

The Rise of Reusable Rockets- A New Frontier in the Age of Space Exploration

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ABSTRACT

This paper reviews how reusable rockets revolutionize space exploration by offering a sustainable and cost-effective alternative to traditional expendable models. Highlighting advancements like SpaceX's Falcon 9, it dives into the scientific principles, historical development, and technological innovations that make reusability possible. Reusable technology reduces launch costs, minimizes environmental impact, and enables new opportunities for missions ranging from satellite deployment to potential interstellar exploration. By examining engineering challenges and economic impacts, this research underscores reusable rockets as a cornerstone for progress in the modern space industry.

Introduction

Since the first humans emerged on our planet Earth, we wondered what lies in and beyond the stars. And now, with modern technology and innovation, we have become a step closer to achieving that dream. Around 55 years ago we sent people to the moon. Now, as we aim to send humans to mars and reach the stars outside our own system, it has become even more important to consider the efficacy of different rocket models.

This article reviews the science behind reusable rockets, the advancements in the commercial space industry, and the comparison between traditional rocket models and its reusable counterparts. In whole, it explores how reusable rockets make a better choice in terms of efficiency.

The Science Behind Reusable Rockets

Historical Evolution of Rocketry

Contrary to popular beliefs, rockets and their technologies possess a deeply intertwined history closely knit to the progress of human knowledge and technology. Their origins can be traced back to the Song Dynasty in China, around the 10th century, where gunpowder-filled tubes were used as primitive rockets in warfare, famously known as "fire arrows." Documented evidence of these applications did not become more prominent until the 13th century, where Mongolians and other cultures adopted such technologies for their own. However, the foundational principles of rocketry were understood even earlier. The first known device that employed basic rocket principles dates back to 400 B.C. in ancient Rome. According to the writings of Aulus Gellius [1], a Greek philosopher named Archytas launched a steam-powered device known as the "Wooden Pigeon" in Tarentum. [1] This early demonstration of jet propulsion predated the formal scientific principles, like Newton's Third Law of Motion—action and reaction—that would be defined, but not until much later in the 17th century.

As the centuries progressed, the usage of rockets within the human race began to progress significantly as well. By the 17th century (and even earlier), European scientists like Isaac Newton began formalizing the principles of motion, which lay the essential groundwork for modern rocketry. Rockets began to shift from being used as rudimentary military weapons to more sophisticated, advanced applications, such as fireworks and ceremonial devices.

By the 19th and early 20th centuries, scientists like Konstantin Tsiolkovsky and Robert Goddard made pioneering contributions. Goddard, who is often considered as the father of modern rocketry, successfully launched the world's first liquid-fueled rocket in 1926. His launch demonstrated that controlled and sustained rocket flight was a possible dream. It was not until the mid-20th century, however, that rockets began to venture into outer space, marked by Germany's MW-18014 test rocket in 1944. This development was pivotal as it set the stage for the space race that defined much of the Cold War era, culminating in achievements like the launch of Sputnik 1 in 1957 and the Apollo missions that sent humanity to the moon.

Modern Advances in Reusable Rocket Technology

With the progression of advanced rocketry into the modern space-age, the focus began to shift from mere space travel to optimizing each launch to the highest competence, reusability and cost-efficiency possible. Hence humanity began developing models of even higher complexity, such as reusable rockets. The introduction of reusable rocket technology has been a revolutionary milestone in this field at the very least, not only granting usage of the same rocket numerous times but also dramatically altering the economics, sustainability and accessibility associated with space exploration. Therefore, when evaluating modern reusable rockets, it is crucial to understand the complex engineering and scientific principles that underpin their design.

SpaceX's Falcon 9 is an example that illustrates the cutting-edge advancements of reusable rockets. The Falcon 9 operates using a two-stage design, where each stage has a specific role. The first stage contains nine Merlin engines, each optimized to maintain the highest efficiency against the vacuum environment of outer space, and provides the initial thrust required to break through Earth's atmosphere, reaching speeds of up to an astounding 7,500 km/h. This stage is equipped with grid fins, cold gas thrusters, and landing legs, allowing it to perform a controlled descent back to Earth. The innovative "boost-back" burn and landing maneuver enables the first stage to land on a drone ship or a landing pad, where it can be inspected, refurbished, and prepared for subsequent launches.

The second stage, powered by only a single Merlin vacuum engine, is responsible for delivering the payload—such as satellites or crewed capsules—into the desired orbit. Unlike the first stage, the second stage is currently not reusable, though ongoing research is exploring ways to recover and reuse this stage as well. The engineering behind the Falcon 9 allows it to withstand the extreme temperatures, pressure fluctuations, and the stress that entail multiple launches to space, which permits its first stage to be reused up to 10 times with minimal necessary refurbishment. SpaceX's advancements have drastically reduced the cost of space launches, with each reusable Falcon 9 launch being up to "65% cheaper, with a 30x reduced cost overrun." [2]



Figure 1-1. Falcon 9 Reuseable Rocket Model

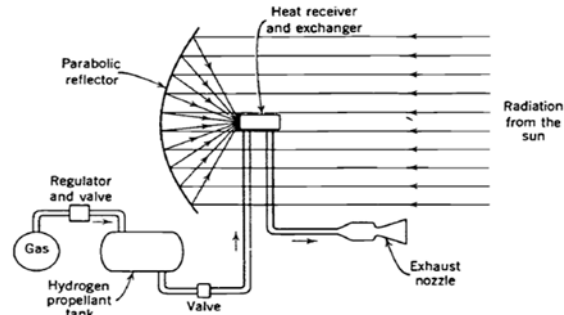


Figure 1-2. Reusable rockets structure diagram

Scientific Principles and Economic Impacts of Reusable Rockets

The underlying science of reusable rockets rests on principles of physics, material science, and advanced control systems. At the core is Newton's Third Law of Motion: for every action, there is an equal and opposite reaction. This principle governs how rockets generate thrust through the expulsion of high-velocity gasses. The engines of rockets like the Falcon 9 burn refined rocket-grade kerosene (RP-1) with liquid oxygen (LOX), producing the immense thrust required for liftoff. The control systems onboard manage complex calculations in real-time to adjust the rocket's trajectory and ensure a safe return of the first stage booster.

Materials science also plays a critical role, as reusable rockets are built from high-grade alloys, capable of enduring multiple extreme thermal cycles without degradation. For instance, the Falcon 9's engines are constructed using Inconel, a superalloy known for its heat resistance. Additionally, advanced thermal protection systems are employed to shield the rocket's components during reentry into Earth's atmosphere, where temperatures can exceed 1,600°C (2,912°F).

The economic impact of reusable rockets extends beyond mere cost savings. The ability to reuse key rocket components allows for a higher frequency of launches, facilitating faster deployment of satellite constellations for global internet coverage, scientific research, and space-based observatories. SpaceX has reported that reusing rockets has resulted in a 30-fold reduction in cost overruns, making ambitious projects, such as missions to Mars and lunar exploration, more feasible. Moreover, the success of reusable rockets has spurred competition in the private aerospace sector, with companies like Blue Origin and Rocket Lab also pursuing reusability in their designs, thereby accelerating innovation across the industry.

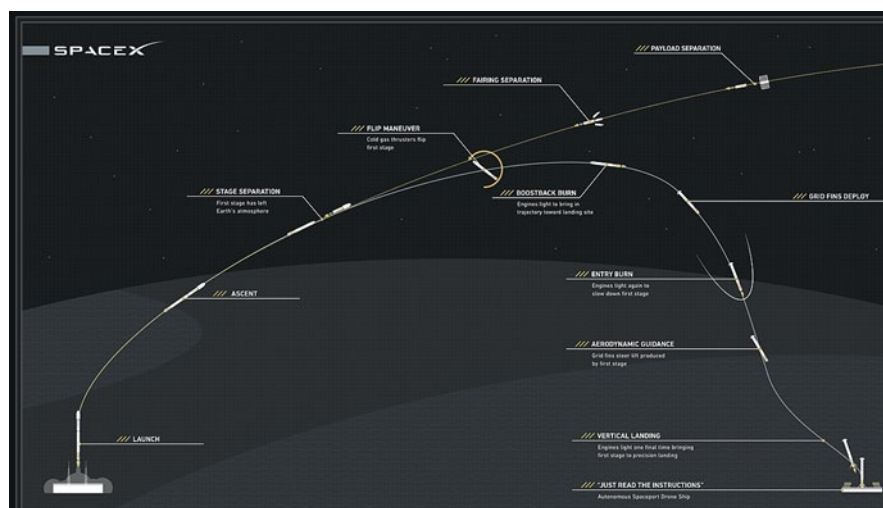


Figure 1-3. The following figure further explains the components of the Falcon-9 operated by SpaceX.

The Different Types of Rocket Models that are Revolutionizing the Space Industry

Reusable rockets are not the only existing technologies aiming to transform human space exploration, only a part of the bigger picture of our cosmos. In the human world if not anywhere else, other innovative concepts promise to push the boundaries of space exploration to the extreme. These alternative propulsion methods are paving the way for unprecedented speeds and distances, reshaping our approach to reaching beyond our solar system.

Solar Sails: Harnessing the Power of Light

A notable example is the Solar Sail, also referred to as light-sails or photon sails. A hypothetical Solar Sail Spacecraft uses the momentum from photons—particles of light—to propel themselves through space. By reflecting sunlight or directed laser beams off a large, lightweight sail, solar sails can continuously accelerate, reaching remarkable speeds. Despite the gradual nature of this acceleration, solar sails could potentially achieve up to an astonishing 10% the speed of light, or over 300 km/s, making them one of the fastest potential space vehicles. Their ability to accelerate without requiring on-board fuel allows for extended missions across the solar system and even interstellar space, making them an ideal candidate for deep-space exploration.

Warp Drives: Reimagining the Cosmos

Another revolutionary concept with groundbreaking potential is the Warp Drive, alternatively referred to as the Alcubierre Drive after renowned physicist Miguel Alcubierre. Rather than the traditional method of having a spacecraft follow a set trajectory through space, the warp drive concept involves bending none less than spacetime itself. How the Alcubierre Drive bends spacetime without breaking the laws of physics—specifically that of Einstein’s relativity—and without breaking the craft and its inhabitants, is no less astonishing. The spacecraft is contracting the space in front of the spacecraft and expanding it behind, using what is referred to as a "warp bubble," enabling faster-than-light travel without breaking the laws of relativity—and without having the craft and its inhabitants affected by the effects of a strangely-warped space fabric in front of them.

Though still purely theoretical—potentially involving an exotic matter that we do not yet know of—and despite its demands of immense amounts of energy and a rigorous understanding of physics, the Alcubierre Drive idea could make the dream of traveling to distant stars within a human lifetime none but possible. The prospect of a warp drive challenges our understanding of physics but offers an enthralling vision of exploring our universe far beyond the limits of conventional propulsion methods, and far beyond what humanity was meant to accomplish at all.

Fusion Propulsion: Power from the Stars

Alongside these advanced models, Fusion Propulsion offers a promising solution for future space travel. Drawing on the same nuclear fusion processes that power stars, this approach uses deuterium and tritium—which are two independent isotopes of hydrogen—to generate grandiose amounts of energy through fusion reactions. If controlled effectively, fusion propulsion could provide high thrust with excellent fuel efficiency, making it all possible to reach the outer planets of our solar system in just a few months. Moreover, this technology holds potential for interstellar missions, bridging the gap between our current capabilities and the dream of reaching other star systems. Although technical challenges, such as maintaining stable fusion reactions in space, remain formidable, the potential rewards could be transformative.

Nuclear Thermal Propulsion (NTP): A Path to Mars and Beyond

Nuclear Thermal Propulsion (NTP) is another promising technology that could reshape space exploration. By using a nuclear reactor to heat a propellant like liquid hydrogen, NTP systems produce significantly higher thrust than chemical rockets, allowing spacecraft to reach distant destinations more quickly and efficiently. For example, NTP could cut the travel time to Mars nearly in half, reducing the risks and challenges of long-duration spaceflight. It is a practical technology within our reach, potentially serving as a crucial step in making crewed missions to the Red Planet and beyond.

Antimatter Propulsion: The Ultimate Energy Source

Antimatter Propulsion represents one of the most exotic and high-energy options for space travel. When antimatter interacts with regular matter, the resulting annihilation releases an extraordinary amount of energy. This makes antimatter a highly efficient fuel source, theoretically capable of propelling spacecraft at a significant fraction of the speed of light. Such propulsion could enable missions to nearby stars within a human lifetime. However, the challenges of producing, storing, and containing antimatter remain daunting, as even minute quantities are extremely difficult and expensive to create. If these barriers can be overcome, antimatter propulsion might become a key to unlocking interstellar travel.

Magnetic Sails (Magsails): Riding Solar Winds

Magnetic Sails, or Magsails, offer another intriguing method for deep-space travel. By using superconducting wire loops to generate a magnetic field, these sails interact with solar wind—streams of charged particles from the Sun—or even the interstellar medium to create thrust. Magsails could enable spacecraft to travel long distances without needing to carry onboard fuel, making them especially suited for missions where mass constraints are critical. Additionally, they could decelerate spacecraft upon arrival at their destination, allowing for smoother insertion into orbit around distant planets or stars. This adaptability makes magnetic sails a versatile tool for future exploration.

Laser-Powered Particle Beams: Shooting for the Stars

Finally, Laser-Powered Particle Beams represent a cutting-edge approach to achieving extreme speeds. In this method, powerful lasers, either from the Earth or space-based platforms, direct energy beams at a spacecraft equipped with a lightweight sail. This targeted energy could propel the spacecraft at a significant fraction of the speed of light, far surpassing traditional propulsion methods. Projects like *Breakthrough Starshot* aim to use this approach to send small probes to Alpha Centauri, our closest neighboring star system, in just a few decades. While building the necessary laser infrastructure poses significant challenges, this concept could enable us to take the first steps toward exploring the nearest stars.

These advanced propulsion concepts, from solar sails and warp drives to fusion engines and laser-pushed probes, embody the spirit of human innovation in space exploration. While many of these ideas are still in their infancy, they have the potential to revolutionize our understanding of the universe and bring the dream of interstellar travel closer to reality. As technology continues to advance, these visionary concepts could serve as the foundation for the next great age of exploration, unlocking the mysteries of the cosmos.

The Rise of Reusable Rockets in the Commercial Space Industry

The environmental impacts of using reusable rockets has sparked numerous controversial debates over the decades, concerns ranging from manufacturing and launching processes. However, it should be understood that the benefits of reduced manufacturing outweigh the damage done from more frequent launches. To fully grasp this, it is crucial to understand the impacts of manufacturing new rockets for each launch and refurbishing and reusing existent rockets.

It is also a crucial part of reusable rockets that they can also be semi-reusable; the process of replacing and refurbishing specific parts between missions is facilitated with this characteristic. This includes popular rocket designs where only the first stage of a rocket is reused, while the second remains disposable. Although this approach doesn't provide all the benefits of fully reusable models, it still offers significant reductions in material waste and energy consumption. It's a middle-ground solution that can play an important role in making space exploration more sustainable.

The flexibility allows for a variety of approaches that balance between the cost, efficiency, and sustainability of the rocket. From commercial space tourism to satellite deployment and space mining, the future of space travel relies heavily on reusable rockets and it is imperative we recognize its historical significance. The idea of reusability dates back to the 1981 launch of the U.S. Space Shuttle, but recent technological advances have taken this further. Companies like SpaceX have led the way in developing rockets that can be reused multiple times, significantly reducing the need to build new rockets for each launch. This shift is set to transform the economics, environmental impact, and global competitiveness of the space industry.

In the past decade, the market for reusable rockets has grown rapidly, driven by rising demand for satellite deployments, space tourism, and other commercial space ventures. By 2023, the global space launch services market was valued at around \$10 billion, with expectations of continued growth as more companies embrace reusable technologies. The entrance of private players like Blue Origin and Rocket Lab has also accelerated this trend, as they develop both partially and fully reusable rocket designs. [13] Lower launch costs due to reusable rockets have made space more accessible, opening up new markets like small satellite constellations and space tourism. As costs decrease, more governmental and private entities are pursuing space-based research, communication, and commercial projects, creating a positive feedback loop of growth in the industry.

Reusable rockets present a chance to reduce the environmental impact of space exploration. The central debate focuses on whether the reduced need for manufacturing new rockets outweighs the environmental costs of more frequent launches. Analyzing this trade-off shows that, generally, reusability results in a net positive environmental outcome.

Manufacturing a new rocket involves significant energy use and resource extraction, such as aluminum, carbon composites, and high-grade alloys. These processes are carbon-intensive, contributing substantially to greenhouse gas emissions. In contrast, refurbishing a used rocket, like SpaceX's Falcon 9, requires far less energy and material resources. This means lower emissions from the manufacturing process, leading to a smaller overall environmental footprint.

The space industry once relied primarily on single-use rockets, which created considerable waste. Discarded rocket stages often ended up in the ocean or remained as space debris, posing long-term sustainability risks. For instance, the Saturn V rockets used in the Apollo program left behind massive stages that became environmental hazards, both on Earth and in orbit.

Reusable rockets have altered this paradigm by enabling multiple missions with the same hardware, significantly reducing waste and minimizing the number of discarded stages. SpaceX's successful reuse of Falcon 9 boosters has been a game-changer, helping to prevent tons of materials from becoming waste and contributing to a cleaner space environment.

In the era of single-use rockets, the concept of recycling was often impractical. Rocket parts typically burned up during reentry or became space junk. Even when parts were recovered, the effort required to dismantle and recycle them made the process inefficient. In contrast, the refurbishment of reusable rockets is far more effective, involving

careful inspection and maintenance of the booster rather than building an entirely new unit. This streamlined process reduces the energy and materials needed to prepare rockets for additional launches.

The development of reusable rockets is not confined to the U.S.; many countries are investing in this technology to strengthen their positions in the space industry. In Europe, Arianespace is working on partially reusable designs to compete on cost-efficiency. China has also made notable progress with its Long March rockets, testing reusable first stages to further its space ambitions. India's ISRO is developing reusable launch vehicle technology to lower costs and expand its global market share.

These international efforts reflect a growing recognition that reusable rockets are not just an American phenomenon but represent a global shift in how space exploration is conducted. This competitive landscape is likely to drive further innovation, making space more accessible and opening new avenues for research and commercial opportunities.

Reusable rockets have redefined the commercial space industry, offering a more sustainable and economically viable approach to reaching space. By minimizing the need for new manufacturing and reducing waste, they provide a solution to the environmental challenges of space travel. As more companies and countries invest in this technology, the promise of affordable and frequent space expeditions becomes increasingly attainable, paving the way for a new era in space exploration.

Case Study

In March 2023, SpaceX's Falcon 9 achieved a significant milestone during its Polaris Dawn mission, launching the first group of non-professional astronauts—civilians—into space. This mission marked a pivotal moment, demonstrating how reusable rocket technology could expand space access beyond professional astronauts and government-funded missions. The Falcon 9's reusable design played a critical role in this accomplishment, significantly lowering the cost of sending humans to space and making such missions viable for private entities and individuals.

The Polaris Dawn mission serves as a testament to the maturity and reliability of the Falcon 9's reusable technology. Unlike traditional rockets that are discarded after a single use, the Falcon 9's first stage returns to Earth and is refurbished for subsequent launches. This reusability dramatically reduces the cost of space missions, making endeavors like Polaris Dawn possible. The success of this mission not only demonstrated the rocket's ability to safely transport civilians but also redefined expectations for the future of space travel.

From a technical perspective, Falcon 9 has completed more than 200 successful launches, with many of those using previously flown boosters. The Polaris Dawn mission highlighted this capability, showcasing the practicality and efficiency of reusing hardware that traditionally would have ended up as space debris or sunk in the ocean. This aspect sets Falcon 9 apart in a market where many competitors are still working to achieve their first successful reuses.

The environmental impact of this reusability is mixed but forward-looking. While a reusable Falcon 9 emits about 27 tons of carbon dioxide per ton of payload, compared to 19 tons for a disposable rocket, the long-term benefits outweigh the immediate drawbacks. Each reuse means fewer rockets need to be manufactured, resulting in less industrial waste and resource consumption over time. The Polaris Dawn mission, by utilizing a reused booster, showcased this balance between short-term emissions and the long-term potential for a more sustainable space industry.

By making commercial spaceflight possible, SpaceX's Falcon 9 not only proved the feasibility of reusable rockets but also set new benchmarks for what private space travel can achieve. The mission redefined the reusable rocket industry by proving that cost-effective, repeated access to space is not just an aspiration but a reality. As SpaceX continues to iterate on this technology, the ripple effects of this success are likely to shape the trajectory of space exploration for years to come.

Conclusion

Reusable rockets propel the space industry into new revolutionary opportunities. By providing lower costs, better sustainability and numerous innovative rocket designs, reusable rockets are not only redefining how we explore the cosmos but also redefining what's possible within. Though traditional models have long served as the vehicle of exploration, reusable rockets allow humanity to think bigger, reach further, and dream of a time when exploring beyond our solar system is possible.

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References

- [1] Benson, T. (n.d.). *Brief history of rockets*. https://www.grc.nasa.gov/www/k-12/TRC/Rockets/history_of_rockets.html
- [2] <https://www.techtimes.com/articles/297262/20231006/japan-jaxa-launch-next-gen-reusable-rocket-research-following-spacex.htm>
- [3] Freeman, D., Talay, T., & Austin, E. (n.d.). Reusable Launch Vehicle Technology Program. *Science Direct*. <https://www.sciencedirect.com/science/article/abs/pii/S0094576597001975>
- [4] Bushnell, D. M., Moses, R. W., & Langley Research Center. (2018). Commercial space in the age of “New space”, reusable rockets and the ongoing tech revolutions. In *NASA STI Program* (NASA/TM–2018-220118). NASA STI Program. <https://ntrs.nasa.gov/api/citations/20180008444/downloads/20180008444.pdf>
- [5] Webb, R. (2016, October 17). *Is it worth it? - The economics of reusable space transportation*. NASA Technical Reports Server (NTRS). <https://ntrs.nasa.gov/citations/20160013370>
- [6] Technology demonstration for reusable launchers. (2014). *ScienceDirect*, 120–43–58, 42–58. <https://www.sciencedirect.com/science/article/abs/pii/S009457651530223X>
- [7] Reese, N. (2024, October 22). *The economic case for a Space Critical Infrastructure model*. SpaceNews. <https://spacenews.com/the-economic-case-for-a-space-critical-infrastructure-model/>
- [8] Lyles, G. (1999, January 1). *Technology maturity towards highly reusable space transportation goals*. NASA Technical Reports Server (NTRS). <https://ntrs.nasa.gov/citations/19990102610>
- [9] Baiocco, P. (2021, December 10). *Overview of Reusable Space Systems with a look to technology aspects*. ScienceDirect. Retrieved October 3, 2024, from <https://www.sciencedirect.com/science/article/abs/pii/S0094576521003970>
- [10] Weck, O. (n.d.). *Journal of Spacecraft and Rockets*. Aerspace Research Central. <https://arc.aiaa.org/toc/jsr/0/0>

- [11] Morgan Stanley. (n.d.). *A new space economy on the edge of liftoff* | Morgan Stanley. <https://www.morganstanley.com/Themes/global-space-economy>
- [12] Santomartino, R., Aversch, N. J. H., Bhuiyan, M., Cockell, C. S., Colangelo, J., Gumulya, Y., Lehner, B., Lopez-Ayala, I., McMahon, S., Mohanty, A., Maria, S. R. S., Urbaniak, C., Volger, R., Yang, J., & Zea, L. (2023). Toward sustainable space exploration: a roadmap for harnessing the power of microorganisms. *Nature Communications*, 14(1). <https://doi.org/10.1038/s41467-023-37070-2>
- [13] Blue Origin. (2024, September 3). *New Shepard* | Blue Origin. <https://www.blueorigin.com/new-shepard>
- [14] Ansar, A. (2023, September 28). *A platform approach to space exploration*. Harvard Business Review. <https://hbr.org/2022/11/a-platform-approach-to-space-exploration>
- [15] O'Callaghan, J. (2024, April 18). SpaceX's Starship could save NASA's beleaguered Mars sample return mission. *Scientific American*. <https://www.scientificamerican.com/article/spacexs-starship-could-save-nasas-beleaguered-mars-sample-return-mission/>