RD-180: History, Analysis, and Comparison of the Russian Rocket Engine

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The RD-180, a Russian rocket engine famously imported by the United States for use in core-stage propulsion, is a highly efficient rocket engine currently used on the Atlas-class launch vehicles. NASA and the U.S. government have received criticism for its prolonged import to the U.S, and many American-made replacements have been proposed and developed. In this report, a brief history of the RD-180 engine is presented, along with very recent developments in its use. Reported chamber pressure values are then used in a simplified technical model to compare its performance to the leading frontrunner in development for its replacement, the Blue Origin BE-4.

I. Introduction

No modern human invention has so literally opened as many new fields of human exploration or captured the imagination of millions as the invention of the rocket. Though the device has its origins in building weapons of war, the chemical rocket is currently the only method of producing the force required to escape the bounds of Earth. Famous German rocket scientist and engineer Dr. Wernher von Braun, arguably the most effective rocket engineer in human history, stated

> "It [the rocket] will free man from his remaining chains, the chains of gravity which still tie him to this planet. It will open to him the gates of heaven."

The rocket, at its most basic form, produces acceleration in the form of thrust. This acceleration imparts a momentum change on the launch vehicle in the opposite direction due to Newton's third law. The rocket engine's purpose is to convert the chemical energy of stored propellants into the work that supplies the thrust.

Rocket engines of today come in a wide array of shapes, sizes, mission purposes, propellants used, nozzle shapes, and many other various design criteria. The design of the rocket engine is typically optimized for a certain mission purpose–such as being man-rated for human missions, heavy-lift capabilities in Earth's atmosphere for first stages, or orbital insertion in near-vacuum upper stages. Much analysis and engineering work go into the design and optimization of the systems of fuel injection, combustion chambers, fuel mixing, nozzle shapes, and feed systems. Due to there

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typically being a relatively large design tolerance window in system requirements, the configuration and specific design specifications of rocket engines can take many forms. This results in many different families of rocket designs, offering various pros and cons in certain situations.

Intense modern rocket engine development began in the early-mid 20th century, in the era during and immediately following World War II. The preeminent rocket pioneers of the time included Robert Goddard of America, Hermann Oberth of Germany, and Konstantin Tsiolkovsky of Russia. Oberth designed some of the first liquid rocket engines (along with his then-student Wernher von Braun), Goddard built and tested early solid rocket motors (and even built and tested an electric ion thruster), and Tsiolkovsky published notes on multistage rockets, airlocks, and space stations. Rocketry saw unprecedentedly rapid development in the years immediately before and during World War II in Nazi Germany at the Peenemünde Army Research Center near the Baltic Sea. It was here that von Braun, Oberth, Arthur Rudolph, and many other genius rocket engineers worked on the Aggregat program–the program that would produce the world's first functional liquid rocket, the Aggregat-4–more famously known as the V-2, used to carry explosive payloads to bomb mainland England.

Rocketry saw further development in the years following World War II due to the Space Race, a symptom of the Cold War between the U.S.S.R. and the U.S. During this time, loosely the era of 1945-1970, both the Americans and the Russians rushed to use the newfound German rocket technology to further develop rocket propulsion systems that would help them establish superiority in the frontier of space. Impressive systems spawned as a result of this race to the stars–the Americans birthed the famous Redstone, Vanguard, Titan, Atlas, and Saturn systems. Models of these rockets are shown below in Figure 1 below, behind Dr. von Braun. The Russians birthed rocket systems such as the Vostok, Molniya, and Soyuz.

Fig. 1 Dr. Wernher von Braun stands with models of American rockets in his office at Marshall Space Flight Center in Huntsville, Alabama. Image credit: NASA.

To finally propel humanity to the moon, the Saturn V–America's moon rocket, often described as the most powerful machine ever constructed–employed five F1 engines in its core stage. The most powerful single-chamber rocket engine ever developed, one F1 produced 7.7 Meganewtons of thrust. Another notable engine produced in America in the years following the space race was the RS-25, the engine used as the Space Shuttle Main Engine (SSME).

Today, the United States has largely depended on the RS-25 developed in the early 1970s, with various engines (notably the RL-10 and Merlin) developed for upper-stages by American corporations such as Aerojet Rocketdyne, Blue Origin, and Orbital ATK. Russia has succeeded greatly in producing powerful, efficient, and reliable rocket engines in this rather dry period for the U.S. Russia today employs engines including, but not limited to, the RD-170, RD-180, and the RD-0124, which all employ a RP-1 (rocket propellant-1)/liquid oxygen propellant. Almost famously, the United States has imported the RD-180 for the past 20 years for use in core-stage propulsion. This study will summarize a brief history and current event developments of the RD-180 and its related politics, then evaluate the RD-180 on given technical parameters. The RD-180 performance will then be compared to its assumed replacement, the Blue Origin BE-4 (currently under development), and finally discuss the findings and analyze why this specific engine is still imported for use in the American market.

II. Background

A. Brief History and Current Events of the RD-180

The "RD" acronym of the RD-180 stems from the Anglicization of the Russian terms for "rocket engine". The development of the RD-180 began with the development of its parent engine, the RD-170. The RD-170, the world's most powerful multi-combustion-chamber rocket engine, utilized four combustion chambers in concert with a turbopump to feed fuel and oxidizer to the chambers. The RD-170 burns RP-1 as fuel and liquid oxygen (LOX) as oxidizer to achieve a joint thrust value at vacuum of 7.9 Meganewtons. This engine was designed for use on the Soviet *Energia* rocket system, though the rocket only saw two flights in the mid-1980s. The RD-180 was a lightweight, scaled-down version of this design. The RD-180 like its predecessor, utilizes RP-1/LOX propellant, yet possesses two combustion chambers compared to the four of the RD-170.

Today, the Russian aerospace company NPO Energomash builds and manufactures the RD-180. NPO Energomash also designed the engine in late 1994. American defense giant Lockheed Martin, newly formed after the merger between Lockheed Corporation and Martin Marietta, sought a new rocket engine for modernizing its line of Atlas launch vehicles. At the time, Lockheed Martin built and manufactured the Atlas family of rockets for launching various military and civilian payloads into space. NPO Energomash submitted proposals to the modernization program and, in 1996, won the contract [1]. By 1999, the first RD-180 arrived in the United States for mating to the Atlas launch vehicle (LV). The engine's first flight was in 2000 on the Atlas III LV.

The Atlas II core stage used three Rocketdyne RS-56 engines and utilized a 1.5 stage design, where two of the three engines of the core staged were jettisoned. The final engine then burned using the machinery previously used by the now-jettisoned engines. The final variant of the Atlas II, the Atlas IIAS, utilized six MA-5 engines on its core stage. Lockheed Martin sought a more reliable upgrade to this relatively risky and complicated system to market better launch reliability to its customers. On the Atlas III, the core stage was then able to be replaced by a single RD-180, due to its powerful thrust and high thrust-to-weight ratio. This design replacement alone increased the overall reliability of the Atlas III from 0.9876 to 0.9955 [2]. Use of the RD-180 as the core-stage propulsion system was continued on the Lockheed Martin Atlas V, whcih was first launched in 2002. In addition to its RD-180 core stage, the Atlas V employs two Aerojet Rocketdyne AJ-60A solid rocket boosters for added lift capability.

Today, the Atlas V is still in service for launching both civilian and military payloads to space. Additional configurations of the Atlas V are able to launch probes into deep space–it was a third-stage appended Atlas V that launched the New Horizons mission to Pluto in 2006. The Atlas V is now built and operated by United Launch Alliance (ULA), a joint venture between Lockheed Martin and Boeing. ULA today imports and mates the RD-180 engines to its Atlas V rocket core stage.

Fig. 2 A group of four RD-180 engines on the assembly floor of ULA's production facility in Decatur, Alabama. Image credit: ULA.

ULA, in recent technical proceedings, attributes the use of the RD-180 to its reliability–Brooke Moseley of ULA cites "hard won maturity in the areas of system design robustness and process discipline that are results of an evolved vehicle design ... being mostly a result of understanding and recovery from past failures in addition to past successes" [2, 3]. Following the fall of the U.S.S.R., Russian technology in rocket engines was first seen around the world. One of the technologies the RD-180 engine employs that its U.S. counterparts did, is a liquid-oxygen staged combustion cycle. In a staged combustion cycle, propellant flows through a *preburner* where a small amount is combusted. The energy of the small amount of combusted flow is then used to drive the turbine powering the turbopump to pump propellant into the main combustion chamber, increasing fuel efficiency. American engineers were hesitant to use this technology due to the increased risk of two combustion stages, increased flow of highly combustible LOX, and much higher chamber pressures required for the process [2]. This was a risk-reward that Russian engineers decided to take. Moseley cites that testing and certification processes around the time of the initial engine purchase in 1999 were "beyond anything achieved in the United States." The RD-180 was able to reach over double the chamber pressures of comparable American rocket engines in its class, which allowed the engine to achieve greater exit pressures, higher specific impulse, and thrust.

However, American-Russian relations have been highly uncertain in recent years. In 2014, these relations reached a point of volatility, with the Russian government annexation of Crimea. The U.S. imposed sanctions on Russian officials with the passage of Executive Order 13,661, which was an effort to put pressure on Russia by preventing Russian property to be "transferred, paid, exported, withdrawn, or otherwise dealt in" [4]. SpaceX, a competitor to ULA in the launch services sector, used these sanctions to argue to the United States Court of Federal Claims in 2014, stating that ULA's purchase of the engines were funneling "hundreds of millions of U.S. taxpayer dollars to Russia's military-industrial base" [5]. Following this argument, the Court ordered an injunction that prevented both the U.S. Air Force and ULA to purchase any products from NPO Energomash while the Court made sure any monies transferred to NPO Energomash did not interfere with the new Executive Order. Days later, the Court decided that ULA could further purchase the engines from NPO Energomash–however, Russian government officials by then had made it clear that disrupting the American supply chain dependent on RD-180s was certainly on the table. This was at a time when, following the ending of the Space Shuttle Program, the only ride to the International Space Station (ISS) was on the Russian Soyuz. In one instance, the Deputy Prime Minister Dmitry Rogozin, in charge of Russian space and defense activities, tweeted that he "suggest[s] to the USA to bring their astronauts to the International Space Station using a trampoline" [5]. A screenshot of the tweet is shown below in Figure 3

These politics led ULA and the United States to begin exploring development alternatives to the RD-180 for use in similar core stage applications of other rocket systems, and to replace those in use on the Atlas V. To date, the RD-180 is still employed today by the Atlas V, with 84 rockets being launched with RD-180 core stages as of June 2019. The current frontrunner for RD-180 replacement is the Blue Origin BE-4 engine, with is a methane/LOX propelled single-chamber engine under current development, with an expected thrust of 2.4 Meganewtons at sea level. Blue Origin has also stated that it will manufacture its new engines in Alabama. Other replacement options include the Aerojet Rocketdyne AR-1 engine and ULA-manufacture of the RD-180 itself, though ULA has indicated that the BE-4 is the planned replacement.

Extremely recent developments to the politics behind the RD-180 include further insight from current ULA CEO Tory Bruno. On April 16, 2020, Bruno responded to a Twitter follower inquiry on the reasoning behind purchasing the RD-180s in lieu of American engines. Bruno responded that the "[United States Government] asked [ULA] to buy

Fig. 3 Tweet from Deputy Prime Minister Dmitry Rogozin suggesting that the U.S. launch astronauts to the ISS "using a trampoline." This tweet was in response to the sanctions imposed on imported RD-180 engines in 2014. Image credit: Twitter, NBC News.

[RD-180s] at the end of the Cold War to keep the Russian Rocket Scientists from ending up in North Korea and Iran." The tweet is shown below in Figure 4.

Deputy Prime Minister Rogozin recently sarcastically commented on this tweet from Bruno, calling it a "strange explanation." "It turns out that a US company is buying our RD-180 engines not because they are the most efficient and reliable in their class (about 90 percent trouble-free launches on the Atlas rocket) but 'so that [our scientists/rockets] will not end up going to the Iranians and North Koreans'," commented Rogozin.

III. Numerical Analysis of the RD-180

A. Methods

In this section, basic equations are developed to calculate relevant values for the RD-180 rocket engine to use in comparing the engine performance to others in its class. This done by using known information such as propellant type, thrust at sea level, chamber pressure values, and nozzle expansion ratio.

Given a nozzle expansion area ratio ϵ, which is the ratio of nozzle exit area to nozzle throat area, isentropic flow in the nozzle can be assumed:

$$\epsilon = \frac{1}{M_e}\left[\left(\frac{2}{\gamma+1}\right)\left(1+\frac{\gamma-1}{2}M_e^2\right)\right]^{\frac{\gamma+1}{2\gamma-2}} \tag{1}$$

where M_e, the mach number at the exit of the engine nozzle, may be solved for iteratively or graphically. Once exit Mach

Fig. 4 Tweet from ULA CEO Tory Bruno responds to a Twitter question, stating the U.S. Government imported RD-180s to keep Russian rocket scientists out of enemy states. Image source: Twitter.

number is determined, the exit pressure P_e can then be determined by using the isentropic relation to chamber pressure:

$$P_e = P_c\left(1 + \frac{\gamma - 1}{2}M_e^2\right)^{\frac{\gamma}{1-\gamma}} \tag{2}$$

The characteristic velocity c^* can be a useful value for comparing engine performance. Characteristic velocity is a measure of energy available from combustion of the fuel and oxidizer in units of m/s. Characteristic velocity can be calculated as

$$c^* = \frac{\eta_c\sqrt{\gamma R T_f}}{\gamma\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2\gamma-2}}} \tag{3}$$

$$R = \frac{8314}{\bar{M}} \tag{4}$$

where η_c is combustion efficiency and R is the specific ideal gas constant of the propellant. Combustion efficiency is selected as a value of 1.05, which assumes frozen flow of propellant. With knowledge of c^*, ϵ, P_e, and P_c, specific impulse can then be calculated as

$$I_{sp} = \eta_n\left\{\frac{c^*\gamma}{g_0}\sqrt{\frac{2}{\gamma-1}\frac{2}{\gamma+1}^{\frac{\gamma+1}{\gamma-1}}\left[1-\left(\frac{P_e}{P_c}\right)^{\frac{\gamma-1}{\gamma}}\right]} + \frac{c^*\epsilon}{g_0 P_c}(P_e - P_a)\right\} \tag{5}$$

where P_a = 101.325 kPa is ambient pressure, assumed to be at sea level, $g_0 = 9.81 m/s^2$ is standard gravity of Earth, and η_n is nozzle efficiency, assumed to be 0.98 in this study. This calculated value of specific impulse $I_{sp,c}$ will be compared to reported values. Once specific impulse is calculated, the delta-v capability of the engine can be calculated using the Tsiolkovsky ideal rocket equation

$$\Delta v = I_{sp} g_0 \ln \frac{m_0}{m_f} \tag{6}$$

where m_0 is the initial mass of the rocket, also known as the "wet mass", or

$$m_0 = m_{inert} + m_{prop} \tag{7}$$

with m_{inert} is the mass of everything on the rocket not including propellant, and m_{prop} is the mass of the propellant to be spent. m_f is then the "dry mass"

$$m_f = m_0 - m_{prop} \tag{8}$$

In this analysis, due to the sake of comparison, the wet and dry masses are assumed to be the wet and dry masses of the Atlas V first stage. The mass of the propellant and dry mass of the first stage are assumed to be m_{prop} = 305143 kg and m_f = 21054 kg. Using the impulse-momentum theorem, an equivalent exhaust exit velocity (if the exhaust was constant velocity through the entire burn) can be calculated from specific impulse by

$$v_{eq} = I_{sp} g_0 \tag{9}$$

which, assuming a constant mass flow rate of exhaust throughout the engine burn, can be used in the equation for thrust using Newton's second law to find mass flow rate $\dot{m}$ of exhaust through the engine

$$\dot{m} = \frac{\tau}{v_{eq}} \tag{10}$$

This methodology will be used in the following section for analysis of both the RD-180 engine and the BE-4 engine.

B. Results for RD-180

Typical rocket engine parameters used for the RD-180 are given in Table 1. All propellant-related parameters (T_{flame}, $\bar{M}$, γ) are read off of appended graphs in Larson et al. for the fuel of RP-1 oxidized with LOX at a oxidizer/fuel ratio of 2.72 [6]. A calorically perfect gas (constant specific heat ratio) is also assumed. Values of specific impulse and thrust are used at sea level (SL) due to the RD-180 being used as a core-stage engine. All of the following equations are also given in Larson et al. [6].

Following the methods established above, the calculated performance values for the RD-180 are given below in

Table 1 RD-180 given values for select engine parameters.

Parameter	Value
Specific impulse I_{sp} (SL)	311.3 s
Thrust τ (SL)	3,827 kN
Nozzle expansion ratio ϵ	36.87
Chamber pressure P_c	26.7 MPa
Propellant	RP-1/LOX
Oxidizer-Fuel Ratio	2.72
Flame Temperature T_f	3600 K
Propellant molar mass $\bar{M}$	23.75 kg/kmol
Specific heat ratio γ	1.2175

Table 2.

Table 2 RD-180 calculated values for engine performance values.

Parameter	Calculated	Given
Specific impulse I_{sp} (SL)	310.63 s	311.3 s
Delta-v capability Δv	8350.90 m/s	-
Characteristic velocity c^*	1808.12 m/s	-
Exhaust mass flow rate $\dot{m}$	1255.86 kg/s	-
Thrust τ	-	3,827 kN

The delta-v capability of the core stage alone contains almost enough budget to get to low Earth orbit, as typical delta-v values for LEO from Kennedy Space Center launch complex range from 9.3-10 km/s (keep in mind that SRBs are used in the boosting stage). For additional comparison, the exhaust flow rate of the mighty Saturn F1 engine used to launch humans to the moon was 2,578 kg/s.

C. Results for BE-4

Design specifications of the BE-4 are not publicly available or speculated yet, so assumptions must be made. The BE-4 is designed to operate on liquefied natural gas (LNG) as a fuel and LOX as oxidizer. Since no oxidizer-to-fuel ratios are given, the molecular properties of the fuel must be estimated. Additionally, the nozzle expansion area ratio is estimated from diagrams published recently by Blue Origin *. Numbers used in calculation are given below in Table 3

Assumed values include oxidizer-fuel (O/F) ratio, flame temperature, and propellant specific heat ratio. These values were based on similar chemical compound parameters given in Larson et al. [6]. Nozzle expansion ratio was estimated by measuring approximate throat diameter to nozzle exit diameter in Figure 5. Chamber pressure and thrust values were given by Blue origin CEO Jeff Bezos in recent interviews †.

Using the assumed O/F ratio of 3, we can estimate the LNG/LOX propellant molar mass by simply adding the molar

*https://www.blueorigin.com/engines/be-4
†https://finance.yahoo.com/news/jeff-bezos-does-deep-dive-002201040.html

Table 3 BE-4 given and assumed values for select engine parameters.

Parameter	Value
Specific impulse I_{sp} (SL)	-
Thrust τ (SL)	2,400 kN
Nozzle expansion ratio ϵ	31.0
Chamber pressure P_c	13.4 MPa
Propellant	LNG/LOX
Oxidizer-Fuel Ratio	3.0
Flame Temperature T_f	3000 K
Propellant molar mass $\bar{M}$	28.0 kg/kmol
Specific heat ratio γ	1.23

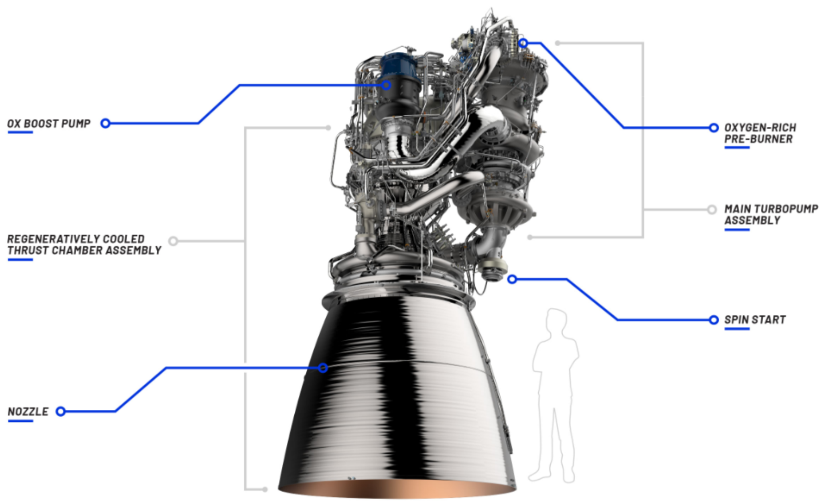

Fig. 5 Blue Origin BE-4 rocket engine diagram, with human presented for sizing scale. Image source: Blue Origin.

masses of both molecules with the associated parts

$$\bar{M} = \left(\frac{1}{O/F+1}\right)\bar{M}_{LNG} + \left(1 - \frac{1}{O/F+1}\right)\bar{M}_{LOX} \tag{11}$$

where molar mass of LNG $\bar{M}_{LNG} = 16$ kg/kmol and $\bar{M}_{LOX} = 32$ kg/kmol. To calculated delta-v, the same assumptions of the Atlas V first stage wet and dry masses were used. The calculated and given performance parameters for the BE-4 engine under the assumptions listed above are given below in Table 4.

These results are combined and discussed in the following section.

D. Performance Comparison of RD-180 to BE-4

The BE-4's use of LNG as fuel is likely due to LNG being a very stable fuel source–the substance can be stored easily in space, and poses a much lower hazard of explosion. On the business side, it is assumed that the development of

Table 4 BE-4 calculated values for engine performance values.

Parameter	Calculated	Given
Specific impulse I_{sp} (SL)	242.03 s	-
Delta-v capability Δv	6506.55 m/s	-
Characteristic velocity c^*	1514.62 m/s	-
Exhaust mass flow rate $\dot{m}$	1010.83 kg/s	-
Thrust τ	-	2,400 kN

such an engine by Blue Origin would like to expand its market to man-rated rockets of the future carrying humans to Earth-orbit and beyond, so this decision seems to be a sensible one. In thrust comparison, the the RD-180 has around 1400 kN of additional thrust than the BE-4, which likely points to multiple BE-4s being required to lift the Atlas V, unless additional SRBs or a longer burn time is used. This points to the BE-4 having a very high reliability requirement to make a sensible replacement for the venerable RD-180, as its adoption was originally all for reliability and simplicity. One interesting parameter for this reliability is chamber pressure. The BE-4 claims to have around half the chamber pressure of the RD-180, which could point to a decreased risk in the engine and a decreased mass (chamber thickness would be reduced due to less required strength for pressurization). The specific impulse of the BE-4 is about 80 seconds lower than the RD-180, largely due to the LNG fuel used, and there were no readily available rocket engines today using LNG to compare the specific impulse calculations to validate assumptions.

Other performance parameters, such as characteristic velocity and exhaust mass flow rate, make sense for the given thrust values. This analysis points at a slight design modification to the Atlas V system to use the BE-4, likely using two of then engines in concert on the core stage or modifications to the SRBs. If the BE-4 can maximize its use of the stable LNG as a fuel and achieve supreme reliability comparable to the RD-180, the replacement using the BE-4 for Atlas V core stage certainly seems to be sensible, especially considering the operational benefit of having the engine developed and manufactured less than an hour from the construction sit of the rocket itself. It seems that the major benefit of the RD-180, and its primary reason for import, is its extremely effective design and construction in handling the relatively high-risk process of LOX-rich multi-stage combustion and dual-chamber design, driving up fuel efficiency of the high-impulse RP-1/LOX combination to produce excellent amounts of thrust and efficiency. NPO Energomash has succeeded in the manufacturing and construction of the engine to the stringent design tolerances required for such a reliable engine, and has reaped the benefits monetarily due to customer satisfaction in the performance of their rocket engine.

IV. Conclusion

In this analysis, a brief history of rocketry and the Russian RD-180 rocket engine was discussed. Very recent current event development from business and government leaders in the U.S. and Russia was shown and discussed, and motivation for considering alternatives to the RD-180 was established. A simplified technical model was presented to produce engine performance parameters for given values and assumptions about both the RD-180 and its most-likely replacement, the Blue Origin BE-4 engine. These engines were then compared and the viability of this replacement was briefly discussed. A few ideas on why the RD-180 is still imported today were given.

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