

Incorporation of RD-180 Failure Response Features in the Atlas V Booster Emergency Detection System

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Abstract

Approximately 70% of the parts on the RD-180 engine as used on Atlas V launch vehicles are common with the RD-170 engine. The RD-170 engine was developed by NPO Energomash and certified in 1985 to power the Energia Buran rocket launch system, which was rated for human spaceflight as defined by the Russian standards. With over 45,000 seconds of operational time, the RD-180 has an extensive history of demonstrated performance, robustness, and reliability as does the Atlas vehicle that it powers. This paper describes why the RD-180/Atlas combination provides an optimal solution for human space flight directly applicable to the near-term commercial crew transportation program. The paper will examine how the RD-180/Atlas booster combination could meet Commercial Crew space flight requirements. An overview of the past NASA human space flight requirements to the Russian approach for manned flight will also be made. The paper will discuss the work that has been done to understand not only the potential failure modes to which the RD-180 propulsion system could be subjected to but also how these failure modes could be quickly identified, mitigated or managed such that a safe crew abort sequence could be initiated. The RD-180/Atlas Emergency Detection System (EDS) will be described and shown to be a viable approach to meeting Commercial Crew space flight requirements. This will include a discussion on the monitoring of key engine parameters that will provide early detection and notification to vehicle computers to verify the onset of the failure and enable rapid response. An explanation as to why the RD-180 offers an affordable solution to Commercial Crew transportation will be presented. Areas requiring further work will also be discussed.

I. Atlas/RD-180 Background and Future Plans for Space

The RD-180 liquid-propellant rocket engine provides boost phase thrust for United Launch Alliance's (ULA) Atlas V launch vehicle (see Figure 1). Additionally, the RD-180 was the propulsion choice for all Atlas III launch vehicles. Providing nearly one million pounds of thrust, the RD-180, is the highest performing state of the art kerosene-fueled booster engine in the world.

Pratt & Whitney Rocketdyne (PWR) and NPO Energomash (NPO-EM), working together under cooperative agreements, have provided reliable, low-cost propulsion to the U.S. Atlas vehicle manufacturer for more than sixteen years. Through Pratt & Whitney's and United Technologies Corporation's financial investment, the RD-180 was designed, development tested, and flight qualified initially for the evolutionary Atlas III launch vehicle. This cooperative effort was further reinforced by the formation of a joint venture (JV) between the two companies known as RD AMROSS, which is the sole distributor of the RD-180 engine in the U.S. Through RD AMROSS, a PWR and NPO-EM JV company, the RD-180 engine has been certified for the more demanding thrust profiles of the Atlas V vehicle. RD-180s have successfully powered thirty-three (33) Atlas launch vehicles; including twenty-seven Atlas Vs with a 100% mission success record.

Representative CTS Atlas V 402 Configuration

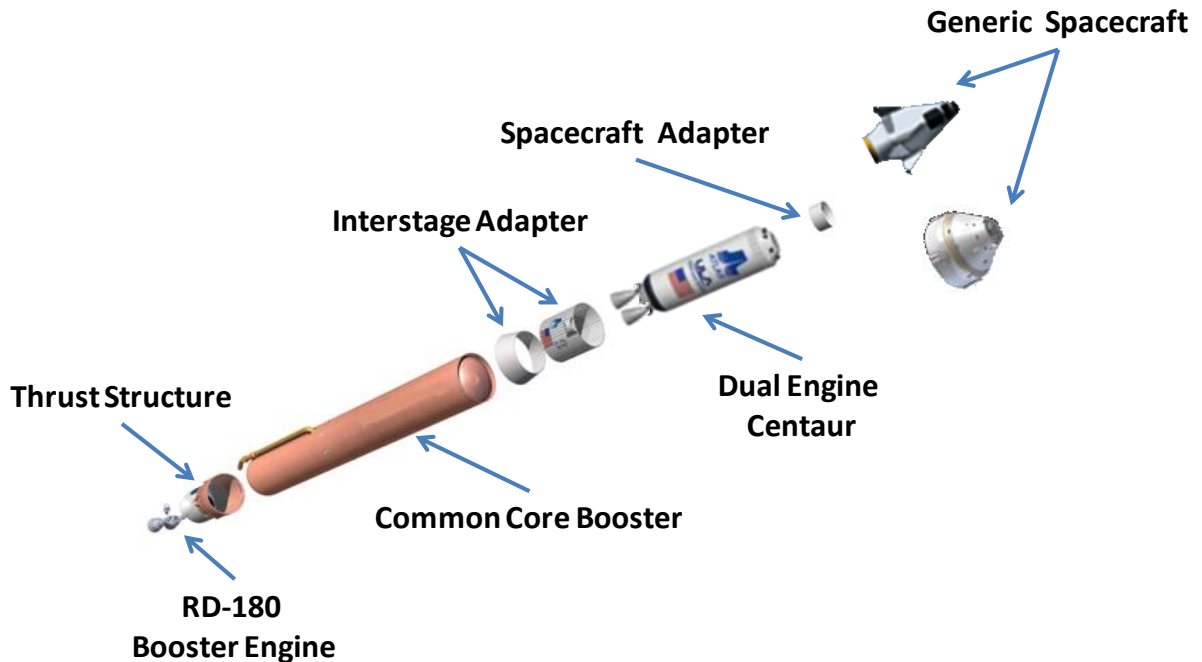


Figure 1. ULA Atlas V Launch Vehicle Configurations.

Governmental agencies are currently assessing commercial launch vehicle and spacecraft systems to provide crewed deployment to low earth orbits (LEO) and the International Space Station (ISS). The Atlas V/RD-180 combination can provide a reliable, low-cost boost stage for this purpose. Under the Commercial Crew Development (CCDev) program, companies are proposing a multitude of technologies and approaches to meet various aspects of the CCDev program objectives. The CCDev program is funded by NASA along with commercial contribution. The CCDev program is intended to stimulate development of privately operated crew transport systems to low earth orbit. U.S. industry participants are working to mature the design and development of commercial crew spaceflight concepts and associated enabling technologies and capabilities. In the first phase of the program, NASA provided a total of \$50 million to five companies with the intention of stimulating research and development into human spaceflight concepts and technologies.

Under the CCDev Phase 1 program ULA received \$6.7M to study an EDS for human-rating of its EELV launch vehicles. The work under this contract has been completed and in-part will be summarized in this paper. This RD-180 work was completed in the spring of 2011 and included evaluations of RD-180 failure modes, Time-to-Criticality assessments, and how these failure modes could be accommodated (fault coverage) in the event that a failure occurred. No NASA CCDev 1 funds were provided to RD AMROSS or NPO Energomash for the RD-180 work. Additionally, ULA conducted a laboratory demonstration of a prototype Emergency Detection System.

CCDev Phase II Request for Proposals were issued by NASA in the fall of 2010 to further mature launch vehicle and spacecraft concepts for project durations of up to ~14 months. Because of the Atlas/RD-180 booster's high level state-of-readiness, low-risk development and flight-proven launch history, ULA did not receive NASA funding for this round. The \$268M in NASA funding was provided to the Spacecraft developers. Many of these Spacecraft developers have chosen Atlas as their baseline launch vehicle. Consequently, ULA continues the CCDev Phase II Crew Transportation System certification work as an internally funded program.

A. Engine Heritage and Description

The RD-180 is a two-chamber liquid propellant engine that utilizes a staged combustion cycle. The oxidizer-rich staged combustion cycle was introduced with the NPO Energomash RD-253 engine in 1965 as part of the first stage of the Russian Proton launch vehicle that continues to fly today. Six gimbaled single-chamber RD-253s provide the first-stage power for the UR-500 Proton launch vehicle. The RD-253 was the first non-cryogenic engine in the world that used staged combustion afterburning of oxidizer-rich hot turbine gas. The RD-253 (and associated derivatives) is also famous because it is the most reliable Liquid Propellant Rocket Engine Assembly (LPREA) in the world having achieved a record >1788 consecutive faultless engine-flights.

The RD-180 (see Figure 2) was derived from the similarly famous RD-170 (see Figure 3); the highest thrust rocket engine to power a space launch vehicle - more than 1.75 million pounds of thrust. The RD-170 engine and its variants use a four-chamber configuration powered by dual preburners and a single Main Turbopump Unit (MTU). The RD-170 engine development initiated under Valentin Glushko, founder of NPO Energomash, over 40 years ago following a series of N-1/NK-15 Moon Program failures. The NK-15 engine was designed and developed under the direction of Sergei Korolev Chief Designer for RKK Energiya (and following his death in 1966, by Vasily Mishin). Following the four (4) N-1 failures, additional changes were made in attempts to improve the system reliability including engine upgrades that resulted in the NK-33 engine configuration. The redesigned expendable rocket was known as the N-1F but was cancelled due to three factors: the rocket with its thirty engines proved unreliable; there were funding shortages within the Russian government; and the U.S. was successful in reaching the moon.



Figure 2. Photo of RD-180 Engine.

At this point in history, Russian rocket engine leadership responsibility was reassigned to Glushko, who was assigned responsibility for providing propulsion power for the Soviet space shuttle Energia-Buran. He felt it necessary to replace the NK-33 with his own higher thrust LOX/kerosene engine and determined that one RD-170

engine could replace four and one-half NK-33 engines, thus allowing for a less complicated, state of the art design and offering a more reliable configuration. The RD-170 was designed and developed for a human spaceflight (HSF) application on the Energia launch vehicle. In addition to the engine being rated for manned flight, it was also designed and qualified to be reusable for up to 10 flights. The RD-171 variant currently provides boost propulsion for the Sea Launch and Land Launch Zenit vehicles (Zenit 3 SL and Zenit 3 SLB).

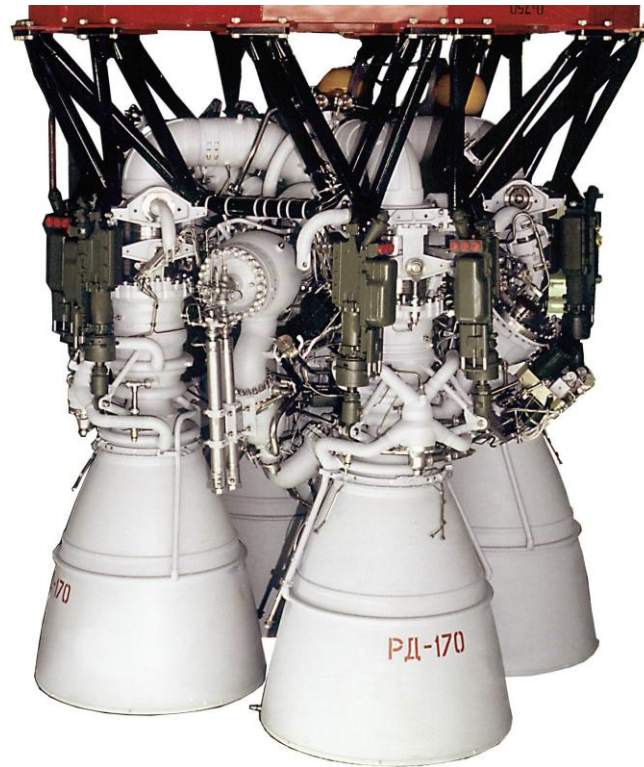


Figure 3. Photo of RD-170 Engine.

Development of the RD-180 engine for use on ULA launch vehicles was initiated in 1996 through contractual agreements between NPO Energomash and Pratt & Whitney, a United Technologies Company. A streamlined development program was possible since the key technologies and full-scale combustion devices had been previously developed in Russia for the RD-170/171 family of engines used on the Energia-Buran and Zenit launch vehicles respectively. The RD-180 matured rapidly as a two-chamber derivative of the four-chamber RD-170/171 engines. It has 70% common hardware with the RD-170, and most of the remaining parts are scaled from the RD-170. The development tasks centered on developing and certifying the new turbomachinery that was scaled for approximately 50% flow at 105% of the RD-170 pump discharge pressures. In addition, a simplified open-loop control system was provided that required new designs for the thrust control regulator valve and the mixture ratio control valve and engine control algorithm. A newly designed engine-mounted fuel pre-valve was also provided to accommodate the necessary interface with the Atlas launch vehicles for engine start requirements. The RD-180 staged combustion design cycle achieves specific impulse close to the theoretical value and affords the maximum degree of chamber nozzle expansion within a limited envelope. As a result the RD-180 has demonstrated a specific impulse specified at 339.3 sec in vacuum.

The RD-180 engine has two chambers and one preburner taken from the RD-170 design. This reduced the risk, cost and development time of the RD-180, when compared to alternative options such as developing two separate engines or a single chamber engine. The first flight-ready RD-180 engine was delivered within two years of the start of the engine development program.

Each Chamber assembly is gimballed in two planes for thrust vector control. This feature is implemented through the innovative construction of the gimbaling unit on each hot oxygen gas line. Strains developed by the actuator for chamber gimbaling are confined structurally to the engine elements. This is an optimal solution that provides flight control not only in pitch and yaw, but also in roll direction.

Primary turbomachinery elements are mounted on a single-shaft MTU, which can be more accurately be described as two coaxial shafts connected with an elastic torsional spring. This traditional Russian engine design characteristic results in engine weight reduction and simplifies engine control during transient and static operation modes.

Engine throttle range of 100%-47% for ascent control is accomplished through the use of only two Electro-Hydraulic Actuator-driven valves, the thrust control regulator valve and fuel mixture ratio control valve. The RD-180 engine has demonstrated throttling capability to 40%. These features provide the capability for Atlas to accommodate a wide range of payload and ascent requirements.

Combustion stability is achieved for a wide range of thrust and fuel/oxidizer mixture ratio values through the application of modular construction of the preburner and main chamber injector heads with raised injectors. The preburner and main chamber injector, being the same as used for the RD-170 family, have the additional demonstrated hot-fire testing time that occurred for RD-170 development, applicable to RD-180 combustion stability.

A robust chamber cooling design is achieved through internal film cooling (annular slot curtains) and external (milled cooling channels) in combination with a protective hot-wall film coating and other advanced combustion chamber cooling technologies. This further accommodates the LOX-rich stage combustion of the engine operating cycle.

Several functional and control devices are included as part of the overall engine design. These include helium bottles for control of pneumatic actuators and purging; a fuel Inlet pre-valve that separates launch vehicle and engine kerosene lines; vacuum ejector for evacuation of kerosene lines before fuel fill and launch; integral hydraulic system for TVC and EHA control valves; in-line filters in all hydraulic and gas lines; heat exchanger for helium heating to pressurize the boost stage oxygen tank; and sensors of various types for monitoring of the engine during test, pre-launch and flight operations. The use of these devices within the engine system provides for a minimum number of connections between the engine, launch vehicle and launch pad thus reducing labor intensity and time of launch preparation operations. It also provides flexibility in response to unforeseen external hurdles during launch preparation and provides efficient monitoring of all pre-launch operations and engine start. Table 1 provides a summary of the RD-180 engine performance characteristics.

Table 1. RD-180 Engine Performance Characteristics

Thrust SL/Vacuum	860,200 / 933,400 lbf
Isp SL/Vac	312.7 sec / 339.3 sec
Cycle	Staged Combustion, Oxidizer rich turbine drive
Throttle Range	47% to 100%
Chamber Pressure	3,722 psi
Mixture Ratio (O/F)	2.72 ± 7%
Length	140 in
Maximum diameter	124 in
Chamber exit diameter	56.3 in
Nozzle area ratio	36.4 : 1
Weight (dry)	12,081 lb

B. Current Design Considerations

The RD-180 engine has an excellent history of dependable operation. Mission reliability has been 100%. Engine development, certification, and operational experience have demonstrated that the engine easily meets its design requirements due to its rugged design heritage. Since the start of the RD-180 production program, all significant issues encountered to date have been a result of manufacturing or quality issues and not design deficiencies. Consequently, NPO Energomash has implemented key manufacturing and test events into the RD-180 production process to enable the detection of manufacturing and quality issues prior to their release to the field. The engine acceptance test provides a final comprehensive test to verify manufacturing and quality of the engine assembly. Since the start of the production program, 55 engines have been delivered to the U.S. for Atlas launches. The RD-180 engine has been test-certified not only for the current Atlas V launch vehicle, but also for the tri-booster Atlas V heavy launch vehicle (HLV), although the Atlas V HLV configuration has not been built for flight service.

PWR and ULA have worked hand-in-hand with NPO Energomash throughout the development, certification, and production programs to assure program requirements are met. In addition to NPO Energomash providing Design Authority and manufacturing of RD-180 engines, PWR has developed extensive analytical and manufacturing capabilities. The analytical capabilities have enabled PWR to independently analyze performance, aero-thermal, structural, and control aspects of the engines operation utilizing state-of-the-art tools. As part of the RD-180 U.S. Co-Production program, PWR developed an extensive set of analytical models that are available to analyze issues should they arise. This was made possible by a license agreement between RD AMROSS and NPO Energomash that resulted in a complete set of design, manufacturing, test, and tooling documents being delivered to PWR to enable full co-production in the U.S. PWR utilized this documentation to demonstrate its ability to produce RD-180 hardware in the U.S. RD-180 stator and preburner assemblies were manufactured, assembled and tested in the U.S. as part of the Co-Production program. This effort also included replication of Russian materials utilized in the stator with preburner assembly.

The partnership of NPO Energomash and PWR for the RD-180 has verified the robustness and reliability of the RD-180. PWR's independent evaluation and analysis of the RD-180 combined with NPO Energomash's vast experience with the unique LPRE engine cycle of the RD-180 has developed a world class LOX/Kerosene booster engine second to none. Additionally, the combined effort of the NPO Energomash, PWR, RD AMROSS and ULA team has resulted in a high degree of program success, greater focus on attention to detail, and improved quality for the RD-180 Atlas V, more than any single company could provide independently.

C. Flight Experience

After engine delivery, the RD-180 engine is integrated with the Atlas V booster. Integration activities are currently performed at ULA's Final Assembly Factory in Decatur, AL. Upon completion of the engine integration work, the Atlas booster is transported to the launch site where upper stage mating and final launch processing tasks are performed. Launches are supported from either the Cape Canaveral Air Force Station (CCAFS) or Vandenberg Air Force Base (VAFB). Thus far, there have been 29 launches from CCAFS and four launches from VAFB.

The RD-180 engine is designed to minimize the work required to integrate, test and launch the Atlas booster. There are a small set of discrete plumbing and electrical interfaces on the engine for the launch vehicle to interface with. With these interfaces the time to integrate the engine onto the Atlas booster in the factory has been significantly reduced, from months for the previous Atlas booster engines to only a few weeks for the RD-180. In most cases, the minimum test requirements are only to verify that the plumbing connections are leak proof and the electrical connections are intact in order to support functional testing of critical systems. The level of engine testing required at the launch site is also streamlined to facilitate tight launch schedules. Currently, all engine integration and engine launch tasks are monitored by a joint NPO-EM/PWR/ULA team.

Currently, six Atlas III and twenty-seven Atlas V boosters have been processed at CCAFS or VAFB, resulting in a 100% mission success record. The lessons learned from these activities include altering test sequences to allow some engine tasks to be performed in parallel, eliminating redundant tests, and optimizing engine limits to reflect worst case vehicle and external environments. Atlas V vehicle processing times continue to be reduced as experience is gained. From an initial duration of over 6 months during first article campaigns, Atlas III and V processing times have been as low as approximately 1-1/2 months, with actual RD-180 engine testing being less than 25% of the total time. The lessons learned process is expected to further reduce launch site engine processing times to assist ULA in achieving even more optimized launch processing cycles. Detailed review of flight data is performed following each flight with NPO Energomash, PWR, ULA, and USAF/NASA customer participation. Data reviews for each flight show that the RD-180 has met or exceeded flight performance requirements.

II. RD-180 Assessments Which Support CCDev

A. Failure Modes and Effects Analysis (FMEA)

Originally, the RD-180 was designed as an expendable engine for use in launching commercial and government payloads. Since the RD-180 has a strong heritage and shares many of the same or scaled parts as the RD-170, it retains many of the features and characteristics required for human spaceflight on the Energia-Buran Russian space shuttle. Assessments have been made that indicate that the engine is currently in a configuration that will provide reliable propulsion for human spaceflights; hence, there is no need for redesigns to improve reliability or structural integrity. Assessments completed to date also indicate that the current instrumentation suite will provide the data required to assess impending engine malfunction and if an engine malfunction were to occur, provide signals to the vehicle Emergency Detection System to allow crew abort/escape.

Under the CCDev Phase I program, assessments were made in several key areas including identification of potential engine failure modes, engine operation characteristics in event that certain failures were to occur, timing assessments known as "Time-to-Criticality", Fault Coverage Analysis, and studies to evaluate behaviors of the LOX pump shaft displacements, hot gas duct temperature sensitivities, and chamber capability assuming variability in the mixture ratio. These assessments continue to support the current RD-180 configuration's ability to meet requirements permitting the engines' use on human spaceflight launch vehicles.

Early in the RD-180 development program, a Failure Mode and Effect Analysis (FMEA) and Fishbone Analysis were performed. Updates to the FMEA/Fishbone have been performed as recently as 2010 to make sure all possible failure modes and hazard controls are identified. The RD-180 FMEA is an integral element of the PWR/NPO-EM reliability analysis process. This analysis, which has been used extensively during the RD-180 program, provides a tool by which the potential failure modes of a design are analyzed to determine the effect on system (vehicle) and subsystem (engine) operation. The FMEA also identifies the hazard controls (such as: design considerations, non-

destructive testing, inspections, acceptance testing and development testing, etc.) that will prevent the occurrence of failure or minimize and control the effects of failure. The FMEA provides the results of the detailed analysis of system effects, failure modes, failure data/probability (at component level), and the design features and margins to preclude operational failure. The analysis identifies failure mode detection methods and design considerations implemented to prevent such a failure or to minimize or control its effect. Block diagrams were used to determine interaction effects between parts and the engine system, define the area of interest of the particular design analysis, and to organize the FMEA. Block diagrams were also used to schematically show the physical and functional relationships between systems, parts, or elements of parts.

The FMEA provided to ULA for the RD-180 program uses the same programming and format as used on other PWR products such as the RL10 Program. The RD-180 FMEA has been performed consistent with the guidelines of MIL-STD-1543B and is updated to reflect any major design changes or changes to any mitigation method that impact the hazard controls.

The fishbone analysis is a top-down, deductive logic, cause and effects process which results in a fishbone diagram. The fishbone process has been used to identify the root causes of a particular failure mode and its end effect; however, it does not provide mitigation. To complement the fishbone analysis, as well as provide mitigation, the FMEA uses an alternate “bottoms up” approach. The construction of the tops-down Fishbone compliments the FMEA to further assure that conceivable failure mechanisms have been identified and addressed. For the RD-180 engine, Fishbone diagrams were constructed consistent with Atlas requirements and formatted to assure ease of incorporation with the Atlas Fishbone analysis. To ensure that failure modes and mitigations are addressed, a cross reference matrix which was performed and provided to the Atlas team submitted with the FMEA/Fishbone documentation. Additional development of the Fishbone and primarily the FMEA is planned and described in later sections of this paper to focus on defining failure mode rates for those catastrophic failure modes that have higher probabilities of failure.

Once completed to the levels required for human spaceflight requirements, the RD-180 Engine FMEA identifies the appropriate characteristic of each FMEA parameter by failure mode. Characteristics for the following parameters are defined in the FMEA:

- Failure Mode & Cause - Data describes the failure mode and cause. At the highest component indenture level the FMEA identification number and component name are listed. At the next sub-tier indenture level the functional failure mode is described, and at the lowest sub-tier indenture level the hardware failure causes are identified. The analysis has been expanded to include separate specific hardware causes based upon the detailed supplier FMEA.
- Subsystem Effect - Data presents the effect of the specified failure mode on the components operation for failure of both redundant and non-redundant elements. Included are such component effects as valve binding or sluggish operation, loss of pressure signal to controller, external leakage of oxidizer, etc.
- System Effect – Data presents the effect of the specified failure mode on the engine and/or vehicle operation as observed by launch or flight personnel without regard to redundancy. Included are such effects as engine thrust degradation, limited engine operation, engine shutdown, loss of start capability, etc.
- Severity Category - Data contains a numerical classification for each failure mode. The classification provides a qualitative measure of the worst case potential consequences of each failure mode on the engine system. The baseline severity classifications of MIL-STD-1629A were tailored as follows:
 - Category 1 - Catastrophic - A failure which may cause a loss of life or loss of vehicle.
 - Category 2 - Critical - A failure which may cause a loss of the mission.
 - Category 3 - Marginal - A failure which may cause mission degradation or Minor - A failure which results in unscheduled maintenance or repair.

Additional classifications are provided for redundant systems. Category 1R, 2R or 3R – Same Criticality’s as listed above; however, the event requires redundant, i.e., like components to fail.

- Failure Detection Method - Data describes the methods by which failure modes, effects and causes are detected. Methods available to the launch or flight personnel, such as telemetry readouts (temperatures, pressures, RPM etc.), built-in test or other diagnostics, prelaunch leak tests and gimbaling tests, visual

inspections, etc. are included.

- Mitigation Methods - This data describes the hazard controls or design considerations that have been or will be implemented to prevent, minimize or control the specified failure modes. Overall mitigation methods that address the top level functional failure modes are shown followed by specific methods that address each hardware failure mode cause.

B. Demonstrated Reliability

Early RD-180 reliability predictions used the RD-170 as the baseline. This baseline was derived from and centered on the commonality of parts between the RD-180 and RD-170. NPO Energomash conducted 626 ground tests and flight firings, after establishing the RD-170 bill-of-material flight configuration. These firings were performed on 141 engines and accumulated over 85,000 seconds of hot-fire run time. During these firings, the RD-170 demonstrated the capability of achieving 25 hot firings on one engine and has achieved 10 or more firings on an additional 18 engines.

During the 626 firings, the RD-170 experienced 13 chargeable failure events for an overall system reliability of 0.9782 at 50% confidence (estimated using the binomial). The primary cause of each of these events has been established and corrective actions have been identified and incorporated. Although the initial RD-180 reliability estimates were based on RD-170 demonstrated reliability with improvements, additional prediction methodologies have since been employed. The RD-180 build and design has benefited from these previous failures and with all the stated corrective actions taken into account, the RD-180 reliability is estimated at 0.995.

The RD-180 has demonstrated excellent reliability. Over 45,000 seconds of operation have been demonstrated to date including 33 successful launches and 238 hot firings. All performance and structural issues encountered in development and certification testing have been addressed successfully to prevent their reoccurrence. The RD-180 design is robust and has proved itself. The main reliability consideration going forward is to assure that manufacturing or assembly related quality issues are not introduced. The engine hot-fire acceptance test provides such assurances and all RD-180 engines are subjected to a rigorous and comprehensive test prior to engine delivery. The hot-fire acceptance test includes operation at a multitude of power levels in addition to exercising mixture ratio extremes and chamber gimbaling sequences. Engine processing following test is conducted to further demonstrate product integrity and includes engine thermal vacuum drying, electrical and hydraulic tests as well as a multitude of inspections.

After the intensive flight-like hot-fire acceptance testing of the fully assembled RD-180 engine with its integral hydraulic system (with TVC actuators and EHA control valve), the RD-180 requires minimal intrusive post test processing, further ensuring the RD-180 is acceptable for flight and no foreign objects or faults have been introduced to jeopardize flight mission success.

The current prediction methodology used for the Atlas V RD-180 configuration used a series of public domain techniques to assess the data and establish an estimated reliability for production hardware design and processing. Using this data, an U.S. Army Materiel Systems Analysis Activity (AMSAA) reliability growth model was constructed. This modeling technique provides the means to evaluate the hardware for changes in growth patterns that indicate changes in the hardware capability. A reliability growth curve that shows a distinct knee demonstrates that changes made to the hardware from test and flight experience have resulted in an improvement to the inherent reliability of the system. This methodology has been proved out through various research where it was found that failure data of different systems during their development programs could be represented by a Weibull process, allowing for statistical procedures to be used in the application of the model in reliability growth. This modeling approach is used effectively on systems when usage is measured on a continuous scale.

Test programs are generally conducted on a phase by phase basis. The Crow-AMSAA model is designed for tracking the reliability within a test phase and not across test phases. A development testing program may consist of several separate test phases. If corrective actions are introduced during a particular test phase then this type of testing and the associated data are appropriate for analysis by the Crow-AMSAA model.

Reliability predictions should be evaluated relative to historical data and comparison to other similar engines is worthwhile. Such comparisons help calibrate the predictions and reduce the uncertainty in the predictions. A proper understanding of any previous failure event should be developed to assure determination of root cause, that assignment of corrective actions will correct the problem, and that its relationship to predicted reliability is assessed. Reliability predictions must properly account for how any given failure event relates to predicted reliability. Due to the relatively low quantity of rocket engines and tests, it is important to assess the uncertainty in the reliability predictions.

C. Engine Sensor Suite for CCDev

A Failure Response System (FRS) sensor suite is critical to the detection of engine failure modes such that action may be taken to protect the lives of the crew. A set of engine FRS sensors will be evaluated to identify high-value measurements that provide adequate response time to detect an impending catastrophic failure. Those that provide timely indications provide a significant benefit to Loss of Crew (LOC) will be incorporated into the Atlas V Booster Propulsion EDS measurement suite. The current RD-180 flight suite of sensors is adequate in assessing overall engine flight health and operability, and has recently undergone a preliminary assessment to determine its compatibility in support of manned flight. To support commercial crew flight there are certain minimum requirements that every sensor suite must meet. While the specific requirements for RD-180 supported commercial crew flight have yet to be finalized, they assuredly will include factors such as: 1) sensor redundancy; 2) high sensor reliability, and 3) quick anomaly detection. The recent FMEA evaluation performed under the CCDev Phase1 contract identified a select number of RD-180 sensors for consideration that have the ability to detect the most critical failure modes and will most likely satisfy future RD-180 sensor requirements for RD-180 manned flight. These sensors include MTU shaft speed sensors, Hot Gas Duct (MTU turbine discharge) temperature sensors, and MTU Oxidizer Pump axial shaft displacement sensors. All of these sensors are currently used by NPO Energomash as part of their ground test failure response system for the RD-180 as well as its family of engines (RD-171M, RD-191), and have demonstrated the capability to meet the three factors noted above (i.e., redundancy, reliable, and rapid anomaly detection).

MTU shaft speed sensors provide an overall indication of engine health, and more specifically, MTU turbo-machinery health. MTU shaft speed represents the output of the power balance between the MTU turbine and combined oxidizer and fuel pumps which rotate on a single shaft. Common to the staged combustion engine cycle, a disruption in this power balance will necessarily be reflected as a change in MTU shaft speed. A variety of factors may cause such a change to occur including turbo-machinery performance degradation, fixed plumbing or joint failures, and valve or valve actuator failures.

Hot Gas Duct (MTU turbine discharge) temperature sensors also provide an indication of MTU health as well as a reflection of preburner mixture ratio. Unexpected changes in preburner mixture ratio are driven by disruptions in preburner fuel or oxidizer flow rates and impact MTU turbine power through the resultant combustion temperature and total turbine flow rate. Such changes may be also be caused by turbo-machinery performance degradation or hardware failure, valve or valve actuator failures, and failures of preburner or Hot Gas Duct hardware.

MTU oxidizer pump axial shaft displacement sensors (proximity probes) provide for an evaluation of internal MTU oxidizer pump/MTU turbine axial load balance health. The MTU incorporates a single-shaft assembly comprised of two coaxial shafts; one encompassing the MTU fuel pump and another encompassing the MTU oxidizer pump and turbine. This allows for individual fuel pump and oxidizer pump/turbine axial load balance systems. Both shafts rotate together but provide for the required individual axial movement in order to balance rotor forces through the use of axial clearances within each of the axial load balance systems. Historically, failure modes associated with high-pressure oxidizer turbo-machinery have shown to produce the most severe or catastrophic consequences, and lessons learned throughout the RD-180 Development program have demonstrated that these displacement sensors have the capability to detect early indications of such failures. These displacement sensors provide for the detection of any off-nominal load imbalances within the oxidizer pump/turbine assembly which may be driven by an unexpected rise in internal pump cavity pressures due to an ignition event within the liquid oxidizer or oxidizer-rich combustion gas environments, failure of MTU oxidizer pump/turbine hardware, or performance degradation.

In addition to the sensors noted above, the RD-180 has several other sensors which have the ability to detect pressure, temperature, control valve/actuator position and displacement, and speed characteristics of the engine. Utilization of the data from these additional sensors is currently not envisioned to be required to assure crew escape in the event of an engine issue during flight.

D. Future Time to Criticality Assessments

Time to Criticality is the term used within the CCDev program to represent the time between failure detection and any potential catastrophic impact to the launch vehicle or crew. An EDS must be capable of both detecting and responding to an engine failure so that action may be taken to allow for crew escape before possible destruction of the launch vehicle to the extent that it represents a safety hazard to the crew. It is therefore important to understand which critical (catastrophic) failure modes are most credible and probable, and how quickly these failure scenarios initiate and propagate.

While the history of rocket engine failures in general would suggest that it is extremely difficult to detect an anomalous situation quickly enough to prevent catastrophic engine damage, it should be noted that the impact to the launch vehicle may be such that there is still sufficient time for the vehicle EDS and Spacecraft to perform crew escape maneuvers. Therefore the earlier that detection can be made, the better. Detailed understanding of these critical failure modes should allow for optimization of the engine sensor suite in order to provide the quickest possible detection and reaction.

An extensive qualitative analysis was performed during CCDev Phase1 to review all potential failure modes with the goal of identifying those with the potential for rapid development and propagation. For the purpose of this initial study, the concept of “rapid” was arbitrary utilizing a time of one second. A better understanding of the overall timing necessary to accommodate successful crew escape will require details of Spacecraft and Launch Vehicle avionics and associated software which will be used in the process of detecting and initiating engine shutdown and crew abort sequences. During CCDev Phase1, initial anomaly detection algorithms for use within an EDS have been developed utilizing RD-180 design, system performance, and development failure history.

While future work is still required to identify the more probable failure modes and likely consequences, emphasis has been given to failures within the liquid oxidizer and oxygen-rich combustion systems; this based upon RD-180 development experience and understanding of the staged combustion cycle with a LOX-rich preburner. This initial study has positioned PWR, ULA, and NPO-EM well for the next phase of CCDev work, which will utilize physics-based math models for in-depth understanding of the most probable failure modes and outcomes, such that a comparison between expected failure development time and Time to Criticality can be assessed.

E. Integration with Atlas

Since the RD-180 EDS system is based on the NPO Energomash failure response system (FRS) instrumentation suite, the instrumentation is already available on the RD-180 production engines at engine acceptance. The EDS instrumentation shall be proven during the hot-fire acceptance test. The MTU RPM measurements (in addition to other engine start health checks) are already used on RD-180 Atlas V for pre-launch engine health checks. These MTU RPM sensors already have the required sensor measurement redundancy, harnessing redundancy, and reliability. The redundant measurements are routed to the Atlas V avionics controller (Booster Remote Control Unit). There the MTU speed pulses are converted to engine pump RPMs and transmitted by the Atlas V communication system (1553 data bus) to the Fault Tolerant Inertial Navigation unit for launch commit health check and also to the EDS Processor Units (EPUs) for flight EDS monitoring. The other FRS measurements shall utilize this existing redundancy and harnessing methods to route the FRS parameters to the EDS Processor Units. EDS algorithm calculations shall be performed in the EPUs. The EDS Processor Units, associated EDS sensors/parameters and algorithms shall determine the Crew Transportation System (CTS) spacecraft abort recommendation. The CTS spacecraft can independently enable a manual abort or inhibit the Launch Vehicle EDS Abort request (Auto Abort Inhibit function).

F. System Assessments

The objective of the Commercial Crew Transportation System Certification requirements system assessments is to show that the intent of the stated requirements is met for the Atlas V/RD-180 CTS. Many of the CTS requirement documents' purpose are to provide requirements for the original design and assessment of the various systems of the CTS. Atlas V and RD-180 are already mature designs that have flight proven reliability that show evidence of meeting the intent of the stated requirements.

III. RD-180 State of Readiness for CCDev

The RD-180 engine is poised in an excellent position to satisfy CCDev program requirements. With its design heritage based on a configuration designed for manned flight, the RD-180 retains the features required to support reliable and safe operation on crewed launch vehicles. The RD-180 has demonstrated high reliability and excellent engine performance. Operability and structural characteristics are well understood not only by the Design Authority, NPO Energomash, but also by PWR and ULA. The RD-180 team has demonstrated that it can work together to quickly resolve any issues should they arise and currently supports an active vehicle integration and launch schedule. NPO Energomash and PWR are the only liquid rocket booster propulsion companies in the world to be design and flight readiness authorities for the most successful human spaceflight rockets ever designed, produced, and launched. Therefore, their collaboration and work together provides enormous heritage in successful human spaceflight propulsion design, verification and execution.

A. NASA Human Spaceflight Certification (HSF Cert) Criteria and RD-180

It is clear that in future manned space vehicles that there is a need for a paradigm shift in the approach to human spaceflight requirements to accommodate available NASA funding. Such shifts can not compromise crew safety and consequently the need exists for a realistic revision to the HSF requirements. In developing the HSF requirements, allowance for the following system capabilities should be considered:

- Understand system (vehicle and engine) failure modes: Using the FMEA/CIL (CIL=Critical Items List), this understanding must capture all potential failures, including inherent (design) and induced (manufacturing, assembly, integration), but it is equally important to have realistic estimates for the probability that the failure could occur. With probabilities established, focus should be on accommodation/mitigation of those failure modes.
- Have adequate fault sensing capability to identify the on-set of failure: The complexity of the sensing system should be minimized but must be reliable and global enough to address all unmitigated but realistic failure modes.
- Demonstrated reliability: Although many predictive tools exist to estimate system reliability, the reliability estimate is still just an estimate. Reliability demonstrated by conducting tests and launching vehicles is the best method to prove system reliability levels. Demonstrated reliability is enhanced by engine features such as high structural margins (which usually go hand-in-hand with fault tolerance), redundancy in fault detection sensors, and controls and software which can evacuate crew in a timely manner.
- Comprehensive Quality System: Historically, HSF requirements have relied heavily on fracture control plans which require thorough testing and analysis. The testing and analysis are required to establish inspection requirements (inspection flaw size, inspection technique, etc.) to assure that if flaws are present, they do not propagate to failure during operation especially in a reusable vehicle like the Shuttle Transportation System (STS). A comprehensive fracture control plan is less valuable for expendable vehicles. It is best to prove out fault tolerance by demonstrated reliability, supplemental margin testing, or through other mitigations. There are alternative approaches to providing an equivalent level of damage tolerance and the cost of the conventional approach may be prohibitive.
- Robust manufacturing processes: This process is best addressed through demonstrated capability by having a historical background of reasonably high manufacturing volume, supplemental inspections, and additional testing, as appropriate. Key to providing a reliable and safe engine is by assuring that each engine undergoes a comprehensive engine acceptance hot-fire test which represents or has margin

over the planned operational flight profile and conditions. The Atlas program has historically relied on a “test like you fly” approach which has provided a reliable product with 100% mission success.

IV. Plans for Future Work

A. Failure Modes and Effects Analysis (FMEA) / Critical Items List (CIL)

Although the RD-180 FMEA is reasonably well developed and is current with experience and knowledge of the engine, an expansion of the failure modes to lower part levels and especially part features is planned for failure modes that could result in a catastrophic failure and have a predicted probability of failure which may be considered to be a concern by human spaceflight criteria. A further expansion of the FMEA into a Failure Modes and Effects Criticality Analysis (FMECA) that evaluates failure modes that are most probable and are determined to be catastrophic would provide the optimum approach to an economical assessment of risk. The current RD-180 FMEA typically considers only single item failures; however consideration of multiple or redundant failures may need to be evaluated. HSF requirements need to establish guidelines on whether engine systems need to consider failure of redundant systems.

RD-180 FMEA severity classifications reflect the worst potential consequences of a failure mode, per MIL-STD-1629A for a single engine installation. Expansion of the FMEA into a FMECA could be done to evaluate severity classifications (and predicted probabilities of occurrence) for the more probable failure modes as this would be the driving factor for optimizing manned flight requirements based on acceptable and agreed to probability levels.

A preliminary RD-180 Critical Items List was defined in 1999 for Atlas V FMEA delivery document for Atlas V. When coupled with the FMEA, the CIL can provide the most value when it is used to summarize hardware having failure modes that either present danger to personnel or result in catastrophic loss of launch vehicle. The value of the CIL is in its ability to identify, track, and control critical items as well as to provide valuable inputs to the RD-180 production program. The CIL output will identify critical design features, tests, inspection points, and procedures which can be implemented to eliminate or mitigate the failure or minimize the probability that the failure would occur. HSF requirements can be met by lowering the probability to acceptable levels.

RD-180 hardware will be identified as a CIL item based on assessment of several factors such as key design characteristics, test results, inspection findings, failure history, and operational experience. Design assessments consider hardware attributes, design features and existing margins inherent in the hardware that can be relied upon to minimize or eliminate the probability of occurrence of the failure mode or reduce or eliminate the potential cause of the failure mode. Key design characteristics associated with hardware with the potential for a catastrophic failure mode are identified as such and actions incorporated to mitigate or reduce the probability of occurrence. Such actions include special notations in design and manufacturing procedures as well as enhanced or supplemental inspections to assure conformance to both design and manufacturing requirements.

An assessment of test results would include a description of specific test events and corresponding results that have been completed that present the opportunity to identify failure modes during component and engine development, certification, and acceptance testing. Inspection assessments would focus on inspection methods, procedures, tools, and techniques used in the hardware manufacturing, assembly, and integration process to detect vulnerability to failure modes.

Historical experience during development, certification, acceptance testing, and operational experience should be assessed to assure that corrective actions identified for past failures are considered in the CIL and properly mitigated or eliminated. Rationale for acceptability of the mitigations or confirmation of elimination of the failure mode is established in the CIL. Operational experience would be reviewed to assure that procedures and engine processing are performed to either prevent a particular failure mode from occurring or to mitigate its effect once it has occurred, and are included as part of the assessment. The results of the assessment may indicate that special actions need to be implemented such as mission procedures, crew procedures, or special crew training.

B. Future Time to Criticality Assessments

Building upon the initial qualitative Time to Criticality assessments performed during CCDev Phase1, future work will concentrate on the following areas: quantitative failure mode assessments, establishment of specific failure response system (FRS) limits, assessment of specific Time to Criticality values, and a final sensor suite recommendation.

Once the most probable engine failure modes have been defined, studies utilizing analytical models will be performed to better understand the physics of each mode initiation and how each propagates to surrounding hardware. RD-180 development experience will help to anchor these models to some of these failure modes. This will begin with an evaluation of available analytical tools to determine the need for further tool development. Specific limit values will be established for the most likely sensors to be used in the FRS. For the RD-180, the initially proposed set of manned flight FRS sensors discussed earlier are currently utilized within a similar abort system for RD-180 ground testing at NPO Energomash's test facility. Consideration will be given to these specific values as well as an overall evaluation of maximum engine capabilities (performance, structural, etc) in order to determine limit values that encompass acceptable margins. Ultimately, limit values will be selected to minimize the time of anomaly detection while also reducing the risk for a false abort due to setting FRS limits too tight. Follow-on simulations utilizing the EDS algorithms initially developed during Phase1 with these updated FRS limits will be performed for updated Time to Criticality evaluation.

Throughout the process, consideration will be given to possible alternate methods of detection if the alternate method results in a safe abort capability or if there are issues in being able to detect specific critical failure modes in a timely manner are highly improbable or do not appreciably affect LOC calculations. Ultimately, a final sensor suite recommendation will be made, ensuring that all sensors utilized within the EDS will satisfy all requirements for detection capability, reliability, redundancy, and other crew escape requirements.

V. Russian Experience with Manned Flights

April of this year marked the 50th anniversary of Yuri Gagarin's first manned flight. From the first flight through the present time all flights have used the Soyuz family of launch vehicles. More than 1,770 launches, including more than 115 manned launches, of the Soyuz launch vehicle derivatives have been completed to date.

NPO Energomash has a long and successful history of providing reliable propulsion for manned flights. The first and second stages of the above mentioned rockets use LOX-kerosene engines designed by NPO Energomash. Both manned and ordinary ("satellite") launches use identical hardware design and configuration. Although the engine hardware configuration is the same, there are differences in the requirements imposed on manned versus unmanned launches. These requirements are primarily in the organization of hardware manufacturing/quality control processes, as well as the requirements for procedures of supporting documentation preparation. In the case of manned flights, the additional requirements are mainly aimed at mitigation of risks associated with the "human factor". Thus, in particular, the requirements call for:

- The supporting documents for separate components and assembly units must have a mark "made for manned flight" signifying the criticality of the hardware and drawing attention to the importance of quality assurance provisions
- Each part, component or assembly, prior to its use, shall have a remaining shelf life of at least 5 years and remaining service life of at least 50% of the warranty period
- All documentation for the launch vehicle component parts shall have a special "label" to testify:
 - That the required certification was completed
 - That the requirements of the Statement of Work for development were met
 - That the requirements of the Russian State Standards were followed.
- Listing of critical production processes and inspection procedures to be performed in the daytime only

To ensure crew safety at power-on phase of flight path, an automatic emergency escape system is used, which, when a mishap comes, provides for shutting down of the propulsion engines and for departure of the crew capsule away from the launch vehicle (launch pad).

VI. Conclusions

As the name implies and the NASA CCDev website states, Commercial Crew Development is "... designed to help spur the innovation and development of new spacecraft and launch vehicles from the commercial industry, creating a new way of delivering cargo – and eventually crew – to low-Earth orbit and the International Space Station. As NASA retires the Space Shuttle, the ability of private industry to take on the task of providing routine access to space is of vital importance." Work completed to date by the Atlas V team indicates that the Atlas/RD-180 combination is in excellent position to provide the required low cost access to space. The Atlas/RD-180 rocket has 33 flights, all which have been successful and both the vehicle and engine are in serial production. Having been developed from the RD-170 (designed and certified for human flight rating in Russia), the RD-180 has the design characteristics required for the CCDev program. Under the Atlas EELV program, much work has been performed to evaluate potential failure modes utilizing the FMEA, Fishbone analyses have been completed, and engine reliability assessed and understood. Additionally, a Failure Response System is in place and is utilized currently for both engine acceptance tests and flight operations, with an Emergency Detection System used during flight operations based on the FRS sensor suite. Initial assessments indicate that the current FRS system will be adequate for EDS purposes; however, some additional work is required to add more depth to the FMEA, develop a CIL and to better quantify Time to Criticality for potential failure modes. Validated through years of test and operational experience, the Atlas V ULA/PWR/Energomash team has the tools and capabilities to thoroughly investigate Time to Criticality of potential engine failure modes. Additional system assessments and further integration of engine sensor capability with the vehicle software is planned for future CCDev program phases.

As the NASA HSF criteria continue to evolve, the Atlas/RD-180 team will reassess system capabilities and as necessary be ready to make changes to meet the requirements if needed. NASA is currently transporting ISS crews utilizing Soyuz rockets which have utilized the Russian approach to certifying rocket systems for HSF. Similarly, the RD-180 stands ready to provide such human transportation propulsion services on the highly dependable Atlas vehicle.