Earth Departure Stage (EDS). The combined system requirements generated to accomplish the missions of these individual missions held a number of significant technical challenges, including:

- High performance – the high vacuum specific impulse of 448 seconds was significantly higher than the original J-2 engine and approached that of the Space Shuttle Main Engine (SSME). This and the increased thrust would put a larger burden on the turbopumps and require the use of an enormous nozzle extension.
- Multiple starts and power levels – The requirements associated with multiple starts and power levels are in order to support the Ares-V EDS for the lunar mission. The J-2X “secondary” mode was identified when early design analyses suggested that the docking ring between the Orion crew module and Altair lunar lander could not tolerate the structural loads imposed by the J-2X at full thrust.
- On-orbit loiter – To support the lunar mission, the Ares-V EDS was required to be launched to Low Earth Orbit (LEO) and remain there for up to 100 days (this was later reduced to 5 days).

The additional programmatic imperatives of low cost and short schedules for system development influenced the decision to utilize an existing engine as a point of departure. Following an exhaustive trade study to weigh the existing systems versus a clean-sheet design, it was decided to leverage the experience base originating with the J-2 and expanded through the J-2S and XRS-2000 engine projects and pursue the next phase of the engine evolution: the J-2X, shown in Figure 1.

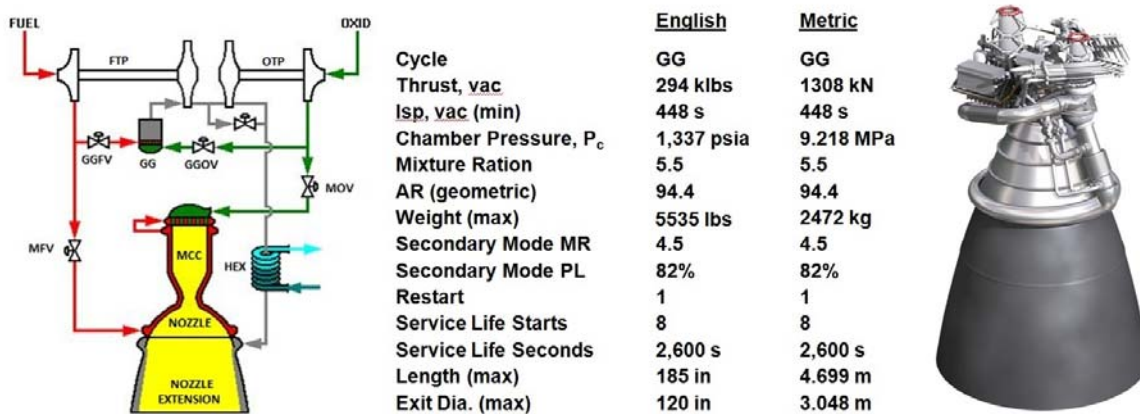


Figure 1: The J-2X System and System Requirements

2. System Engineering Challenges

The advantage of hindsight is to allow an engineer to reflect on his experiences and identify what decisions worked and what didn't. The evolution of systems engineering is largely advanced by the promotion of the former and avoidance of the latter. The SE approach evolved by the J-2X team, including both NASA and PWR, has relied on the key attributes of flexibility, responsiveness, and communication. While a broader discussion of SE tools used by the J-2X team has been documented [1], the following items are specific challenges encountered:

2.1 Requirements Development and Decomposition

It has been recognized that the development cycle for a rocket propulsion system can often be the prime driver for the critical path of a launch vehicle development program. With that in mind, it was determined that in order to

achieve the aggressive goal of initial operational capability (IOC) of the Ares-I vehicle by 2014, initiation of J-2X development had to begin immediately despite the absence of fully-defined propulsion system requirements from the vehicle(s). The risk from “flying blind” without officially-baselined vehicle requirements was reduced by the successful synthesis of top-level engine requirements from higher-level CxP documents (i.e., concept of operations, architecture requirements) in addition to the ESAS report. It was accepted that enough was known regarding the vehicle requirements to proceed at risk with the preliminary J-2X system design and adjust later as the vehicle definition solidified. Accomplishing this required a high level of communication and coordination with the Ares-I Upper Stage element and the Vehicle Integration organizations.

2.2 Safety, Design & Construction Standards

System development for NASA space flight systems, especially for human-rated systems, is guided by a number of safety, design and construction (D&C) standards. Compliance with these standards is generally mandatory unless a defensible rationale can be provided for any deviation from them.

The safety standards applied to rocket engines originate from a variety of sources and topic areas, including industrial safety, launch range safety, military standards, NASA standards, and, if required, human rating requirements. All these standards are collective and complementary, addressing a different facet of the manufacture, handling, test, and operation of the engine system. These standards address the safety concerns presented by the rocket engine as it applies to the public and those directly involved with it. It is generally important that consideration of the safety standards be applied as early as possible to the engine design process to prevent an expensive and time-consuming corrective implementation of the necessary standard later in the engine life cycle.

The design of rocket engines is governed by specific standards, originating either from the government or the engine contractor. In instances where the content of the contractor standard overlaps that of a government standard, it must show that it “meets or exceeds” the requirements specified in the government-prescribed standard. These standards define the minimum criteria that must be met in the system design and are the result of exhaustive experience in the topic areas. Examples of the government standards used include structural margins of safety, fracture control, non-destructive evaluation and materials selection. The results of the “meets or exceeds” comparison and the approval record is captured in a Compliance Verification Record (CVR) report, a SE process originated for the J-2X development effort.

It must be emphasized that some restraint be applied in mandating (aka “piling on”) standards even with the honorable intent of improving the system design. Unless the standard is already an accepted practice of long standing, imposition of a new standard can be prohibitively expensive, disruptive to the development path and difficult to effectively implement and verify. The effort that the J-2X program has expended in addressing these mandates is significant and will need to be similarly attended to by any subsequent propulsion system development effort.

2.3 Risk Balance

The effective application of an encompassing risk management process has been shown to be an essential enabler in achieving programmatic and technical objectives. The cost and schedule constraints imposed on the J-2X development effort led to the utilization of a rigorous risk management approach to balance risks to cost, schedule and technical performance. The prime driver was cost due to the fact that the J-2X effort was initially cost constrained, and became increasingly more so due to repeated budget challenges resulting from changes in CxP funding and priorities.

With the reluctant acceptance that there were not sufficient resources to mitigate all concerns, a process for evaluating viable risks and establish progressive mitigation plans to reduce the likelihood and/or consequence to an acceptable level. The status of element risks were frequently reviewed to assure an optimal balance between budget, schedule and technical parameters, and tune the risk mitigation plans accordingly. Examples of successfully mitigated risks such as self-induced thermal loads on the engine controller, GG combustion instability, procurement and fabrication of long-lead components, and several risks associated with the achievement of the more aggressive system requirements.

2.4 Vehicle/System Integration and Communications

It is generally accepted that designing a launch vehicle is a complex activity and the amount of information to be developed is immense. Being able to control the level of chaos demands a high level of organization and efficient communications at all levels. Looking at Figure 2, the organizational boundaries are shown and are highly interactive with each other, both vertically and horizontally. The vertical interactions running downward include the decomposition of requirements, the loads and environments that the vehicle systems must tolerate, and specified D&C standards that the vehicle and its aggregate systems must be compliant with. Information flowing upward are primarily responses to the inputs flowed from the upper levels, primarily verifications and certifications of the vehicle and systems. The horizontal interactions are primarily composed of interface agreements between lateral organizations. For actual system interface definitions developed at the Element level (i.e., Level-IV), such as between the J-2X and Upper Stage elements, these agreements are maintained in an Interface Control Document (ICD) controlled at Level-III by the Vehicle Integration organization.

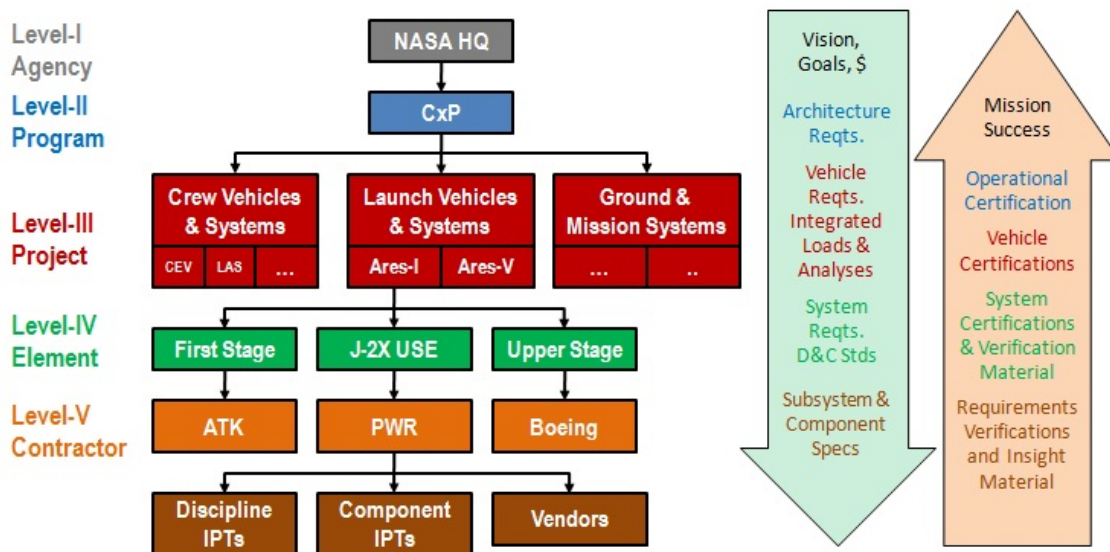


Figure 2: J-2X Programmatic Interfaces and Information Flows

Effective system integration required an internal and external perspective. The internal “down-and-in” perspective focused on ensuring that all the constituent components operated seamlessly and reliably as an integrated system. The external “up-and-out” integration perspective focused in two directions: the overall Ares vehicle, and the Upper Stage element that the J-2X engine mounted to. As previously described in Figure 2, the first vehicle-level integration perspective is in the vertical direction and the Upper Stage integration perspective is in the horizontal and must be executed concurrently.

Enabling the evolution of the integrated vehicle requires secure, highly efficient communications. This was largely accomplished through the use of the Windchill and NexPrise™ information management platforms. Windchill is used by NASA and its contractors while NexPrise™ is controlled by PWR. Both are 100% Web-based systems designed to facilitate improved communication, change management and project execution with remote partners, suppliers, customers and employees.

2.5 Compressing the Schedule

The initial 2014 IOC target for the Ares-I vehicle dictated a compressed development schedule for the J-2X development, with the system operational certification accomplished via the Design Certification Review (DCR) conducted in December 2012, approximately six years after receiving Authorization to Proceed (ATP). Keeping in mind that experience shows that the preliminary and critical design phases each generally takes at least two years to accomplish, the J-2X schedule required that these design phases be completed in half that time (~1 year each). This

required a high-level of phasing of development activities to be conducted in parallel and a constant focus on risk management to evaluate development risks and adjust priorities accordingly.

The careful orchestration of events was showing itself to be effective on progressing toward the December 2012 DCR date when a GFY09 change in the CxP budget profile required a Level-II replan resulting in the J-2X DCR date to slip to September 2014. From a development standpoint, even though the schedule pressure had been stretched by almost two years, the lack of additional funding was equivalent to putting a person to work for eight days, but only giving them six days of food. This in itself required careful management of development activities.

However, in February 2010, NASA announced the plans for termination of the CxP program which was followed by an extended period of programmatic uncertainty. During this time, the NASA and PWR teams working on J-2X cooperated in accelerating the production schedule of the first development engine, E10001, for the immediate initiation of system testing in order to promote the application of the J-2X design for the next vehicle to be developed under the Space Launch System (SLS) program. The recent completion of the E10001 assembly is a significant achievement.

2.6 Milestone Reviews

In connection with accommodating the compressed development schedule was accomplishing the milestone reviews required by NASA. These reviews have the specific function of ensuring the progressive advancement of the system development by periodically evaluating their technical status. The design reviews are known as the System Definition Review (SDR), Preliminary Design Review (PDR), and Critical Design Review (CDR). Each review must show a specific level of advancement before being authorized to precedes to the subsequent design phase. The SDR examines the proposed system architecture and design and flowdown to all functional elements of the system. The PDR demonstrates that the preliminary design meets all system requirements with acceptable risk and within the cost and schedule constraints and established the basis for proceeding with the detailed design. The CDR demonstrates that the maturity of the design is appropriate to support proceeding with full-scale fabrication, assembly, integration, and test. CDR determines that the technical effort is on track to complete the flight and ground system development and mission operations, meeting mission performance requirements within the identified cost and schedule constraints.

On average, the time required to complete each design phase and conduct the milestone review is about two years. As seen in Table 2, the J-2X design phases were completed in about half that time. This was accomplished by leveraging experience and design features from existing PWR systems, including J-2, J-2S, XRS-2200, and RS-68.

Table 2: J-2X Milestone Reviews

Phase (ϕ)	Description	Exit Milestone	Milestone Date
A	Definition	SRR/SDR	October 2006
B	Preliminary Design	PDR	July 2007
C	Detailed Design	CDR	September 2008
D	System Development	DCR	TBD

Another means of accommodating the compressed schedule, especially in the case of the performing the CDR, was to stretch out the review into a “campaign” of component and subsystem reviews, finishing with a system level review. In the case of the CDR, there were also several reviews focused on the engine control system that were conducted after the system CDR. While this is generally not done, these “lagging” reviews were regarded as largely independent of the integrated and could be regarded as separate from the system CDR with an acceptable level of risk.

While the J-2X system CDR was considered successful, the compressed timeframe made it was important to manage the expectations to where the emphasis was not so much that the system design was mostly finished, but that the design was sufficiently mature to allow the long-lead manufacturing to commence while the rest of the design catches up (lagging reviews).

3. Technical Challenges

3.1 Achieving and Verifying Required Performance

From the beginning, the high performance requirements demanded to utilization of many innovations, especially when challenged by the mandate of using existing “heritage” designs as much as possible. The rationale for using heritage systems was based on the debatable assumption that their use would provide a significant reduction in development costs. Consequently, emphasis was placed on using elements from the J-2, J-2S and RS-68 system designs that would collectively enable the achievement of the high performance needed from the J-2X system, primarily in the areas of thrust and specific impulse.

As an upper stage engine, the J-2X will have the highest specific impulse of any GG cycle engine in its thrust class (448 seconds vacuum I_{sp}). This is achieved by increasing the chamber pressure and area ratio beyond that of the baseline J-2 engine. The high chamber pressure was accomplished by increasing the system operating pressures as much as possible without having to subject the turbomachinery to a significant redesign. Even so, a moderate redesign of the original Mark-29 turbopumps used on the J-2S was performed to enable the higher operating point and bring the turbomachinery design to be compliant with current D&C standards.

The expansion area ratio of the J-2X was increased from 27.5:1 used on the J-2 to 92:1 to further achieve higher performance. The larger area ratio is achieved by the utilization of a large radiatively-cooled nozzle extension mounted after the regeneratively-cooled nozzle. The large size and high heat load of the nozzle extension requires that it be made of a robust high-temperature refractory metal alloy and its unprecedented size incurs significant technical risks to be overcome.

Another contributor to the specific impulse is the recovery of turbine exhaust gases and injection at the interface plane between the nozzle and nozzle extension. Usually for GG-cycle rocket engines, this exhaust is dumped overboard and is generally an accepted performance debit. Accomplishing this form of performance recovery requires uniform, high-velocity injection of the gas, which also provides a measure of film cooling for the metallic nozzle extension.

The high performance requirement also made it imperative to select a main injector element pattern and density to optimize performance with minimum complexity and cost. To accomplish this, subscale main injector testing was one of the first development test series performed, at MSFC 2006-2007.

Another of the concerns associated with developing a rocket engine with a high area ratio nozzle is being able to test it on the ground in order to verify the requirements and enable system certification for flight. Because of the backpressure from atmospheric pressure, nozzles with area ratios generally higher than 25:1 are prohibited from being operated at ground conditions because the under-expanded exhaust in the nozzle can generate unstable sideloads against the nozzle wall that can result in catastrophic engine damage. Being able to operate an in-space rocket system on the ground requires that it be mounted in a vacuum test cell that can simulate the ambient pressure conditions at the system’s operational altitude (i.e., near-vacuum). After all available test facilities were evaluated for their ability to effectively test the J-2X, the decision was made to construct the A-3 altitude test facility at the NASA Stennis Space Center (NASA-SSC). The technical challenges of the design and construction of this imposing facility certainly merit a separate discussion.

3.2 Fracture Control

In order to achieve NASA’s goal of producing flight systems with a high degree of reliability and safety, the use of good engineering practices is emphasized, primarily in the design, analyses, inspections, testing, fabrication, and operation of flight structures. In keeping with this policy, all human-rated space systems shall be subjected to fracture control to preclude catastrophic failure. Fracture control is a specialized engineering discipline that provides a methodology to mitigate the consequences of naturally occurring or operationally-induced flaws, damage, or cracks in a part or structure. The implementation of a viable fracture control program relies on design, analysis, testing, non-destructive evaluation (NDE) and tracking of fracture critical hardware. The requirements associated with fracture control were levied on all CxP flight systems [2].

Applying the fracture control mandates of NASA-STD-5019 across the entire engine was recognized as being prohibitively and unnecessarily expensive, so a tailored fracture control approach was evolved that will mitigate the risk associated with fracture-induced system failure. The fracture control philosophy being implemented analytically identifies fracture critical parts which may have critical initial flaw sizes (CIFS) smaller than can be detected through standard NDE techniques and applies more focused fracture control methods on them. The implementation of a

viable fracture control program specifically defined for a rocket propulsion system was first accomplished by the J-2X effort.

3.3 Risk Mitigation Testing

While the development of any complex mechanical system relies heavily on analysis, the confidence in the analytical codes used is tempered and anchored by actual test data. Even though the J-2X system was leveraging existing heritage hardware, the conditions in which this hardware was to be used was off the original design point the collective system impacts were difficult to evaluate. In addition, there were non-heritage design approaches or where elements of dissimilar heritage (i.e., GG from RS-68 and turbomachinery from J-2S) were merged and required testing to better understand the system effects. With this in mind, several focused avenues of risk mitigation testing were pursued to address key risk areas where it was considered more cost-effective to perform at the component or subsystem level than risk system-level assets. Although a more complete description of the risk mitigation testing is available in other literature [3], some of the tests include the following:

Turbomachinery Tests: In upgrading the Mark-29 turbomachinery to the Mark-72 design, redesigns of various key components have required various focused component tests to anchor design attributes. These test activities have included fuel inducer waterflow tests at PWR, subscale oxidizer inducer waterflow tests at MSFC, fuel turbine “whirligig” tests performed at MSFC, OTP interpropellant seal testing at PWR and the J-2 Heritage Fuel Airflow Turbine Test (HFATT) at MSFC.

Combustion Devices Tests: In addition to the subscale main injector testing already mentioned, design issues with the J-2X GG component and the GG duct leading into the fuel turbine required the use of a “workhorse” test rig to study performance, combustion stability, structural loads and downstream temperatures. As part of this effort, various GG injector element patterns, duct lengths and configurations were extensively tested to converge on an optimal design solution. Other combustion devices testing included cold-flow testing of a subscale nozzle to evaluate side loads, nozzle extension film cooling provided by the turbine exhaust gas injection and coupon testing of the emissivity coating used on the nozzle extension.

Powerpack 1 (PPA-1): The J-2X development effort relied on early testing December 2007 – May 2008) of the propellant feed subsystem, known as Powerpack 1, in order to establish a performance baseline for the heritage Mark-29 turbomachinery as well as risk mitigation tests on other components in the hot gas subsystem (i.e., helium spin start, heat exchanger, GG, spark igniter, ducts, etc.). The six PPA-1 tests accumulated a total of 1343 seconds and helped resolve differences in the historical Mark-29 performance data and more recent component-level tests.

Powerpack 2 (PPA-2): This high-fidelity test article to be used for testing the same components used in PPA-1, only at a higher level of design maturity. This will include the upgraded Mark-72 turbomachinery, GG, etc. In addition to risk mitigation and model anchoring, PPA-2 testing will also allow some higher-risk verification testing, such as low inlet pressure excursions, without risking system-level assets.

3.4 Accelerated Manufacturing

Given that the J-2X design was more than a straightforward upgrade of the heritage J-2 system, a prudent development approach would typically be expected to produce prototypes of the more challenging piece-parts as Manufacturing Technology Demonstrators (MTDs) prior to committing to fabrication of the first development component. However, the limitations of budget and schedule only allowed for this to be performed in a few cases where the technical risk outweighed the cost/schedule risks. In hindsight, this did not always work out as hoped, resulting in unfortunate impacts to cost and schedule that a MTD could have prevented.

As mentioned previously, the prolonged period of uncertainty resulting from the cancellation of the CxP program motivated the J-2X management team to press for an accelerated manufacture and assembly of the first development engine. At the same time, preparations to the A-2 test facility at NASA-SSC also accelerated to allow the initiation of system testing months earlier than planned. It is also important to point out that this challenge was accomplished under conditions of extraordinary budget austerity.

4. Conclusion

In conclusion, looking back over the last five years shows that the J-2X development effort has never been without a range of challenges, not the least of which being the straightforward technical challenge of developing a human-rated rocket engine. The collective perseverance, cooperative spirit and unflinching sacrifice demonstrated by the NASA

and PWR development teams has (so far) overcome many unexpected obstacles, culminating to date with the first development engine (E10001) beginning full-up system testing.

In addition to the continued pursuit of the finished system development and certification, the next challenge seen on the horizon will be the realignment of the design and supporting organizations from the CxP program to the SLS program. It is certain that more unforeseen challenges will be encountered in the future.

References

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