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U.S. Engineering and Operational Capability for Atlas V RD-180

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Engineering and operational capability have been established within the United States to support RD-180 use on the Atlas V launch vehicle under a joint program involving Lockheed Martin, RD AMROSS, Pratt & Whitney Rocketdyne, and NPO Energomash. The newly established engineering capabilities provide the Atlas V team the ability to supplement and complement NPO Energomash technical contributions with U.S. expertise. Additionally, U.S. operational capabilities have been established to support nominal engine and launch vehicle operations in the unlikely event NPO Energomash were unable to provide their normal level of on-site support. The successful implementation of these capabilities by the Lockheed Martin and Pratt & Whitney Rocketdyne team provides Atlas V customers increased confidence in Assured Access to Space while expediting technical and programmatic solutions for maintaining 100% Mission Success.

I. Introduction

THE RD-180 engine (shown in Figure I-1) in use on the Atlas V launch vehicle is the most advanced LO_2-Kerosene engine ever put into operational use. The advances in technology that enable this engine to perform at such extreme conditions were innovated, designed, developed, validated, and put into production by the leading liquid rocket engine design company in Russia – NPO Energomash (NPO EM).

In 1995, Lockheed Martin selected the NPO EM and Pratt & Whitney Rocketdyne (PWR) team to develop the RD-180 engine for use on its Atlas III and Atlas V launch vehicles. The engine was derived from the flight-proven NPO Energomash designed RD-170 engine. The first production RD-180 engine was delivered to Lockheed Martin in early 1999, and was successfully launched on the first Atlas IIIA vehicle on 24 May 2000. Since then, the RD-180 engine has also been certified for use on Atlas V, which had its successful maiden launch on 21 August 2002. NPO EM currently retains design authority and production responsibility for the RD-180.

Production engines are provided to Lockheed Martin by RD AMROSS (RDA), a PWR / NPO EM Joint Venture company incorporated in the U.S. Current production engines are being built and acceptance tested by NPO EM in Russia, and delivered to Lockheed Martin in Denver for integration with the vehicle. All launches to date have taken place from Cape Canaveral, Florida however preparations are currently under way to start launching Atlas V

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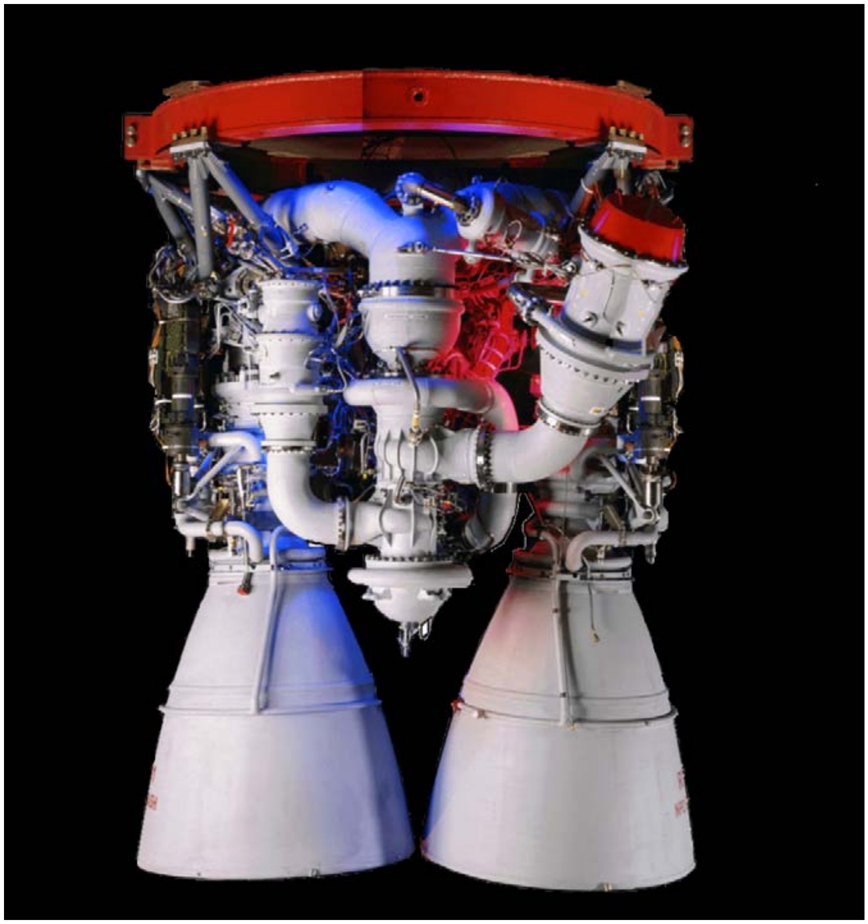
vehicles from Vandenberg Air Force Base, California. Engine acceptance processing, engine integration and launch support activities are conducted by joint NPO EM / PWR teams. To date, this activity has been primarily led by NPO EM with PWR performing an oversight role.

Figure I-1 RD-180 Engine 4A Shown Mounted to Handling Frame



U.S. engineering and operational capability to support the use of this engine has been steadily increasing since 1995 when the engine was initially selected for use on the Atlas launch vehicle. This capability, and its successful application on the Atlas V program, has taken a major step forward thanks to a joint program involving Lockheed Martin, RDA, PWR, and NPO EM. This program started in December 2003 and a major portion was concluded in June 2006. The PWR capabilities developed during that time are the subject of this paper.

Transfer of detailed RD-180 engineering and manufacturing technical documentation from NPO EM to PWR was completed in May 2004 in compliance with the license agreement. This technical documentation included engine part and component drawings, specifications, technical requirements, manufacturing operation sheets and tool drawings, and test procedures. Over 225,000 pages of such documentation were transferred from NPO EM to PWR. A major portion of this Russian language data was translated into English by PWR in order to make it available for technical use by U.S. engineers. While not the subject of this paper, this portion of the program provided the ability for PWR to develop their engineering expertise for the RD-180. Once this data became available, PWR had a much more complete database of design, manufacturing, test, and operational information to rapidly begin developing an initial level of engineering and operational capability to support the RD-180 on Atlas V.

The engineering capability that has been achieved provides PWR the ability to assess engine processing data (engine integration to the vehicle in the Lockheed Martin factory, pre-launch processing, launch countdown, and flight) and verify that the engine is operating within established limits. In the event of non-conformances, PWR has the capability to perform routine maintenance or determine if the problem can be resolved by replacing a Line Replaceable Unit (LRU). On a case-by-case basis, the engineering capabilities that were developed also allow PWR to better assess non-LRU non-conformances. These additional capabilities have already been utilized to help the Atlas V team assess and resolve various RD-180 issues and are available to be used to assist the Atlas program in the future.

The operational capability that has been established gives PWR the expertise to independently perform all routine engine integration and launch processing activities performed in the U.S. Another part of the operational capability involved the development of procedures to diagnose, remove, replace, and checkout all of the line replaceable units (LRUs). These procedures did not previously exist and were developed and verified at PWR's facility in West Palm Beach using a development RD-180 engine installed into an Atlas V thrust section mock-up. Having these procedures developed and validated ahead of time will enable the Atlas V team to quickly resolve any issues related to these components.

PWR performed a wide range of tasks to achieve these capabilities. To guide the work, an Engineering Capability Demonstration Plan was written which identified the tasks that PWR would perform, the capabilities that would result, and the specific approaches that PWR would use. This Plan was reviewed and agreed to by Lockheed Martin and became the guiding document for the remainder of the work. Various Design Evaluation Reviews and Operational Readiness Reviews were conducted so that PWR could present the results of their activities to Lockheed Martin and obtain concurrence that the desired capability was in-place.

Development of analytical models was a major portion of the engineering capability development activity. Detailed stress, flow, thermal, performance, and functional engineering models were developed for a wide variety of engine components. These models, combined with the NPO EM data, enable PWR to supplement and complement NPO EM technical contributions with U.S. expertise.

The combination of advancements in engineering and operational capability increases the ability of Lockheed Martin to provide Assured Access to Space for our customers. Additionally, a combined PWR and NPO EM expertise can now be brought to bear on any RD-180 anomalies to help continue achieving 100% Mission Success on Atlas V. The accomplishments demonstrate that the Atlas V team has developed a more robust U.S. capability that will benefit Lockheed Martin and their customers.

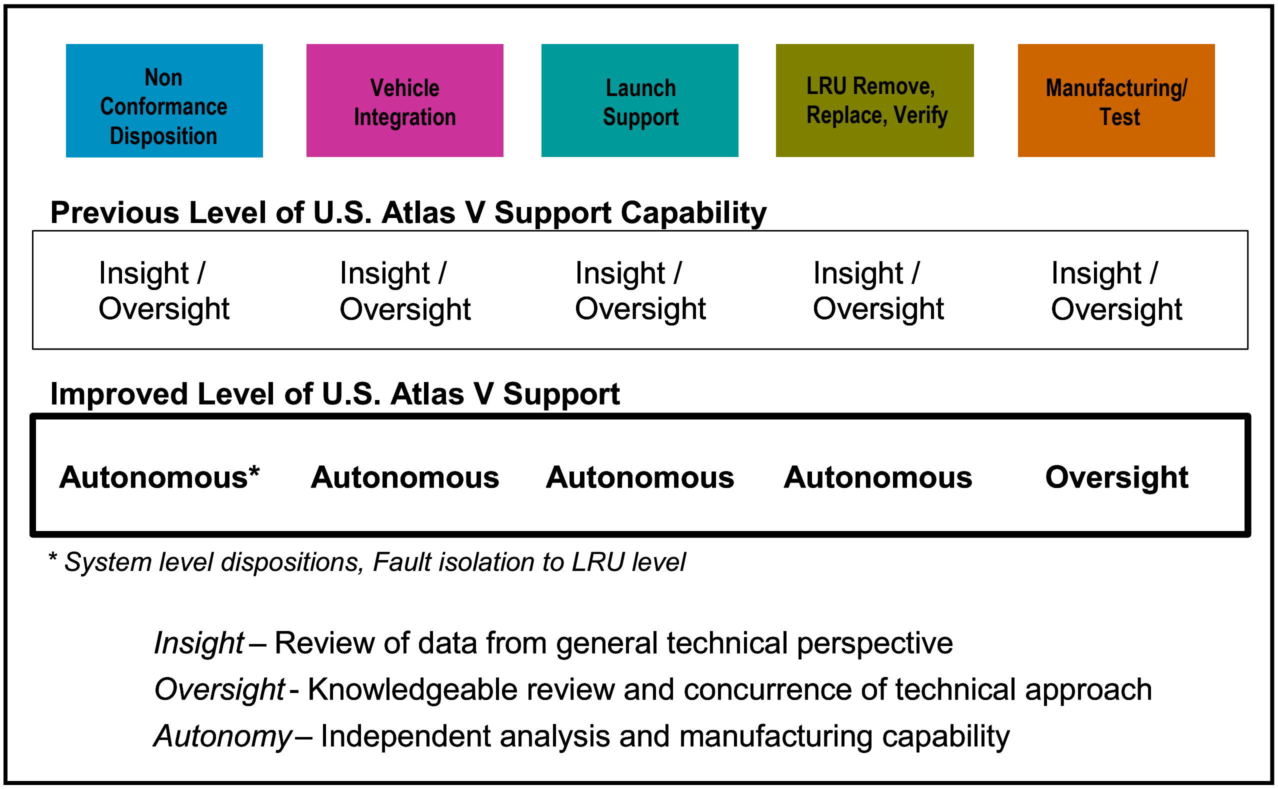
II. Goals of U.S. Engineering and Operational Capability for Atlas V

The Atlas V program has relied on the combined team of RDA, NPO EM, and PWR to perform all the support required to utilize the RD-180 engine. Primarily, NPO EM has provided technical support with PWR providing an oversight role. This has worked very well and has resulted in a 100% Mission Success record for the Atlas III and Atlas V vehicles, however, Lockheed Martin and RDA desired to strengthen the U.S. technical capability to achieve three primary goals.

First, a stronger U.S. technical capability would contribute to ensuring that future launches would continue achieving Mission Success. Second, improved response time can be achieved by addressing issues using a qualified and trained domestic capability that is closer to the launch vehicle source. Third, PWR could provide temporary coverage in case of any interruption due to export, licensing, or other events that could arise when using a non-domestic source.

With these goals in mind, the level of expanded technical capabilities that PWR has developed is shown in Figure II-1. Across five major areas of program technical support, PWR has increased the U.S. capability to support the Atlas V program from the previous level of performing insight/oversight to the increased capability levels shown where much greater autonomous capability exists. This improved level of PWR capability can now be utilized in support of future Atlas V missions. An initial proposal has been provided to continue to utilize and expand these capabilities.

Figure II-1 Evolution of RD-180 Engineering and Operational Capability



III. Approach Used to Enhance PWR's Capabilities

To address the requirement for an increased level of engineering and operational capability, PWR identified the engineering and field operations support skills and knowledge that would be required to become more self-sufficient. These skills and knowledge are elaborated upon in Figure III-1 and can be summarized into five primary strategies:

1. Develop the ability to disposition non-conformances unique to the RD-180
2. Support engine-to-vehicle integration at Lockheed Martin's Denver facility
3. During engine-to-vehicle integration and launch processing, be able to disposition faults to the LRU level
4. Support launch operations
5. Support manufacturing operations including disposition of non-conforming conditions generated in the course of making engine hardware.

To achieve these five skill/knowledge strategies, PWR then developed engineering models and conducted analyses to provide tools to be used to assess engine conditions (strategies 1 and 5), implemented a rigorous instructional program to train field support personnel (strategies 2 and 3), and created procedures for the removal and replacement of LRU's including troubleshooting procedures (strategy 4).

Figure III-1 Engineering and Operational Capability Objectives

Non-Conformance Disposition Review	Vehicle Integration	LRU Diagnosis, Remove/Repair, Verification	Launch Support	Manufacturing Demonstration
• Develop capability to resolve anomalies to the LRU level • Develop capability to assess data to determine if an anomalous condition exists • Establish database containing non-conforming data • Establish set of requirements to be used when judging non-conforming conditions • Establish analytical models that could be used to assess anomalous conditions	• Train and certify additional support personnel • Develop capability to support routine integration activities • Develop capability to resolve simple integration problems not requiring breaking of a interface • Establish models & analysis tools that could be used to assess integration data	• Train and certify LRU maintenance personnel • Develop LRU removal and replacement procedures • Develop LRU troubleshooting and post-installation checkout procedures • Establish models & analysis tools that could be used to assess integration data	• Train and certify additional support personnel • Develop capability to support routine launch activities • Develop capability to resolve simple launch problems not requiring breaking of a interface • Establish models & analysis tools that could be used to assess launch data	• Establish engineering expertise to support manufacturing and assembly activities • Establish models & analysis tools that could be used to assess Mfg and assy equipment and tooling requirements • Develop models to be used to evaluate the condition of US-built hardware

PWR's approach to developing engineering and operational capability for the RD-180 engine employed a multi-faceted process including the following aspects:

- Receipt of all required information needed to manufacture the RD-180 in the U.S.
- Assess delivered data to assure compliance with data transfer requirements
- Convert select data to appropriate U.S. standards
- Develop engineering knowledge required to manufacture / support the RD-180 engine in the field, including:
  - Evaluate and assess component requirements
  - Identify most critical components and failure modes
  - Define modeling and analyses plan
  - Develop engineering models, conduct analyses
  - Validate models
- Develop field support capability including training materials, procedures, tools, ground support equipment (GSE), etc.
  - LRU definition
  - GSE

To receive information required to manufacture and support the RD-180 in the field, a review of RD-180 source documentation categories was conducted with participation of NPO EM. PWR also conducted its own independent review of desired information. From the reviews, a list of documentation to be transferred was defined and finalized by PWR and NPO EM. Subsequent to signing the existing agreement by appropriate agencies, NPO EM proceeded with assembling and shipping the documentation to RDA and PWR in the U.S. This documentation included all engine drawings, parts lists, design and manufacturing specifications, analytical reports, material specifications, manufacturing operation sheets, test procedures and tool drawings.

Assessments of the transferred documentation have been conducted and current findings confirmed that all significant technical and manufacturing documentation were transferred. PWR has conducted audits of the transferred data to assure its completeness. Where discrepancies or inadvertent omissions were identified, PWR and

NPO EM worked to resolve them and in some cases this has resulted in additional data to be transferred. All transferred data are secured at PWR facilities and controlled to prevent unauthorized access. The transferred design, test procedures and tooling documentation is in paper format (copied from NPO EM originals) while the manufacturing documentation was transferred on CD and consists of scanned copies of NPO EM manufacturing operation sheets. The transferred documentation set is considered adequate and appropriate to manufacture the RD-180 in the U.S. once converted to PWR U.S. standard formats for internal and supplier usage.

Engineering Capability

Conversion of a subset of the transferred documentation to U.S. standards has been accomplished. This effort was composed of three primary steps: conversion of Stator with Preburner drawings, specifications, and manufacturing operation sheets; conversion of Russian paper design documentation for generation of computer aided design (CAD) models; and conversion of a sampling of the engine drawings to evaluate the completeness of the transferred documentation.

The conversion process started with the Russian source documentation and through an integrated product development (IPD) process, PWR established U.S. drawings, specifications, CAD models and manufacturing operation sheets. Several challenges were encountered in this process and had to be overcome, not the least being significant differences in drawing standards between the U.S. and Russian drawings. A couple of examples are the use of third angle projection used by NPO EM while PWR typically uses first angle, Russian tolerancing process which defines a feature's basic size and uses fit classes to define the tolerance while PWR uses the mean dimensional value with a bilateral tolerance, older NPO EM drawings lack geometric tolerancing (roundness, parallelism, true position, etc.) relying on "limits of size", the use of unspecified dimensions, and over dimensioning. PWR has successfully converted all Stator with Preburner drawings and specifications and is in the process of manufacturing hardware to these drawings. Additionally, PWR has generated over 800 CAD models representing the majority of critical RD-180 hardware. These CAD models were used for finite element modeling (FEM) and analyses, which are discussed in the subsequent paragraphs.

All CAD modeling was initiated with a nominal (geometric mean) representation of the component being modeled. A copy of the nominal model was made and modified or simplified as required for FEM modeling purposes. PWR FEM modeling standard work typically models the nominal geometric dimension then ratios the results to represent the minimum material value (which usually results in higher stress concentrations). Additionally, to reduce FEM mesh sizes and promote quicker computer solutions, certain geometric features were suppressed in the CAD model used for the FEM. All such suppressed features were determined to have minimal impact to the overall thermal or structural model.

As part of the conversion process, PWR conducted functional assessments of the RD-180 hardware. This process reviewed each feature of the hardware being converted and evaluated the purpose that feature played in the operating characteristics of the engine. PWR found that the functional assessments were critical to obtain a proper understanding of the feature(s), ensuring that the converted documentation (drawing, specification, etc.) correctly replicated the original design intent.

To further facilitate the development and understanding of design requirements, PWR embarked on an effort to develop a product requirements document (PRD) for the Stator with Preburner. PWR uses PRDs to document component requirements that must be maintained to assure design integrity. PRDs are essentially a component specification and document all engineering requirements that must be designed into the component. Verifications of these requirements are a crucial step in the development process and methods for the verifications are documented in the PRD. PWR used a standardized outline to generate the RD-180 PRD. Included in the PRD are component interface requirements such as interface loads and geometric constraints. To create the PRD, PWR reviewed NPO EM documentation and, to the extent possible, derived component requirements. In those cases where the requirement could not be derived, PWR defined requirements based on prior engine development experience, modified as necessary for RD-180 application.

The plan for expanding RD-180 engineering capability was established early in the process for reducing risks to the Atlas program and assuring access to space. The plan was documented in what is known as the Engineering Capability Demonstration Plan (ECDP). This plan documented the modeling and analysis planned by PWR to expand engineering knowledge and expertise of the RD-180 engine operating and functional characteristics, critical design features that needed to be maintained, and design margins. This work represented a crucial first step towards obtaining a level of knowledge that would permit PWR to produce the RD-180

The ECDP focused on assigning modeling and analysis tasks to the most critical components, components with lowest margins, and more probable failure modes. The modeling and analysis included engine system and component performance, aerodynamic, thermodynamic, structural, rotor dynamics, controls functional, and design analyses (fits and clearance). Examples of critical components chosen for analyses included the chamber, main turbopump unit (MTU), boost pumps, hot gas ducts, control components, and thrust frame. The modeling and analysis task requirements were identified on a component basis using an analysis requirements matrix. The matrix listed each component that was planned to be analyzed across the top. On the left hand side of the matrix were listed all possible analyses that are typically performed on rocket engines. Matrix blocks were then checked off for all planned analysis/component combinations.

The primary purpose of the performance models are to analyze engine acceptance test and launch data, however, these models can also be used to assess hardware non conformances, especially those associated with propellant flow path geometric discrepancies. Aerodynamic and thermodynamic models are typically used to generate loads for structural models but these too can be used to assess propellant flow path geometric discrepancies or evaluate component test data. Their use in engine test or field anomaly investigations is called upon when the need arises. The structural and rotor dynamics models are primarily intended for use in assessing hardware non-conformances generated during the manufacturing and assembly process. In the rare event of an operational anomaly being encountered either during integration or launch operations, the structural models can be used as an investigative tool. Control functional models are used primarily in engine test or field anomaly investigations.

Development of the engine system performance model was accomplished in a multi-step process starting with a model evolved from the NPO EM performance model. The NPO EM model was a combination of empirical and physics-based code. PWR first refined this model by installing code to permit additional performance parameter output. Supported by PWR's Aerodynamic group, pump and turbine performance maps were generated at a component level and then rolled into the engine system performance model. Additionally, PWR conducted secondary flow and thrust balance modeling which were also incorporated in to the engine system performance model. An interim step in the modeling process was to replace the NPO EM empirical code with physics based code. PWR also converted the model into a standard modeling code used in the U.S. known as Rocket Engine Transient Simulation (ROCETS). PWR validated the ROCETS model by comparing it to the NPO EM model and then using the extensive amount of engine test data that was available for this purpose. The ROCETS engine system performance model has data reduction capability permitting the evaluation of specific engine performance based on measured parameters from the engine being evaluated.

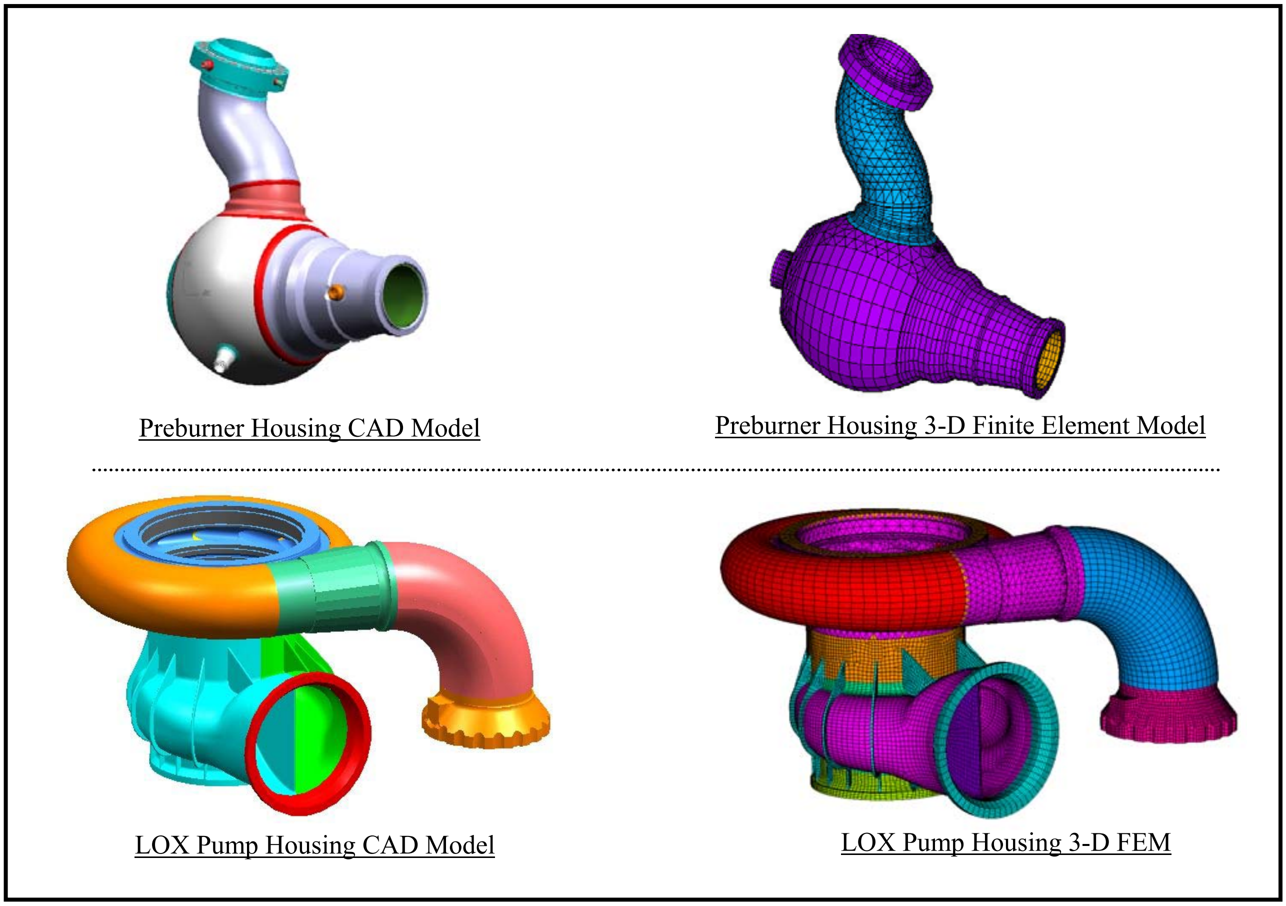
The engine performance model has been exercised at various operating conditions. Engine performance characteristics (pressures, temperatures, and flows) are typically output to computer files that are later used to generate boundary conditions for aero, thermal, and structural analyses. Upon completion of the engine system performance model, PWR conducted component sensitivity studies to evaluate and understand how changes in specific performance parameters could affect engine performance characteristics. These sensitivity studies were conducted over a wide range of possible operating conditions, typically varying one parameter at a time. Plots of these sensitivity studies were made for future reference.

Secondary flow path and thrust balance analyses were performed to calculate pressures in the cavities in the RD-180 engine turbomachinery. These analyses were conducted for the MTU as well as for both boost pumps. In addition to supporting the performance modeling, these analyses provide loads used in thermal, structural, and design (clearance) analyses. In the course of doing this work, several unique and intriguing features of the RD-180 engine were uncovered, once again providing expanded insight to the engine design.

Aerodynamic and thermodynamic models have been generated and analyses completed. The aerodynamic analyses included computational fluid dynamics (CFD) models for the blade, vane, impeller, and inducer components. Results of these analyses have provided new insight to the design characteristics of the RD-180 engine. Pressure and temperature outputs from the CFD models were used as boundary conditions for the structural models. Thermodynamic models were made for many of the more critical components. Heat transfer analyses were performed using ANSYS FEM. The output from the heat transfer FEM analyses was then used in structural analyses. To reduce workload, the ANSYS FEMs were meshed to accommodate both thermal and structural requirements. Using a common FEM mesh permitted easy mapping of the heat transfer-generated temperatures to component geometry for application in structural modeling.

Structural modeling and analyses were performed for most major components. The work was accomplished using ANSYS FEM code as well as hand calculations where necessary or appropriate. Over 48 FEM models were created in the course of the program. Examples of some of the FEMs created are shown in Figure III-2. In contrast, most available NPO EM structural analyses were conducted using hand calculations.

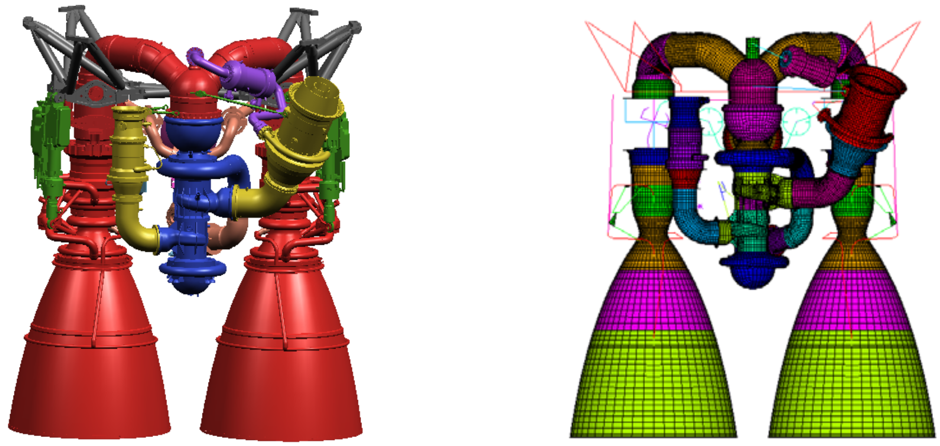
Figure III-2 Examples of RD-180 Component CAD and Finite Element Models



Boundary conditions were derived from the performance, aero, and thermal modeling as well as from calculated component interface loads generated using a complete engine structural loads model. The engine structural loads model, along with the engine CAD model, is illustrated in Figure III-3. This loads model included a super-element representative of Atlas V vehicle. Structural margins were calculated and compared to the NPO EM margins and in most cases, good agreement was achieved. In those cases where reasonable agreement was not achieved, an effort to rationalize the difference was performed. These structural models will be very useful in assessing non-conformances and can easily be modified to represent non-conforming conditions, if needed.

Rotor dynamics modeling and analyses were conducted for the MTU and both boost pumps. PWR used a Pratt & Whitney-proprietary computer code known as Advanced Rotor Dynamics Analysis (ARDA) for prediction of critical (resonant) rotor speeds. The results of these analyses showed that most critical speeds were well out of the engine operating range indicating good design practice on the part of NPO EM.

Figure III-3 RD-180 Engine Structural Loads Finite Element Model



Engine CAD Model   Engine Structural Loads FEM

To support the various analyses, PWR constructed over 375 material property curves using NPO EM design documentation, material specifications, and public domain literature. Typically, U.S. aerospace industry requires full material characterization where the important material properties are defined over the complete operating range of the hardware employing the material. However, the Russian material data provided to PWR identified material property definition at the maximum design condition (and possibly one or two other temperatures) and not over the full range of operating temperature. This difference makes FEM more difficult and less accurate hence PWR was required to fill in the gaps in the material property curves. PWR was able to do this due to its extensive experience with material development and characterization testing. Filling in the material property curve gaps was typically done by finding a U.S. material of similar chemistry to the Russian material and using the U.S. material curve shape plotted through the available Russian data. These estimates were reviewed by NPO EM. PWR then developed a database containing the Russian material properties that permits the mapping of properties to FEMs and allows quick access to property values.

Controls functional analyses were conducted for individual control components and were then assembled into control subsystem models. A total of twenty-five component and three subsystem, physics-based math models were generated. PWR used the EASY5 computer modeling software package for this purpose. The models were constructed for evaluation and study of the control component dynamic response as well as for future anomaly analyses. Control component drawings and requirements were studied in detail to properly represent the models in EASY5 code. Model outputs were typically validated using component and engine test data. Overall, good correlation with available test data was achieved.

Fits and clearances analyses for the MTU and boost pumps were conducted and documented using an engineering spreadsheet. The fit and clearance analyses initially calculated static build (not operating) gaps and interferences using the drawing prescribed tolerances. The influence of assembly transference of fit and chill-down and operating temperatures and pressures were then applied to provide fit and clearance predictions at various mission operating points. The spreadsheets have been set up to allow various combinations of hardware tolerances to be calculated by simply indicating the tolerance value(s) requiring study. Additionally, to calculate clearances, the results of the structural FEMs were required for deflections and growth of rotating and static hardware.

Model validation was accomplished using component and engine test data as well as existing NPO EM analyses, where available. PWR made use of this information and also relied on its many years of conducting similar analyses for other rocket engines as well as gas turbine engines. There is a long history of successful RD-180 engine testing in which much data has been gathered. With over 36,000 seconds of engine test experience, this data proved useful in calibrating and validating the engine system performance model. The engine test data was also used for the control component and subsystem functional model validation. PWR also conducted limited component testing to assist in understanding design characteristics. Flow model tests were conducted for the partial admission supersonic LOX boost pump turbine.

Following completion of the modeling and analyses, PWR held a series of design reviews concentrating on the models as compared to the NPO EM predictions and highlighted any significant findings uncovered in the course of conducting the work. These reviews were known as Design Evaluation Reviews (DERs) and the System Design Evaluation Review (SDER). The DERs focused on component modeling and analyses while the SDER focused on subsystem and system-level analyses. A combined total of five reviews were conducted. The reviews included PWR, Lockheed Martin, and USAF customers and found that PWR had met the objectives of establishing engineering capability to date as defined in the ECDP.

Operational Capability

The second element of enhanced mission assurance was the development of operational capability. This element addressed the need for improving PWR's ability to support field operations (engine-to-vehicle integration and launch support). Although PWR already had some field support capability, it was limited to a few individuals and PWR did not have a structured training program. With the expectation of increased launch rates as well as implementation of launch capability at multiple sites, it became apparent that additional personnel would be required if a responsive support level was to be provided. PWR embarked on an effort to enhance the then-current support level by developing training materials that could be used to train additional personnel, and document proficiency levels of the trained personnel. Associated with this effort was the ability to remove and replace LRU's in the field environment.

To develop the training materials, PWR worked closely with Lockheed Martin personnel to document all steps required to process the engine starting with the engine delivery in the U.S. (at Lockheed Martin's Denver factory facility) through final closeout in the post launch data reviews. The training manuals were developed in two parts, the first focusing on engine-to-vehicle integration and the second addressing launch-associated operations. Each training manual describes every step required for engine processing and has sign-offs indicating concurrence that the trainee has successfully demonstrated his/her ability to perform the task to the level of proficiency required.

The effort to develop LRU capability required PWR and NPO EM to evaluate the RD-180 engine to identify components that could be removed and replaced in the field without inducing unacceptable risk to the engine. Replacement of LRU's also required that any LRU component replaced would not require that the engine be hot fire tested to verify the integrity of the maintenance action. However, other non-engine test verifications are required.

The list of LRUs was initially defined by PWR and subsequently reviewed and negotiated with NPO EM and Lockheed Martin. The list was developed with specific criteria designating whether the component would qualify for LRU status. Once the list was established and agreed to, PWR set about writing the removal, replacement, and verification procedures. The structure of the procedure was modeled after procedures developed for other engine programs. In earlier phases of the RD-180 program, a development engine known as engine 4A had been acquired. In conjunction with NPO EM source documentation (drawings, specifications, manufacturing operation sheets, etc.), this engine was used to develop and verify the removal, replacement, and verification procedures.

PWR converted a portion of its facility in West Palm Beach, Florida, to accommodate the planned expansion in operational capability. In addition to being capable of supporting field operations task development, the facility was modernized and designed to accommodate final engine assembly (for U.S. production capability). PWR had to design and procure GSE and tooling required to support the maintenance actions. A photo of the engine support frame with engine 4A mounted to it is illustrated in Figure III-4. Also shown in the figure is the PWR RD-180 Assembly Facility. The original orientation of the engine in its shipping mount required that the engine support frame be capable of rotating the engine. To better simulate the configuration of the engine and vehicle while on the launch pad, PWR procured a scrapped Atlas V fairing and replicated floor, which were then mounted to the engine frame. PWR now has the engine configured as it would be in the launch vehicle.

PWR designed tooling included simple customized wrenches as well as more complicated tools. Electrical, pneumatic, and hydraulic carts identical to those being used in the field were also procured. In addition to the PWR-designed tooling, some tooling such as wrenches and adapters were purchased from NPO EM. Consumable materials and expendable parts used in the removal and replacement procedures were procured from NPO EM.

Figure III-4 RD-180 Engine Mounted in Support Frame

With the first draft of the LRU removal and replacement procedures complete, PWR ran a series of procedural validation trials using engine 4A. A photo showing removal of a Thrust Vector Control (TVC) actuator (a designated LRU component) is shown in Figure III-5. Results of the trials were confirmed by NPO EM. The trials proved beneficial in identifying areas requiring improvement. The procedures were updated and a second series of trials were successfully performed. PWR also created troubleshooting and diagnostic procedures enabling PWR to disposition anomalies to the LRU level. With full validation of the procedures, the RD-180 Field Service Manual was updated to incorporate the LRU removal, replacement, and verification procedures including the trouble shooting procedures.

Some of the tasks are fairly complicated requiring highly skilled mechanics. PWR has trained engineering and mechanic staff that are now ready to perform any task associated with LRU activity should the need arise. Periodic retraining is planned to assure this staff stands ready to accommodate any request for LRU maintenance.

To assist in future anomaly resolutions, PWR has also developed a database of all RD-180 non-conformances. The database includes various forms of field issues, deviations and waivers, as well as manufacturing generated non-conformances. The database allows the field engineer to quickly access the historical data to see if the same or a similar anomaly has occurred in the past and, if so, allows the original anomaly report to be pulled up for quick reference.

Figure III-5 Removal of RD-180 TVC Actuator Conducted During Trial Removal

TVC Actuator Being Detached from Engine Mount

TVC Actuator Being Lowered from Engine

PWR has used the engineering models and analyses discussed in this paper to evaluate prior engine anomalies as well as recent engine investigations as directed by the customer base. The models and analyses have already proven their worth, not only for these investigations but for providing design insight not previously available. PWR now has training programs in place, additional trained field support staff, and the capability to replace LRU components should the need arise. This level of enhanced support now available reduces risk and improves responsiveness to field problems. With this new level of engineering knowledge that PWR has built up and the enhanced level of field support capability, PWR stands ready to support the RD-180 as never before possible.

IV. Conclusion

Assured Access to Space and Mission Success for Lockheed Martin customers continues to be reinforced through the joint efforts of the Lockheed Martin, RD AMROSS, Pratt & Whitney Rocketdyne, and NPO Energomash team. The skills and models that have been established by Pratt & Whitney Rocketdyne engineering and operations support personnel provide expanded capability to address technical issues in order to minimize impacts and expedite solutions for the Atlas V program. State of the art modeling tools have been generated for the critical components of the RD-180 engine that enable Pratt & Whitney Rocketdyne to analyze in detail most problems that may be observed. In the process, Pratt & Whitney Rocketdyne has established a high level of design understanding of this unique NPO Energomash-designed engine. Detailed procedures for supporting field operations reinforces the ability of the Atlas V team to successfully integrate, test, and launch the RD-180 engine. The level of U.S. capability to support the RD-180 and Atlas team in mission success is significant and viewed as an important contribution to the Atlas V program.