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The US Department of Defense (DOD) increasingly depends on space assets for everyday operations. Precision navigation; communications; and intelligence, surveillance, and reconnaissance satellites are highly leveraged space assets. The launch vehicles that place these satellites in orbit are a major limitation of current space systems. If higher-performing launch vehicles were available, many satellites could accommodate additional capabilities, whether in terms of more sensor channels, types of payloads, electrical power, or propellant for orbital maneuvering and station keeping. Space assets are typically designed to conform to a particular launch vehicle's limitations (e.g., engineers might design a satellite to be carried by a Delta IV-2 medium launch vehicle). Essentially, this choice of vehicle fixes the maximum mass of the satellite and, thus, its capabilities. If a launcher capable of placing more mass in the desired orbit were available at similar cost, the satellite's design could allow for additional capability. Furthermore, some payloads are too heavy for present-day launch vehicles to place into a particular orbit. A better-performing launcher would enable us to put those payloads into the desired orbits, permitting new missions and capabilities. To overcome these limitations, the Air Force Institute of Technology (AFIT) conducts ongoing research into rocket propulsion technologies to improve space launch performance.

Two significant problems hinder space launch today: launch performance and cost. Performance involves the payload mass that a vehicle can place into a given orbit, whether low Earth orbit (LEO) or geosynchronous Earth orbit (GEO). The Delta IV Heavy, capable of delivering 50,655 pounds into LEO or 14,491 pounds into GEO, represents the current limit on DOD launch capacity.[1] Increasing this capacity necessitates either larger launch vehicles or higher performance from existing ones. Larger vehicles drive a series of additional expenses, including more propellant, expanded launch facilities, and bigger processing facilities. Although improved vehicles entail new development costs, they may be compatible with existing facilities.

Launching any medium or heavy vehicle costs hundreds of millions of dollars. One estimate puts total launch costs of a Delta IV Heavy launcher at $350 million; other estimates are somewhat lower.[2] A

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study by the RAND Corporation in 2006 places launch costs for DOD payloads at $100–$200 million.[3] The true expenditure of each launch is probably closer to the higher values at our current launch rates; however, more launches would push the cost per launch towards the lower values. Regardless, launch expenses are immense. Using the capacities and costs above, we can determine that the price of lifting payload to GEO amounts to $7,000–$25,000 per pound, and to LEO $2,000–$7,000 per pound. A Delta IV Heavy weighs about 1.6 million pounds at liftoff. Approximately 85 percent (1.3 million pounds) is propellant (fuel and oxidizer). If we assume an expenditure of approximately $5 per pound for both hydrogen and oxygen (averaged among hydrogen sources), then we spend about $6.5 million for propellant.[4] Because the price of fuel depends upon the cost of natural gas (the most convenient source of hydrogen), any estimates are quite volatile. However, even substantial changes in the cost of hydrogen will not have a great effect on overall expenses since the current propellant makes up less than 5 percent of the overall launch outlay; this simple analysis also applies to the cost of oxidizer. Thus, two large categories comprise about 95 percent of expenditures: launch base operations and launch vehicle materials and production. Clearly, reducing launch expenses entails (1) bringing down labor costs associated with the launch base by using simpler processes and designing for maintainability and higher reliability, and (2) lessening material and labor expenditures associated with the vehicle by making components reusable where possible, simplifying assembly of the launch vehicle, avoiding exotic materials, simplifying the geometry of component parts to reduce difficult machining steps, and so forth. AFIT's research in aerospike rocket engines, sponsored by the Air Force Research Laboratory Propulsion Directorate, seeks to increase vehicle performance and decrease launch costs.

Current Research: Improved Upper-Stage Engine

Current research at AFIT involves designing and optimizing a cryogenic liquid hydrogen / liquid oxygen upper-stage engine. This new engine design, known as the dual-expander aerospike nozzle (DEAN), will serve as an orbit-transfer engine to propel a payload from LEO to GEO. The DEAN differs from other cryogenic upper-stage engines in two ways. First, it utilizes separate expander cycles for the oxidizer and fuel. Second, unlike bell-nozzle engines, it employs an aerospike (radial inflow plug) nozzle (fig. 1).

In a typical engine-expander cycle, the fuel alone regeneratively cools the combustion chamber and nozzle.[5] Regardless of engine design, the chamber walls require some form of cooling since combustion temperatures typically reach about 5,000° F (stainless steel melts at about 2,550° F).[6] Energy transferred to the fuel during regenerative cooling acts as the sole driver for the turbo pumps that inject the fuel into the combustion chamber. Since the energy available to drive the pumps is limited to whatever heat transfer occurred during cooling, expander-cycle engines typically have relatively low chamber pressures. Higher combustion-chamber pressures would improve engine performance in three basic ways: First, greater pressures lead to more efficient combustion and enhanced energy release from the fuel. Second, higher pressures improve the potential specific impulse produced by the engine—improving thrust and performance.[7] Finally, elevated chamber pressures lead to smaller chamber volumes and potentially less engine weight, although this advantage is partly offset by the increased material thickness necessary to withstand the greater pressure.

The RL-10, the standard evolved expendable launch vehicle's upper-stage engine, utilizes the expander cycle. This cycle has the advantage of simplicity. Specifically, it does not require the preburners or gas gen-

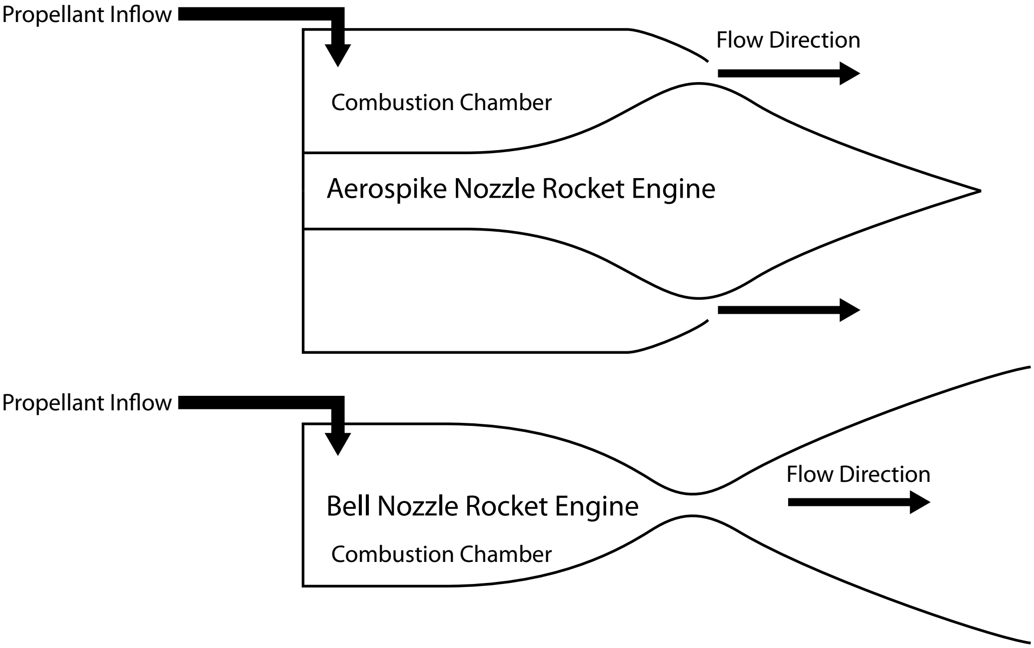

Figure 1. Geometry of aerospike and bell-nozzle rocket engines

erators needed by some other liquid-fuel cycles; it permits the use of lightweight turbo pumps because the working fluids in the turbines remain relatively cool (approximately 80–440° F rather than 2,200–3,100° F seen in other designs), allowing designers to choose lighter materials. Moreover, the cycle facilitates smooth ignition and start-up because it reaches full thrust with a much more gradual ramp-up, whereas staged combustion and gas-generator cycles tend to yield full thrust very rapidly.[8]

Although the DEAN uses the expander cycle, it is unique in that the oxidizer and fuel pass through separate expander cycles. The oxidizer cycle drives the oxidizer turbo pumps, and the fuel cycle drives the fuel turbo pumps. Since the pump and turbine sides of turbo pumps must share a common shaft, seals separate the high-pressure (pump) side and the low-pressure (turbine) side. A conventional expander-cycle engine has one turbine, driven by the fuel and two pumps on the single shaft—one for fuel and one for oxidizer. Although seals separate fuel in the turbine, fuel in the pump, and oxidizer in the pump, they have a potentially disastrous failure mode. If a seal between the high-pressure fuel and high-pressure oxidizer fails, the mixture of fuel and oxidizer can produce an explosion that would destroy the engine, launch vehicle, and payload. Separate fuel and oxidizer cycles have the advantage of physically separating the oxidizer and fuel until injection into the combustion chamber, thus eliminating the risk of explosions caused by failure of the interpropellant seals. Since the latter scenario represents one of the more catastrophic failure modes in traditional expander-cycle engines, the DEAN's dual-expander design can improve operational safety and mission assurance.[9]

The DEAN also uses a radial inflow plug nozzle primarily to enable the dual-expander cycle but also to allow a shorter, lighter engine. The direct performance advantages of the aerospike nozzle are not exploited in the upper-stage application for which the DEAN is designed. In low ambient pressure, which applies to upper-stage engines operating at high altitudes, aerospike nozzles behave like conventional bell nozzles. For these missions, the rocket engine requires a high expansion ratio for the nozzle, which increases the length and weight of the engine. For example, the Delta IV's second-stage RL-10B2 engine has a deployable nozzle extension to attain the required expansion ratio; the extendable portion of the nozzle, almost 6.5 feet long, weighs a little more than 203 pounds (an additional 86 pounds of equipment supports deployment).[10] In low ambient pressure, the aerospike offers savings in weight and size compared to an equivalent expansion-ratio bell nozzle, especially if the spike is truncated or chopped short of reaching a fine point, leaving a planar, blunt end (fig. 2). Research shows only negligible performance losses for the aerospike nozzle due to moderate spike truncation.[11]

DEAN Advantages and Design Considerations

The DEAN design offers many benefits over the currently operational orbit-transfer RL-10B2 engine, all of which would save the Air Force money, improve mission assurance, and help assure access to space for years to come. The DEAN engine, designed for high performance, saves engine weight and fuel, lends itself to manufacturing that uses today's technology, features robustness and tolerance of extensive ground testing,

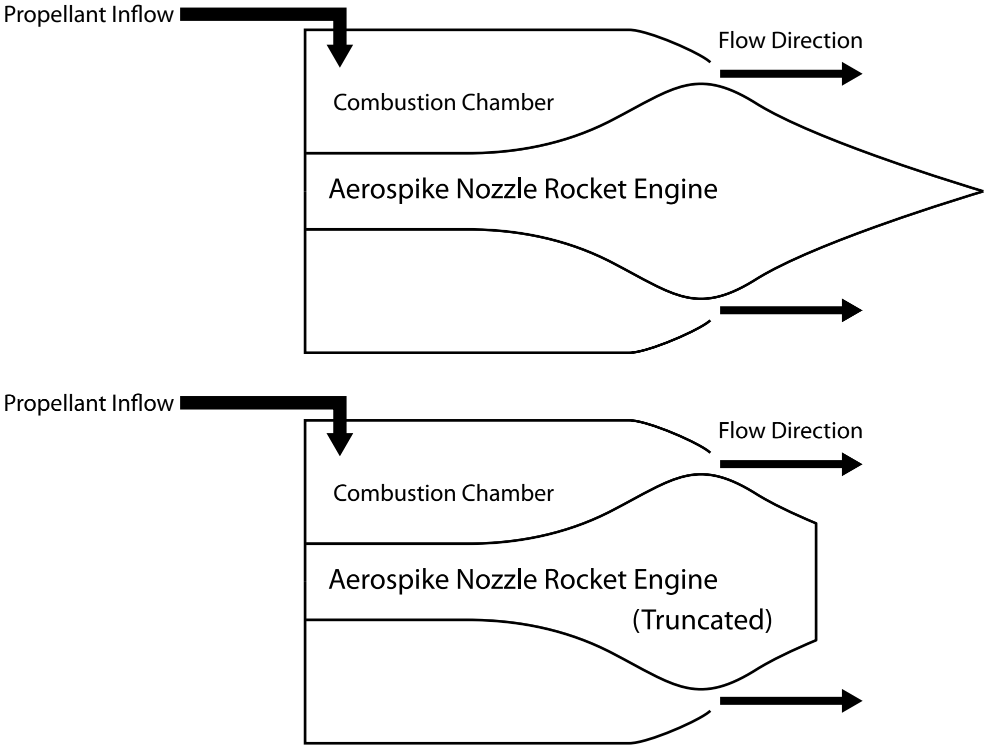

Figure 2. Geometry of truncated and nontruncated aerospike engines

and incorporates features that eliminate some catastrophic failure modes for upper-stage engines.

Any design strives to improve upon previous designs. Delta IV's RL-10B2 represents the current state of the art in upper-stage rocket engines, but the DEAN is designed to outperform that technology. When completed, AFIT's current models indicate that the DEAN will provide just over twice the thrust and weigh approximately 20 percent less than the RL-10B2.[12] Using a higher propellant-mixture ratio (i.e., less fuel and more oxidizer), the DEAN will operate leaner, demand less fuel, and thus decrease the money spent on fuel slightly since liquid oxygen is somewhat cheaper than liquid hydrogen. Furthermore, AFIT performance calculations indicate that matching or improving the specific impulse of the RL-10B2 results in a minimum stage-weight savings of 105 pounds due to the reduced estimated weight of the DEAN.[13] Any improvements in specific impulse would enable additional weight savings for the launch vehicle as a whole. The higher the specific impulse, the less propellant needed to realize the desired thrust. This weight savings permits an increase in payload weight, which may include the addition of new capabilities to the satellite being launched. Because of the costliness of launches, a savings in weight equates directly to one in expenditures; therefore, a 105-pound weight savings can save the government on the order of $1 million (at about $10,000 per pound, based on mean values of the costs discussed earlier).[14]

Utilizing an aerospike upper stage also brings indirect benefits to the first-stage booster. The interstage (part of the first stage) encapsulates the upper stage to protect its components during atmospheric travel. This component is dead weight in the sense that, though necessary for the mission, its weight decreases the amount of payload, engine, and propellant the vehicle can carry, so engineers seek to make the interstage as small and light as possible. Because the aerospike design is shorter than a bell nozzle and can produce the same amount of thrust, especially when the aerospike is truncated, the interstage structure can be made smaller and lighter compared to the interstage for the RL-10B2. Doing so equates to indirect benefits to the booster stage in weight, size, and performance.

The considerations discussed above influence the DEAN's design. Its combustion chamber and nozzle will use standard metals and ceramics compatible with the propellants. Furthermore, the engine will use current off-the-shelf turbo pumps and plumbing. Combined, these two features will improve the design's near-term manufacturability.

The DEAN's designers wish to make the engine reusable and robust enough to withstand extended ground testing prior to launch. Taking a conservative approach, AFIT engineers determined a maximum wall temperature for both the combustion chamber and aerospike that would prevent degradation of material strength. Our modeling rejected designs unable to maintain combustion chamber and aerospike temperatures below the limits established for the materials simulated.

Future Work: High-Performance Booster Engine

The next step in aerospike rocket research at AFIT calls for applying the aerospike nozzle to first-stage (booster) engines. The nozzle offers the significant performance advantage of operating nearly optimally at all altitudes below its design altitude, thanks to a capability known as altitude compensation. Conversely, a conventional bell-nozzle engine, such as the space shuttle's main engine, is designed for optimal operation at a single design altitude, suffering performance losses at all other altitudes. The aerospike design has significant performance advantages during operation through the atmosphere. In rocket engines, the nozzle expansion ratio is a key to maximizing engine performance. A high expansion ratio leads to low exhaust pressure, increasing the conversion of potential output (represented by the chamber temperature and pressure) to thrust output (exhaust momentum and pressure). Exhaust pressures in excess of the ambient atmospheric pressure for the flight altitude generate some thrust, but a larger expansion ratio could convert that extra pressure into increased momentum and more thrust than the pressure alone can provide. Therefore, for all rockets, the largest expansion ratio nozzle possible represents a performance advantage. However, for conventional bell-nozzle rocket engines, the nozzle's size has limitations. If the exhaust pressure is less than about 25–40 percent of the ambient pressure, the exhaust flow will separate within the nozzle, forming shock waves and causing large thrust losses. To avoid this condition, engineers generally design rocket engines to operate with exit pressures no lower than about 60 percent of the ambient pressure, providing some margin of safety.[15] This sets a practical limit for bell-nozzle expansion ratio, based on the lowest altitude at which the rocket is expected to operate. Normally, the engine designer sets the design altitude to about 12,000 feet, where the atmospheric pressure is about 62 percent of sea-level pressure.[16] Setting the design altitude any higher creates the potential for separated flow within the nozzle and greatly reduced thrust. Therefore, at all altitudes above that, the rocket produces substantially less thrust than it could ideally (see fig. 3).

The aerospike nozzle does not suffer from this disadvantage. Increased ambient pressure effectively reduces the expansion ratio to a point where the exhaust pressure matches the ambient pressure. In this way, the aerospike nozzle compensates for altitude up to its design altitude, represented by its physical expansion ratio. Above this altitude, the aerospike nozzle acts much like a bell nozzle, with the excess exhaust pressure generating some extra thrust as the rocket climbs above its design altitude. Since no fluid-dynamic reason exists for limiting the nozzle expansion ratio, the practical limit to the aerospike's ratio comes from the fact that the outside diameter of the engine effectively sets that ratio; thus, an extremely large expansion ratio requires a very large-diameter engine, adding considerable weight. The challenge lies in balancing the increased performance with the increased weight to find an optimal point for the launch vehicle.

This near-ideal performance becomes especially important during the low-altitude boost phase of the rocket flight. With no other performance changes to the launch vehicle, AFIT's initial modeling studies indicate that changing the first-stage engine to aerospike nozzle engines could produce an approximately 6 percent increase in the mass that the vehicle can lift to GEO. The difference in performance, calculated for identical chamber pressures and mixture ratios, could see improvement with changes to these and other parameters. AFIT's research aims at identifying an optimal engine design (or a set of optimal designs) that may not share operating conditions with current lift engines such as the RS-68 used in the Delta IV launcher. Performance alterations such as increasing the combustion-chamber pressure can significantly enhance specific impulse and payload capacity. If the aerospike operates at double the RS-68's chamber pressure, the improvement in mean specific impulse also doubles, as does the increase in payload capacity to GEO.

We have modeled the performance of a conventional bell-nozzle rocket, an aerospike-nozzle rocket, and an ideal rocket with an infinitely adjustable area-ratio nozzle and no thrust losses due to friction or other factors (fig. 3). The conventional rocket, built around a 12,000-foot design altitude to allow separation-free operation at sea level for launch, assumes a 95-percent-efficient nozzle design to account for friction and other loss effects. Note that the specific impulse remains below that of the aerospike at all altitudes except 12,000 feet. Furthermore, the shape of the curve for the conventional rocket does not track the ideal nozzle, indicating less-than-optimum performance at all altitudes. The aerospike rocket features

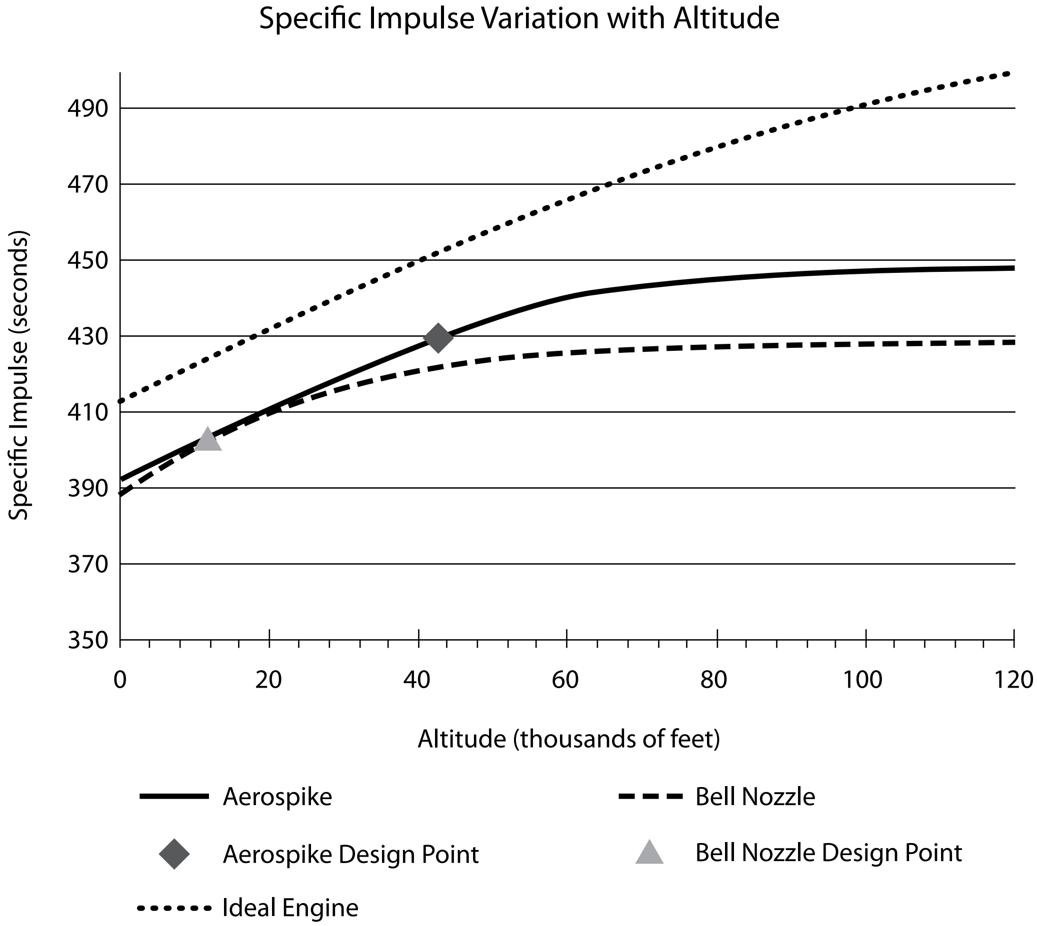

Figure 3. Performance advantage of aerospike engines in the atmosphere

chamber conditions identical to those of the conventional rocket but has a design altitude of 43,000 feet since that setting produced an engine slightly smaller than the diameter of a Delta IV first stage. The figure shows that the aerospike's specific-impulse curve runs parallel to the ideal curve, up to 43,000 feet. The aerospike curve assumes a 95-percent-efficient nozzle to account for losses, thus falling below the ideal. Notably, although the aerospike nozzle has a diameter of nearly 13 feet to reach exhaust-gas expansion appropriate for pressure conditions at 43,000 feet, the adjustable nozzle must expand from about six feet in diameter at sea level to almost 52 feet in diameter at 118,000 feet. To continue this performance until the rocket reaches near vacuum at 262,000 feet, the nozzle would have to expand to 672 feet in diameter—clearly impractical. Long before this point, the engine would become too heavy to lift itself, much less any fuel or payload.

Through a boost of slightly more than 3 percent in mean specific impulse on the first stage with an aerospike, without accounting for any weight savings by using the DEAN engine on the upper stage(s), current AFIT modeling indicates the possibility of realizing a 6 percent gain in maximum payload to GEO. Improving from a Delta IV payload limit of 14,491 pounds to GEO to 15,355 pounds would enable a significant increase in spacecraft capability as well as a decrease in the payload's launch cost per pound. Doubling the chamber pressure produces a 6 percent rise in specific impulse and a 13 percent increase in GEO payload—to 16,437 pounds. Similar performance improvements would also result from utilizing the first-stage aerospike engine to attain LEO orbits.

As with the DEAN's upper-stage engine, the aerospike-nozzle booster engines would be more compact than conventional bell-nozzle engines. Replacing the bell nozzle with the radial-inflow plug nozzle can expand the maximum diameter of the engine, but using a truncated aerospike allows a much shorter engine. Doing so can translate into weight savings and might make the aerospike engines more adaptable to multi-engine operations for larger lift capabilities.

AFIT set a goal of improving performance and producing a more compact engine while maintaining operability with key subsystems such as propellant pumps and materials. By ensuring that the performance required of the turbo pumps lies within that demonstrated in testing for realistic launch conditions (the National Aeronautics and Space Administration refers to this as technology readiness level six, a system adopted by the DOD acquisition community), AFIT can reduce the risks associated with depending on outside developments.[17] By restricting material choices to conventional metals and ceramics, the AFIT design team can avoid needing any breakthroughs in materials. However, the team will take advantage of any such advancements in scientific material to further improve the aerospike engine's performance in the future.

Conclusion

As an Air Force, we find ourselves at a decision point for space operations. Most of our rocket engines reflect decades-old technology in all aspects of their construction. Costs are high, and the vehicles are generally not reusable, even if we recover them after launch. At AFIT, our rocket team thinks that the Air Force can do better. The reduced weight of the DEAN would result in incremental improvements to launch capacity without extensive reworking of the lower stages. The increased specific impulse available from the aerospike first-stage engine could produce a significant improvement in the satellite weight we can place in orbit. Currently, the overall weight of the launch vehicle limits the capabilities of our space platforms. In many cases, we must omit adjunct payloads that could offer new or enhanced capabilities because we simply cannot launch the extra weight or provide electrical power (more power implies more weight in solar panels) to support the additional equipment. Enhancing our launch capability helps solve this problem. Moreover, designing engines for reliability, maintainability, and operability from the start will improve launch costs and launch rates. At AFIT we believe that the Air Force needs a push in the direction of building an updated launcher since we know that developing the technology will take many years, and building a new launcher many more years. As an air and space force, we cannot wait for obsolescence of current platforms to start development of a follow-on space launch platform. We must start now, and AFIT research is pointing the way. ✪

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Notes

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