Post-Chemical Spacecraft Propulsion by Ferris McDermott

In his April 1932 letter to H. G. Wells, Robert Goddard stated that “How many years I shall be able to work on the problem, I do not know; I hope, as long as I live. There can be no thought of finishing, for ‘aiming at the stars,’ both literally and figuratively, is a problem to occupy generations, that no matter how much progress one makes, there is always the thrill of just beginning.”[1]

The work of Robert Goddard on liquid-fueled chemical rockets created the foundation for space exploration. Much more versatile than the solid-fueled rockets that came before, Goddard’s invention and subsequent refinements made space travel a practical pursuit. Since the beginning of the Space Age, liquid-fueled rockets have been a mainstay in space programs the world over. Yet it seems that even Goddard understood that his technology was limited. Today, engineers continue to brush up against limitations on the efficiency of chemical rockets. This inefficiency largely stems from the system’s slow exhaust velocity; for each particle of propellant expelled by the engine, it receives less force in return[2]. As a result, the scope of space missions using these engines is reduced. Because of this, a new age of rocket propulsion has long been underway, with a variety of new technologies being developed to go faster and further than chemical rockets currently allow.

This essay and accompanying infographic strive to evaluate a host of emerging propulsion technologies based on their capabilities and mode of operation. Technologies intended for launching from Earth typically need high thrust in order to move a payload out of the Earth’s gravity well. Interplanetary technologies opt more for efficiency, accelerating slower but with a higher top speed. Interstellar propulsion continues with this trend, with extremely high efficiency and proportionally high top speeds. In addition to these operational regimes, each propulsion system can be further categorized by the way they generate thrust.

Propulsion systems that use magnetism are a viable alternative to existing chemical rockets due to their greater efficiency. A technology that best demonstrates this is the Launch Loop. While not an engine in the strictest sense, the Launch Loop, also known as the Lofstrom Loop, uses magnetic fields in two separate ways during the course of its operation. The Launch Loop takes the form of a long and flexible tube situated at the equator. At either end are motors that use magnetic fields to accelerate a series of weights along the tube, which lifts it into the outer atmosphere at a maximum altitude of 80 kilometers at its peak[3]. When fully upright,

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[1] “The Papers of Robert H. Goddard.” *The New York Times*, 2 Aug. 1970, www.nytimes.com/1970/08/02/archives/the-papers-of-robert-h-goddard-the-papers-of-rhgoddard.html.

[2] Forsley, Lawrence, et al. *An Extremely High Isp Spacecraft Propulsion System*.

[3] “Launch Loop.” *NSS.org*, 2018, nss.org/settlement/nasa/Nowicki/SPBI116.HTM. Accessed 18 Jan. 2026.

payloads could be sent into orbit using a magnetic track[3], which would be much more economical than current chemical launch systems.

External Power is also a versatile replacement for chemical propulsion due to its weight-saving capabilities. External Power systems use a source of energy for accelerating propellant that is not stored on the spacecraft itself. An example of this would be the Laser Thermal Rocket system, wherein a high powered laser is directed at a collector, which in turn uses the generated heat to accelerate propellant[4]. The propellant can either be stored onboard or sourced from the ambient atmosphere, allowing for use in both launching and orbital applications[4]. Similar systems have been proposed using directed microwaves instead, but both operate on the same principle of keeping the vehicle itself light by having the main source of power (the laser or microwave emitter) on Earth[4].

Fission propulsion systems utilize the process of nuclear fission, either to accelerate propellant via heat transfer, or by directly expelling the products of the reaction. These systems are likely replacements for chemical propulsion due to the high energy density of fissile material as opposed to typical chemical fuels. The exemplar of this category is Nuclear Pulse Propulsion (NPP). In its original form as proposed by Project Orion in the late 1950s, Nuclear Pulse Propulsion derives thrust from the repeated detonation of specialized nuclear explosives against a reinforced pusher plate[5]. While an extreme example when compared to more modern systems, Nuclear Pulse Propulsion is particularly notable for balancing high thrust and high efficiency, as opposed to sacrificing one for the other.

Electrical engines accelerate their propellant using electrical fields. The best example of this is the Ion Engine, which has been successfully used in numerous applications from communications satellites and stationkeeping to deep-space probes[6]. Broadly speaking, an ion thruster accelerates ionized gas (typically xenon) by passing it through a positively charged grid, which accelerates the ionized gas at extremely high speeds out of the thruster[6]. While not possessing high thrust, the efficiency of the ion thruster, along with its extensive flight heritage makes it an attractive option for interplanetary missions.

Thermal engines use the heat generated by another source (external or internal) to accelerate propellant, generating thrust. A developing example of this concept is the Solar Thermal Rocket, which uses concentrated sunlight to heat propellant and expel it from a nozzle[7]. While not nearly as efficient as Ion Engines[7], Solar Thermal systems are still viable for

[4] Parkin, Kevin. “Microwave and Laser Thermal Rockets.” *Parkin Research*, 2 Mar. 2025, parkinresearch.com/microwave-thermal-rockets/.

[5] Schmidt, G. R., et al. AIAA 2000-3856 *Nuclear Pulse Propulsion -Orion and Beyond*. 16 July 2000.

[6] Patterson, Michael. National Aeronautics and Space Administration *NASA Facts - Ion Propulsion*. 2015.

[7] “Unconventional Rocket Drives - Solar Thermal Propulsion.” *Ic.ac.uk*, 2020, www2.ee.ic.ac.uk/derek.low08/yr2proj/solarthermal.htm.

a variety of applications, including orbit-to-orbit transfer and interplanetary missions[7]. Not only is it a demonstration of the principles of a thermal rocket, but it is also a near-term technology that could benefit future space missions, both crewed and uncrewed.

Field Propulsion refers to systems that derive thrust from existing natural fields, such as sunlight, solar wind, or planetary magnetic fields. While similar to External Power, Field Propulsion refers only to systems that directly derive thrust from these field interactions, as opposed to using the energy to propel a working fluid. The most well-known example of this is the Light Sail, which can be propelled either by natural sunlight or by laser[8]. Such sails, which have already been tested in space, use the radiation pressure of photons emitted by the sun to exert force on the spacecraft[8]. While photons are massless, they do impart a small amount of force when striking a surface. Although possessing an extremely slow acceleration, light sails require no fuel and have a high top speed, making them an attractive option for both interplanetary and interstellar exploration[8].

Fusion propulsion systems derive their thrust from the process of nuclear fusion, either by expelling the products of this reaction, or by using the generated energy to heat a separate propellant. This category of propulsion is one of the most expansive, and encompasses a variety of proposed concepts. Most notable among them is the Inertial Confinement Fusion (ICF) drive. Inertial Confinement Fusion uses an array of lasers to initiate fusion in a pellet of fuel, typically a mix of the hydrogen isotopes deuterium and tritium[9]. The resulting reaction is directed via a magnetic field to produce thrust[9]. Fusion engines are considered to be some of the most efficient possible given our current understanding of the laws of physics[9].

Lastly, the ultimate expansion of spacecraft propulsion capabilities are systems powered by the energy released by an antimatter annihilation reaction. Engines utilizing this principle can use the direct byproducts of this reaction, or the generated energy to heat propellant. Antimatter can also initiate a fission or fusion reaction in a separate target. The best example of an antimatter engine is the Beam-Core Antimatter (BCAM) concept, which uses the direct products of a reaction between protons and antiprotons to expel the resultant particles at relativistic velocities[10]. Such a system could theoretically propel a spacecraft at speeds up to 40% the speed of light[10]. These engines could make fast interstellar travel a reality, fulfilling the ultimate dream of taking humanity to the stars.

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[8] Johnson, Les. *From Solar Sails to Laser Sails*. 2017.

[9] Orth, Charles, et al. *THE VISTA SPACECRAFT-ADVANTAGES OF ICF FOR INTERPLANETARY FUSION PROPULSION APPLICATIONS*, 2 Oct 1988.

[10] Schmidt, G. R., et al. “Antimatter Requirements and Energy Costs for Near-Term Propulsion Applications.” *Journal of Propulsion and Power*, vol. 16, no. 5, Sept. 2000, pp. 923–928, https://doi.org/10.2514/2.5661. Accessed 18 Jan. 2026.

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As illustrated by the infographic, many of these concepts utilize more than one operational principle. Fusion engines using magnetic nozzles, thermal rockets using external power, etcetera. The current stage of propulsion engineering cannot be distilled into a single successor technology to the chemical rockets first pioneered by Robert Goddard. A century ago, the first liquid-fueled rocket graced the skies of Auburn, Massachusetts, ushering in a new era of space exploration. In cosmic timescales, 100 years is infantesimal, yet so much has been accomplished and learned as a direct result of Goddard’s work. In much the same way that Goddard sought to expand Humanity’s capabilities of exploration, scientists and engineers today continue to be inspired by his innovations, proving that “...aiming for the stars…is the work of generations...”.

Infographic Details and Citations

All engine renderings were created by Ferris McDermott using Blender. Development files can be provided upon request. AI was not utilized in the development of these files.

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